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Practical partial discharge pulse generation and location within transformer windings using regression models adjusted with simulated signals

Arismar Morais Gonçalves Júnior[a,*], Hélder de Paula[b], Wallace do Couto Boaventura[b]

[a] Federal University of Minas Gerais, Electrical Engineering Post Graduate Program, Belo Horizonte, MG, Brazil
[b] Federal University of Minas Gerais, Electrical Engineering Department, Belo Horizonte, MG, Brazil

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ABSTRACT

The early identification and location of high-frequency current pulses related to partial discharges (*PDs*) in the solid insulation of power transformers enable the optimization and planning of maintenance interventions, preventing unexpected power interruptions and reducing downtime. Even though several techniques for *PD* signal experimental generation and location have been proposed in the literature, limitations can still be noted, such as the difficulties in generating current signals similar to the *PDs* in incipient conditions and in the appropriate location. In view of these, in this work, new methods of experimental *PD* high-frequency current pulses generation and location are proposed, based on, respectively, the realization of small capacitive disturbances along the transformer windings and the use of multiple linear regression models. The proposed strategies allow the generation of current pulses similar to the *PDs* resulting from the initial degradation of the solid insulation and their effective location along the windings, even if only computational simulated data is employed in the adjustment of the locator linear regression models.

1. Introduction

More recently, due to the steady growth in demand for electricity and the volume of transferred energy, as well as the resulting operational stresses, a higher incidence of failures has been noted in power transformers [1]. In this scenario, studies show that internal faults in the windings present a high percentage of occurrence, around 30%, being directly related to the end of the equipment service lifetime [2,3].

Winding failures are essentially governed by the degradation of the solid insulation system, especially paper impregnated with oil. Operating stresses such as overvoltages and overloads, combined with the possible presence of moisture and/or oxygen inside the transformers tank, cause several chemical reactions that continuously deteriorate the electrical and mechanical properties of the solid insulation, until the point where a collapse occurs and a short-circuit is established.

According to [4,5], during its degradation process, small imperfections appear on the surface of the solid insulation, which represent electrically weak regions where the activity of small discharges takes place – the so-called partial discharges (*PDs*). Once the *PDs* are a precursor phenomena to the insulation failure and since the current pulses related to these discharges can be externally captured, mainly by coupling capacitors or high-frequency current transformers (*HFCTs*) installed in the accessible terminals of the windings, the early identification and the location of *PDs* in transformer windings have been largely investigated in recent years. The aim is to avoid the unexpected occurrence of a failure and the resulting power supply disruption and financial losses, also reducing the time of repair activities, due to the arduous and time-consuming visual inspection of the insulation degraded regions.

For the study of the *PDs* in transformer windings, different ways of experimental generation of the high-frequency current pulses have been reported in the literature. In general, the dielectric rupture in external arrangements of electrodes (rod-plane configurations), involving or not insulation samples, is adopted in most works, as in [6–13]. Even though current pulses similar to those of *PDs* originating from the solid insulation degradation can be obtained, with rise times of the order of some tens of nanosec-

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* Corresponding author.
E-mail address: arismarmgj11@gmail.com (A.M. Gonçalves Júnior).

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onds, the magnitude of the discharges can not be controlled, being difficult to generate current pulses with magnitudes corresponding to the *PDs* in incipient conditions. In [14,15], commercial and standardized *PD* calibrators are used, allowing the creation of current pulses with controllable rise times and magnitudes; however, the necessary expensive device is not always available in research laboratories. In [16], a simple arbitrary functions/signals generator is applied for the *PDs* generation; nevertheless, this type of device is not able to generate signals with power applicable in practical cases, and, besides, the generated current pulses presented a duration of 5 μs, which is considerably longer than the actual ones related to the *PDs* resulting from solid insulation failures.

Regarding the location of the *PDs*, the variation of the zeros of the transfer functions frequency response between these discharges occurrence point and the accessible terminals of the windings can be used, as their frequency values increase as the *PDs* move away from the measurement terminal [6]. Although this method is able to correctly determine the location of the *PDs*, results show the existence of a considerable “blind region”, where the zeros of the terminal frequency responses cannot be observed and, consequently, the regions where the *PDs* occur cannot be determined. In [17], pairs of transfer functions are used to estimate the *PD* waveform from the high-frequency signals captured at the accessible terminals of the windings, being the discharge location associated with the pair of transfer functions that estimates the input signal with the best similarity. Even though the *PDs* can be located with up to 5% accuracy, errors of up to 20% can occur for discharges next to the central regions of the windings, as noted in a later work [7].

Over the recent years, comparisons between the terminal measured waveforms, or certain features extracted therefrom, with sets of reference waveforms, whose *PDs* locations are known, have been used, as in [13,15,18,19]. Despite the significant increase in the performance and percentage of hits, in general, advanced signal processing and classification techniques are necessary. In this context, due to the limitations identified in the literature, both in the generation and location of *PD* signals along the transformer windings, new methodologies for both tasks are proposed in this work.

For the injection of high-frequency current pulses similar to *PDs*, very simple capacitors, but conveniently designed and constructed, are used to insert small disturbances in taps distributed over a winding, with similar rise time and amount of charge of the *PDs* resulting from the initial degradation of the transformer insulation.

Concerning the *PDs* location methodology, the multiple linear regression modelling (*MLR*) is applied, which represents a more elementary signal classification method, being the models adjusted by means of statistical features extracted from computational simulated signals at the accessible terminals of the transformers windings. Several advantages arise from such a simple method, which is not computational intensive and which does not need long period observations (data sample of tens of microseconds). It is particularly useful, for example, when dealing with incremental insulation degradation such as those caused by switching or lightning surges. Since the method uses very short time data samples, a pre and pos event analysis can be easily accomplished. Furthermore, *MLR* deployment, which is basically characterized by a set of equations, presents an adequate portability to allow its implementation in simpler hardware, facilitating the migration of the proposed methodology to the field.

2. Experimental setup

The prototype used in the investigations of this work corresponds to a winding with 4 concentric layers, each one composed of 438 turns, designed and constructed according to the specifications of an high-voltage winding of a 10 MVA, 8 kV, 60 Hz power transformer.

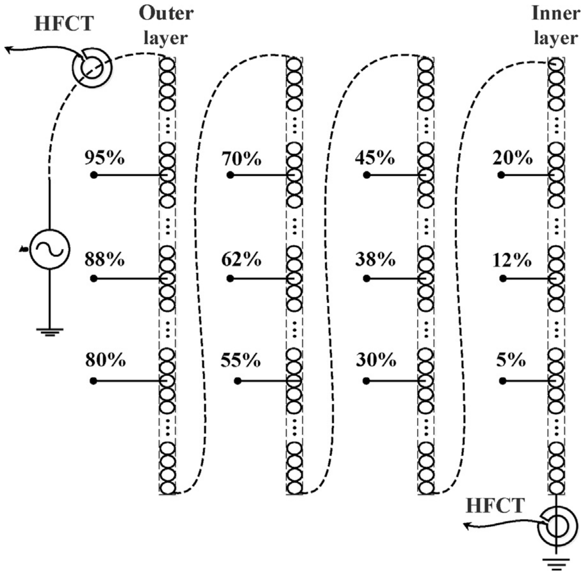

Fig. 1. Scheme of the 4-layer winding prototype.

The winding was built on one of the legs of a rectangular ferromagnetic core, using 20 AWG copper conductors. For the insulation between adjacent winding layers, as well as between the innermost layer and the core, 0.5 mm of Kraft paper with a polyester film was employed in addition to the insulating varnish of the conductors of 0.082 mm thickness. Between adjacent turns of the same layer, only the insulating varnish was used.

Throughout the winding construction process, 12 taps were derived along it, being 3 in each layer, to represent approximately 95%, 88%, 80%, 70%, 62%, 55%, 45%, 38%, 30%, 20%, 12% and 5% of the total turns, counting from the last turn situated at the base of the innermost winding layer, where the electrical grounding is fixed. The other winding ending, i.e., the first turn in the top of the outermost layer, was allocated for the electrical energy supply. Fig. 1 illustrates the 4-layer constructed winding, as well as the extracted tap positions.

Aside from the winding prototype, the experimental test rig consists of the following equipment: a single-phase, 10 kVA, 220–120 V/6.6 kV, 60 Hz transformer, used to increase the supply voltage of the constructed winding; a three-phase, 9 kVA, 220/240 V, 60 Hz variable autotransformer, to adjust the voltage for the step-up transformer; voltage sensor; high frequency current transformers (*HFCTs*) to capture the *PD* current pulses, installed at the extremity terminals of the test winding; and a 4-channel, 1 GS/s, digital storage oscilloscope (*DSO*), for the observation and recording of the measured signals. Fig. 2 shows an overview of the experimental test rig, with the tested winding and the equipment used.

2.1. PD *current pulse generation*

The experimental tests performed on the winding prototype sought to reproduce the *PDs* still in incipient stages of the failure. In general, current pulses are injected into the winding at the occurrence point of the discharges, tending to conductively propagate to the extremity terminals where they can be captured.

In order to generate current pulses similar to the *PDs*, it is proposed the use of properly designed capacitors for the insertion of small disturbances between the extracted taps of the energized winding and the ground. In each connection, the energy stored