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Evaluating the Improvement of Partial Discharge Localization Accuracy Using Frequency Response Assurance Criterion

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Abstract

Partial Discharge (PD) is the most important source of insulation degradation in power transformers. In order to prevent catastrophic failures in transformers, PDs need to be located as soon as possible so that maintenance measures can be taken in time. Due to the structural complexity of windings, locating the PD source inside a transformer winding is not a simple task. In this paper, the efficacy of the proposed Frequency Response Assurance Criterion (FRAC) correlation technique for finding the location of a PD source in a transformer winding is evaluated and compared with two well-known correlation techniques in this regard, that are Time domain correlation and Kullback- Leibler divergence. The responses of the winding to PD pulses, generated by Heidler function, of known pulse duration applied in parallel along the whole sections of the winding are considered as the reference data. In addition, the captured responses of the winding generated by injecting the PD pulses of arbitrary shapes and magnitude along the various sections of the winding are taken as the test data. Subsequently, the location of the PD source is determined by finding the maximum FRAC value between the reference signals and the test signal. First, a simulation case-study is carried out to show how the proposed method can be applied to locate a PD source. Subsequently, the results of the proposed method are compared with the time-domain and Kullback–Leibler divergence correlation techniques. Finally, the proposed method is validated with the experimental results. The simulation and experimental results demonstrate that the proposed method is more effective in precisely determining the location of a PD source even in a very noisy condition.

Keywords: Partial discharge; Correlation method; Transformer winding; FRAC; PD location; PD
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1. Introduction

Partial Discharge (PD) is the main source of insulation failure in transformers. The capital cost of a transformer is very high, and the economic penalties of transformer failures as the result of PD activities are significant [1]. The PD activity, which occurs over time, inside a transformer leads to further aging, degradation, and ultimately catastrophic failures [2]. Therefore, it is necessary to estimate the magnitude and precise location of PD sources in order to enhance the security and reliability of power grids. However, determining the accurate location of a PD source is a difficult task due to a highly complex and non-uniform structure of transformer windings, and the stochastic nature of a PD as well [3]. Estimating PD location at early steps enables us to make decisions about taking the power transformer out of service for maintenance or to increase monitoring while operating [4]. According to the literature, determining the PD location can be classified into two categories: acoustic methods and electrical methods [5]. A number of algorithms and acoustic sensors have been devoted to finding PD location in transformers [6-8]. Although the acoustic methods are simple, they have low sensitivity [5]. In addition, the sensors used in acoustic methods increase the cost of locating PD sources [9]. The electrical methods, proposed in numerous papers, are more precise and economical [3]. Early works [10] on locating PD presumed that a transformer behaves like a capacitive network, but the capacitive network model is only valid for a certain range of frequency. In [11], a digital filtering technique is employed to extract the proper frequency range of a capacitive pulse distribution due to a PD. The transfer-function-based method for determining a PD location using the frequency positions of the poles and zeros is proposed in [4, 15-14], but according to the authors, it might become difficult to locate a PD precisely in an interleaved winding [3]. In [15] a method based on time-domain correlation is proposed which estimates the PD location successfully only when the width of the PD test and reference pulse is the same [16]. To overcome this limitation, in [17], the time domain PD response is converted into the frequency domain, then signals are ortho-normalized, and finally, the correlation technique is applied to find the PD location. A technique based on the Archimedean Copula is also employed in [18] to locate the PD source. Moreover, in [5, 19-22], different denoising processes are suggested to increase the reliability and accuracy of estimating the PD location in transformer windings. In this paper, a technique based on the Frequency Response Assurance Criterion (FRAC) is used to determine the location of a PD source in a transformer winding. Further, to evaluate the proposed method, a lumped parameter model RLC is used to model a transformer winding and obtain reference signals. Finally, the efficacy of the method is compared with the Time domain and Kullback–Leibler divergence correlation methods.

2. Transformer Winding Model

Ttransformers winding modeling is an important task in electrical methods. For transformer winding modeling, two models are usually used – the lumped parameter model and the MTL model [5, 23, 24]. In this paper, a partially interleaved winding is used to realize the concept of correlation and evaluate the accuracy of the proposed method. The percentage of interleaving is 20% and the number of winding sections is considered 10. Fig. 1 shows a 10-section lumped parameter transformer winding model with 20% of interleaving. The model consists of the series capacitance (Cs), the ground capacitance (Cg), the resistance (R) and the inductance (L). The parameter values of the lumped circuit model are listed in Table 1 [25].

Table.1.
Circuit parameters of the transformer windings

Parameter	Value
R (Ω)	1.5
L (µH)	4.5
C_S *(pF)*	50
C_g *(pF)*	46.7

3. pd Location Using FRAC

The Frequency Response Assurance Criterion (FRAC) is used to determine PD location in the transformer winding. In the proposed algorithm, FRAC values are calculated among the set of simulated reference and test PD signals, and it shows a linear dependence between two signals. FRAC is the frequency domain equivalence of the correlation coefficient which is described as follow [22]:

$$FRAC_k = \frac{\left|\sum_{f=f1}^{f2} S_k(f)\, X_x^*(f)\right|^2}{\sum_{f=f_1}^{f_2} S_k(f)\, S_k^*(f) \sum_{f=f_1}^{f_2} X_x(f)\, X_x^*(f)} \qquad (1)$$

where f1 and f2 are the lower and upper limits of the frequency, respectively. S_k is the PD reference signal generated by injecting Heidler function along the section 'k', and X_x is the winding response generated by applying the PD test pulse to unknown section 'x'. The symbol '*' also indicates the complex conjugate of the corresponding signals. In order to utilize the FRAC value to measure the correlation among the set of simulated reference and test PD signals, both PD reference and test signals are converted into the frequency domain, $S_k(f)$ and $X_x(f)$ respectively, using MATLAB functions. The values of the FRAC is variable between +1.0 and 0. The values close to +1.0 indicate a linear dependence among the signals. Therefore, the location corresponding to the PD reference signal which returns the maximum value of the FRAC with the PD test signal is the location of the PD source.

4. Simulation Results

In this paper to locate the PD source, reference and test signals are used. The reference signals are obtained by applying Heidler function in parallel along each section of the simulated lumped parameter transformer winding, as described in [19, 22]. As shown in Fig.2, Heidler function is equal to a charge of 50 PC according to IEC 60270 [22]. Simulation of the winding model and obtaining the corresponding reference and test signals is carried out in Alternative Transient Program (EMTP) software. The output is the winding current and it consists of 3001 points that span a duration of 0.3 ms of the simulation time. According to the number of the section, ten PD reference signals were achieved at the neutral terminal. Fig. 3 shows the current signals captured at the neutral terminal when the PD pulses generated by Heidler function were injected at sections 2, 5 and 9 of the transformer winding. The responses of the winding are captured using the impedance circuit, known as ERA device, described in [26]. Furthermore, results in Table 3 demonstrate that when a PD pulse with the magnitude of 500 pC is applied to sections 2 and 9 as a PD test signal, the proposed method can estimate the PD location correctly. The bold data given in Table 3 indicates the location of the PD source. In practice, a measuring instrument or system may bring Gaussian noise to the captured currents [5]. To make the simulation investigations more practical, a Gaussian noise with a signal-to-noise ratio (SNR) of -36 dB is added to the neutral-end currents. The results of adding the noise with SNR of -36 dB when a PD pulse is injected into sections 2 and 9 are presented in Table 4. Simulation results show that the method is more accurate than the other methods such as time domain correlation method and Kullback–Leibler divergence [15, 17, 20]. Thus, the performance of the proposed method in a noisy condition is compared with the time domain correlation method and Kullback–Leibler divergence, which also applies DWT, in regards of precise determining of a PD source location in the transformer winding. The results show that not only is the proposed method able to estimate the PD location in noise-free conditions, but it is able to find the PD location in a noisy condition with the least error in comparison to the other mentioned methods, as well. Table 5 and 6 illustrate the location of a PD source for x=2 and 7 under a noisy condition with SNR of -36 dB using time domain correlation and Kullback–Leibler divergence methods, respectively. The maximum of FRAC occurs at k=x, indicating the location of the PD in sections 3 and 7. The bold data given in Tables 5 and 6 specify the location of a PD source.

5. Experimental Validation

Validating of the proposed method was carried out on an air-core laboratory winding, shown in Fig. 4. To simulate the core, a thin cylindrical aluminium foil with a diameter of 520 mm was placed concentrically inside the winding. The results were achieved by injecting a PD pulse of 500 pC using a PD calibrator into the Taps of the unrecognized winding. Then, its corresponding responses were considered as the PD test signal. Likewise, a PD pulse of 5 nC was injected into each tap, and its responses were taken as the PD reference signals. PD locations are the points where the FRAC values of two signals are maximums. Table 7 demonstrated the validation results.

6. Conclusion

In this paper, a method based on using the Frequency Response Assurance Criterion (FRAC) has been proposed in order to determine a PD location in a winding. The method has been compared with two well-known methods in this regard, that are time domain correlation method and Kullback–Leibler divergence. Simulation results show that using the FRAC value to measure the correlation between PD signals can significantly increase the reliability of locating PD source in a noisy condition. The error of using FRAC in a noisy condition is compared with other methods is the least. Therefore, using the FRAC values and analyzing signal correlation in the frequency domain can notably increase the reliability of locating PD source when the noise level is high.

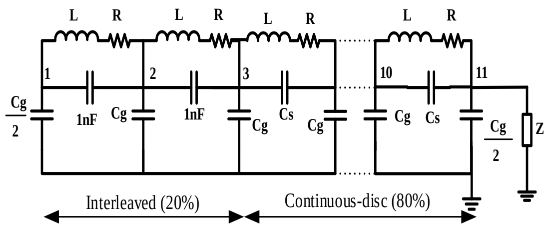

Fig. 1. Lumped parameter model of transformer

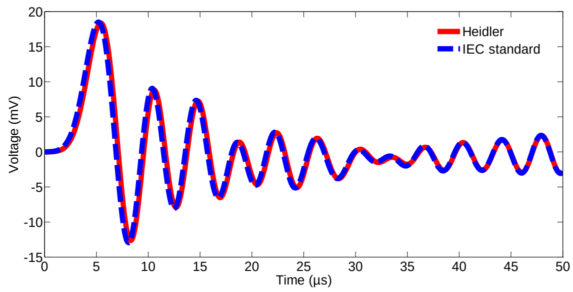

Fig. 2. The relationship between the Heidler function and IEC standard calibration

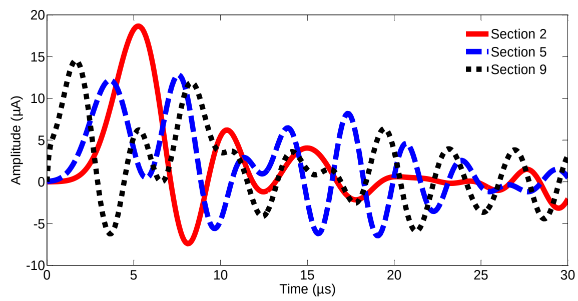

Fig. 3. Transformer winding responses to the Heidler function injected into sections 2, 5 and 9.

Fig. 4. Air-core laboratory winding

Table.2.
Simulation results for locating the PD source along sections 2 and 9

		Reference signal along sections									
		1	2	3	4	5	6	7	8	9	10
		FRAC value									
Test signal along section (x)	2	0.111	**0.868**	0.205	0.009	0.115	0.024	0.040	0.047	0.026	0.038
	9	0.021	0.033	0.039	0.048	0.021	0.061	0.017	0.099	**0.885**	0.147

Table.3.
Simulation results for locating the pd source along sections 2 and 9 in a noisy condition

		Reference signal along sections with SNR of -36 dB									
		1	2	3	4	5	6	7	8	9	10
		FRAC value									
Test signal along section (x)	2	0.001	**0.008**	0.003	0.000	0.001	0.000	0.002	0.002	0.000	0.000
	9	0.000	0.000	0.001	0.000	0.000	0.001	0.002	0.003	**0.008**	0.000

Table.4.
Simulation results for locating the pd source along sections 2 and 9 in a noisy condition with time domain correlation

		Reference signal along sections with									
		1	2	3	4	5	6	7	8	9	10
		Time domain correlation value									
Test signal along section (x)	2	0.087	0.287	0.204	0.000	0.043	0.098	**0.289**	0.249	0.023	0.011
	9	-0.030	-0.020	0.041	0.066	-0.136	0.285	0.484	**0.493**	0.242	-0.035

Table.5.
Simulation results for locating the PD source along sections 2 and 9 in a noisy condition with the proposed method in [20]

		Reference signal along sections with									
		1	2	3	4	5	6	7	8	9	10
		Time domain correlation value									
Test signal along section (x)	2	1.103	1.027	**0.995**	1.018	1.079	1.041	1.090	1.149	1.150	1.103
	9	1.088	1.013	**0.999**	1.034	1.070	1.043	1.075	1.130	1.149	1.088

Table.6.
Experimental results for locating the PD source along sections

		Reference signal along sections			
		1	2	3	4
		FRAC value			
Test signal along section (x)	1	**0.577**	0.522	0.522	0.377
	2	0.570	**0.562**	0.574	0.480
	3	0.575	0.562	**0.575**	0.475
	4	0.498	0.537	0.555	**0.544**

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