Electric Power Systems Research 136 (2016) 398–405

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Partial discharges location in transformer winding using wavelets and Kullback–Leibler divergence

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ARTICLE INFO

Article history:
Received 18 May 2015
Received in revised form 17 January 2016
Accepted 12 March 2016
Available online 4 April 2016

Keywords:
Partial discharges
PD location
Transformer windings
Discrete wavelet transform (DWT)
Kullback–Leibler (KL) divergence

ABSTRACT

A new algorithm to partial discharges (PD) location in transformer windings by means of the discrete wavelets transform (DWT) and the Kullback–Leibler (KL) divergence is presented. When the insulation system of transformers has considerable damage, high levels of PD appear. A PD analysis will help to prevent and to avoid catastrophic faults in the transformer insulation system, and is also useful to quantify the damage level into it. However, it is a complex task, because PD signals have a small magnitude and are presented during some microseconds. In this paper, a lumped parameter model RLC is used to model the transformer winding and to obtain PD reference signals. The DWT is used to process those signals. PD location is finally estimated by means of the minimum entropy concept that minimizes the Kullback–Leibler (KL) divergence between PD signals (test and reference signals). Different time durations and amplitudes to the PD signals were considered. The results of computer simulation confirm the accuracy of the proposed algorithm, with an error less than 5%. Also, the algorithm is validated in a distribution transformer winding.

1. Introduction

Transformer windings suffer different types of stress such as mechanical, electrical, and chemical, among others. High levels of those give as a result major degradation into the insulation system. As a matter of fact, high levels of partial discharge (PD) appear when the insulation system has considerable damage, for that, PD in power transformers are widely studied precisely because are linked to the insulation system faults. Moreover, PD monitoring is used to diagnostic and to quantify damage in the transformer insulation system [1,2]. An early detection and location of PD in transformers can be useful to implement corrective actions, due to it has been reported as the second cause of failure [3], and to avoid that the power transformer can be out of services in an unexpected moment. Moreover, recurrent or periodic monitoring of the transformer is essential to guaranty the useful life of it. It is a fact that the reliability of the results will be directly related to the techniques used to asses their condition [4–6].

Several electrical methods in both time and frequency domains have been developed to detect and to locate PD in transformer windings; e.g. in [7] correlation technique in time domain is applied to PD location in transformer windings. Also, this technique is combined with the DWT, where detail (also called wavelet) coefficients are used to estimate the PD location [8]. However, these methods have their own limitations, so that in [9] a new algorithm in the frequency domain is proposed, in order to improve the time domain limitations.

Moreover, in [10] a neuro-fuzzy technique is presented for locating PD signals in power transformer, which uses unsupervised pattern recognition. In addition, other works have been developed for locating PD in transformer windings, e.g. in [11] a new technique based on series resonance frequencies is presented. In this way, transfer functions per section to PD location have been utilized in other researches [12–14]. However, these methods can be affected by noise, which limits their reliability and accuracy. By this reason, denoising processes have been included in some works, e.g. in [15] an adaptive morphological filter is applied to estimate the PD location in transformer windings.

A new algorithm to PD location is developed in this paper, where the algorithm is evaluated at different noise conditions and validated in a distribution transformer winding. Signal processing is carried out in time domain using the discrete wavelet transform

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http://dx.doi.org/10.1016/j.epsr.2016.03.020
0378-7796/

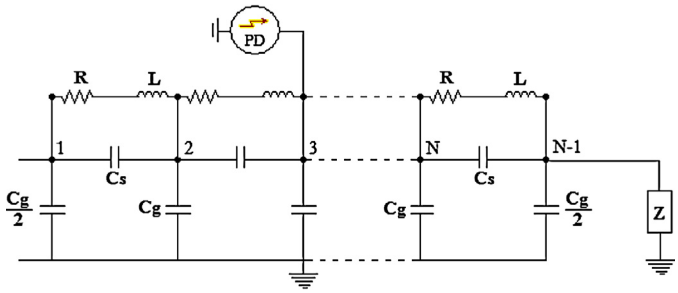

Fig. 1. Winding transformer model (*R* is the series resistance of the winding, *L* is the series inductance of the winding, *Cs* is the series capacitance, *Cg* is the capacitance to ground of the winding (turn-to-earth)).

(DWT), so as a new methodology to PD location is introduced based on a modification of the minimum Kullback–Leibler (KL) divergence called KL-modified. The proposed algorithm uses a ladder network for modeling the transformer winding. Moreover, a model for injecting PD signals between winding sections is also proposed. The algorithm requires PD reference signals which will be used to estimate the PD location, so that PD pulses in parallel along each winding section and between winding sections are analyzed. The results of computer simulation validated with measurements in a transformer winding confirm the accuracy of the proposed algorithm.

2. Transformer winding model

Winding modeling has been widely studied for analyzing internal voltage distribution in transformers, as well as other fast transient phenomena like partial discharges. As a matter of fact, the most used models for modeling a transformer winding are the lumped RLC detailed model and the multiconductor transmission line (MTL) model, each one with its own limitations and advantages, as well as its frequency range of validation [16].

This work is aimed at evaluating partial discharges along different transformer winding locations in order to estimate the PD position. The analysis is performed using a single transformer winding modeled by a ladder network with lumped parameters *R*, *L* and *C*, which is shown in Fig. 1 [17]. Although the used model has its own frequency limitations, this model is well suited for locating PD pulses in transformer windings [18], and it is used to simulate them in parallel along each winding section and also between winding sections. Moreover, the proposed method is validated by comparing the obtained simulation results with measurements in a distribution transformer winding.

In Fig. 1, each circuit section represents a disc of the transformer winding, i.e. it has *N* sections if there is $N+1$ nodes. When there is a PD pulse in a transformer winding, it produces signals that will be captured at the neutral terminal using an impedance circuit *Z*. Due that the proposed method requires PD reference signals, these signals are obtained from a calibration process according to [19].

In order to obtain the calibration signals and to show the viability of the proposed methodology, the transformer winding model parameters are taken from [20], which has 10 sections and its parameters per section (disk) are $L = 180\,\mu\text{H}$, $R = 1.2\,\Omega$, $Cs = 13\,\text{pF}$, $Cg = 3000\,\text{pF}$.

3. PD signals in windings

In practice the PD signal waveform cannot be handled easily, however, several PD effects can be analyzed using basic circuit models. In order to be able to adjust the pulse characteristics, in this work the PD pulse is characterized by the Heidler function, which is described as follows [21]:

$$S_{PD}(t) = A\left(\frac{t}{t+T_f}\right)^n e^{-(t/\tau)} \qquad (1)$$

where *A* is the amplitude of the PD signal, T_f is the rise time or front duration, τ is the time where the function amplitude has fallen 37% of its peak value and *n* is a factor influencing in the exponential function. For instance, if there is a PD pulse at section 3 of the winding (see Fig. 1), its response will be captured at the neutral terminal using the impedance circuit presented in [22].

The proposed algorithm should be calibrated theoretically and experimentally, so that the obtained information can be used as a numerical template [23]. The calibration process is carried out using the Alternative Transient Program (ATP/EMTP) software [24], so that a PD pulse is injected in parallel at each section of the winding. In fact, the Heidler function is used to model the PD pulse form and the calibration has an equivalent charge of 50 pF regarding to the standard calibration. This is shown in Fig. 2 where the obtained signals are quite similar with a slight phase shift. This shows that the use of the Heidler function is advantageous in order to handle the PD pulse characteristics.

Due to the proposed algorithm requires PD reference signals for each winding sections, these signals are obtained from simulations using the following data to Heidler function: $A = 327\,\mu\text{A}$, $T_f = 1\,\text{ns}$, $\tau = 200\,\text{ns}$ and $n = 2$. For instance, if a PD pulse is simulated at sections 1,2 and 3 of the transformer winding, the obtained PD reference signals are presented in Fig. 3; these signals are used to estimate the PD location, and are quite similar in each section, making more complex the PD location. Therefore, some researches are focused on this subject with the aim to know PD signal propagation characteristics, so as its damping factors due to the position of occurrence, among others [22]. In this sense, the proposed algorithm uses the information of PD reference signals with the aim to improve the PD location and to overcome the limitations of the algorithms in time domain.

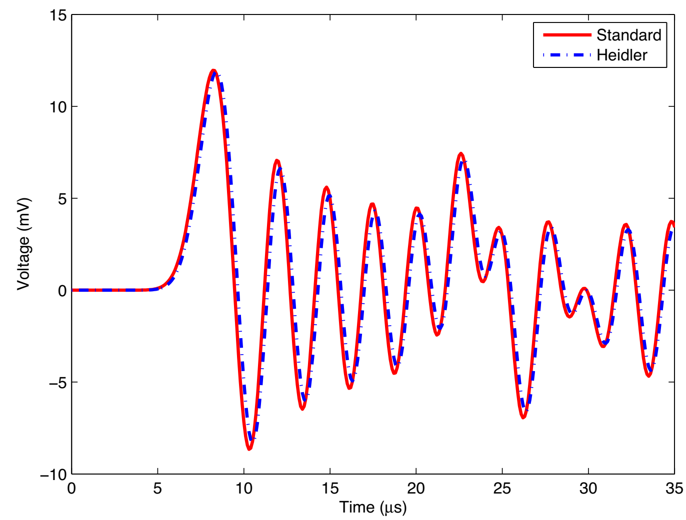

Fig. 2. Comparison between the standard calibration and Heidler function.

4. Discrete wavelet transform

Signal processing for PD location in transformer windings is carried out using the DWT, which has been introduced for locating PD in windings by Naderi et al [25]. Despite of the fact that the WT is considered as a very good tool for PD signal processing there are still some trial and error in its application. In this paper, its coefficients