Partial discharge location in power transformer windings using the wavelet Laplace function

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ABSTRACT

Insulation system conditions in power transformers can be evaluated by means of partial discharge (PD) analyses. In fact, PD analysis is used to detect premature damage in transformer insulation system to avoid catastrophic faults. Detection and location of PD is a complex problem and has been widely studied by several researchers. A new method for PD location in transformer windings based on Wavelet Laplace (WL) is developed in this paper. First, the PD reference signals are obtained from a lumped parameter model (RLC) and those signals are used to determine the WL parameters, then PD signals are analyzed using the WL and each PD reference signal is replaced by its envelope wavelet transform (EWT) coefficients. Then, if a PD signal occurred in any section of the winding, its location will be defined by Hellinger distance between the EWT coefficients and the new PD reference signals. Results are discussed for PD along the winding and between sections of the winding.

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1. Introduction

Partial discharges (PD) monitoring in power transformers is a useful technique to evaluate the condition of the insulation system. PD signals are linked to the transformer insulation system, high levels of these signals may lead to breakdown of the insulation [1]. In fact, PD analyses in power transformers has been widely applied for detecting and quantifying premature damage in insulation systems [2], therefore detection and location plays an important role. However, detection and location of PD in power transformer has been a complex task, since its random occurrence may produce a wide frequency spectrum from 10 kHz to 3 MHz [3].

Several electrical methods for PD location in transformer windings have been developed in previous studies. For instance, a method in the frequency domain is preposed for PD location in transformer windings using correlation techniques [4]. Furthermore, Nafar et al. [5] applied wavelet packages for PD location, where the high frequency information is used to estimate the PD position, particularly detail coefficients at the first decomposition level are analyzed. Transfer function method is applied in [6], where the PD location is determined by series resonance frequencies. In the same way, transfer functions per section have been applied to determine the PD position along the winding transformer [7–9].

This paper proposes a new method for PD location along the transformer windings and between winding sections. PD signals are processed using the wavelet transform (WT), where the Laplace function is taken as the mother wavelet (Wavelet Laplace, WL), given that WL has a similitude with a PD signal (both have exponential damping). In this work, WL function is applied to PD location in transformer windings. Hence, WL parameters have to be determined and defined using the maximum correlation coefficient between the WL and PD reference signals obtained in the standard calibration process. Furthermore, for each PD signal the Envelope Wavelet Transform (EWT) is computed and the signal references are replaced by the EWT coefficients. Finally, PD signals are compared with the new PD reference signals and the Hellinger distance is applied to determine the PD position along the winding or between sections of the winding. Results show that WL is a better alternative for PD location in transformer windings.

2. Transformer winding model

The transformer winding can be represented by a lumped parameter model or by a multi-conductor transmission line (MTL) model. Both has been used to locate PD, e.g. in [10] a MTL model for PD location in windings using the transfer function method is explained. For other phenomena, like fault location in transformer

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Fig. 1. Lumped parameter model of a winding.

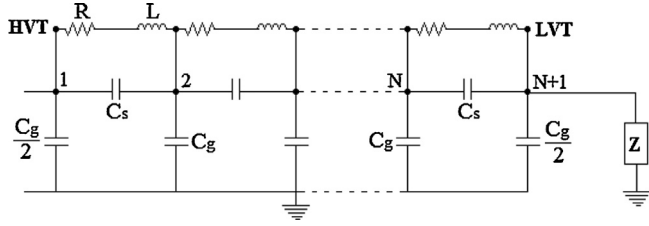**Fig. 3.** Calibration signals.

windings, the lumped parameter models are also used [11]. The transformer winding model to be used in this work can be seen in Fig. 1, each section of the winding is represented by lumped parameters of R, L and C.

In Fig. 1 R is the series resistance, L is the series inductance, C_s is the series capacitance, C_g is the capacitance to ground (disc-to-earth). The transformer winding model has N sections with number of nodes equal to $N+1$. In this application, the transformer winding model has 10 sections and their parameters were taken from [12] and are equal to $L = 180\mu$ H, $R = 1.2\Omega$, $C_s = 13$ pF, $C_g = 3000$ pF.

3. PD signals in transformer windings

A PD signal is characterized by an exponential damped function which can be represented using the Heidler function defined by [13]:

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

where t is the time variable, 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 to 37% of its peak value and n is the factor influencing in the rise time of the function. Besides (1), a PD model to acquire the PD signals between winding sections is shown in Fig. 2, where the circuit solution for the voltage terminals a and b is defined by (2), and its parameters are equal to $R = 2k\Omega$, $C_1 = 300$ pF and $C_2 = 50$ pF.

$$V_{ab} = Ae^{-\left(\frac{t}{RC_1}\right)}$$ (2)

If a PD occurs at any position of the transformer winding, its response will be captured at the neutral terminal using the impedance Z in Fig. 1, this circuit is also known as ERA device [14].

Regarding the reference signals, they are obtained from a simulation process using the Alternative Transient Program (ATP) software in agreement with the standard calibration process described in [15]. The calibration process is carried out using a voltage pulse with a capacitor in series, where the amplitude pulse is equal to 1 V and the capacitor value is 50 pF, equivalent to a charge of 50 pC. The voltage or current signals are captured at the neutral terminal and used as references for PD location in transformer windings. In Fig. 3, the voltage when a PD signal is injected to the
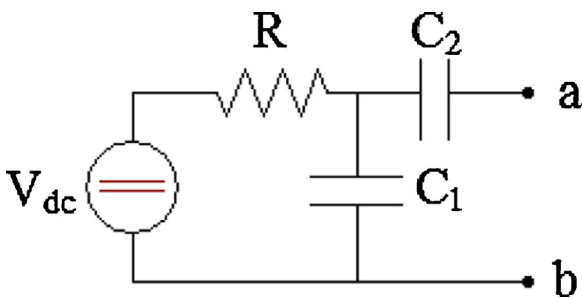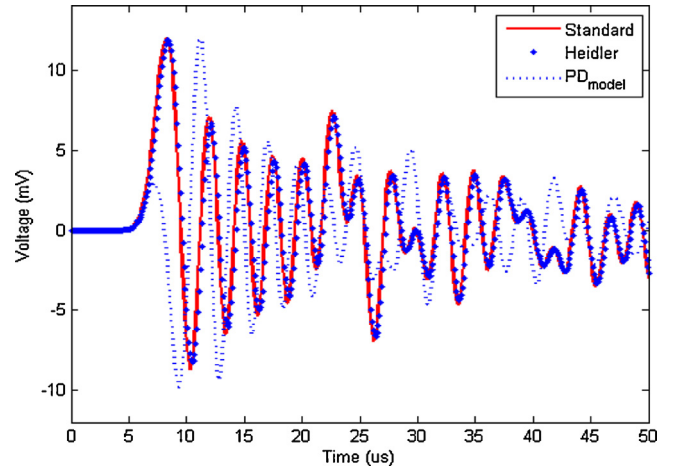
high voltage terminal is shown (solid line). Taking into account that a PD signal was previously characterized by the Heidler function, an equivalent calibration process should be done.

Calibration process using the Heidler function must be equivalent to the standard calibration. Hence, the equivalent responses are also shown in Fig. 3, where the standard calibration signal is quite similar to the PD signal corresponding to the calibration due to the Heidler function. It is also shown the calibration signal for PDs between sections (dotted signal), which is equivalent to 50 pF, this signal has slight differences with respect to the standard calibration signal.

The PD reference signals used in this work are the obtained from the Heidler function, using the following parameters: $A = 327\mu$A, $T_f = 1$ ns, $\tau = 200$ ns and $n = 2$. In Fig. 4 the current signals measured at the neutral terminal, when PD signals were injected at different sections (1, 5 and 9) of the transformer winding, are shown. The number of reference signals will be equal to the number of the winding sections. The complete PD reference signals will be processed using the WT to determine the PD location in transformer windings.

4. Wavelet transform and the Laplace function

The continuous wavelet transform (CWT) for a signal $x(t)$ is defined by the inner product of the signal and a complex conjugate
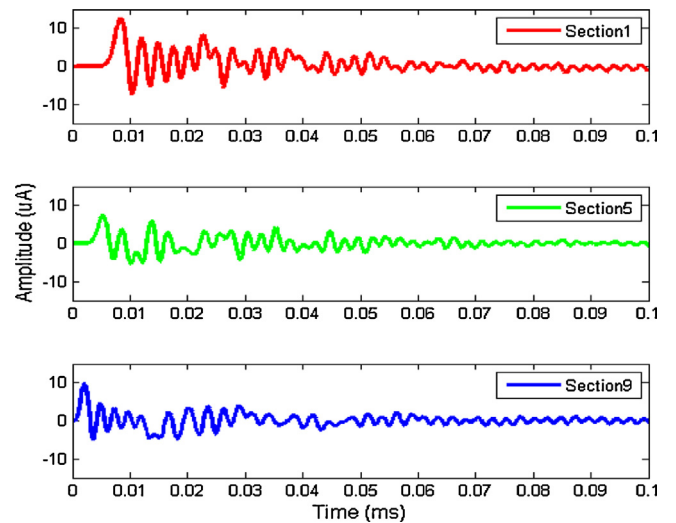

Fig. 2. PD Model among winding sections.

Fig. 4. Current signal measured at the neutral point.

mother wavelet $\psi^*_{a,b}(t)$ [16]. The basic concept in Wavelet analysis is to select a proper wavelet, called its mother wavelet and then perform an analysis using its translated and dilated versions, as can be seen in the following equation:

$$WT(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\psi^* \left(\frac{t-b}{a} \right) dt \tag{3}$$

where a and b are the scale and translation parameters respectively, and $\psi_{a,b}$ is the chosen mother wavelet, and $*$ represents operation of complex conjugate. The selection of the mother wavelet depends on the given application. It must be as similar as possible to the signal under study. More details of the wavelet transform can be found in [17] and [18].

In this work, the selected mother wavelet is the WL function defined as [19]:

$$\psi(t) = \begin{cases} Ce^{-\left(\frac{\beta}{\sqrt{1-\beta^2}} + j \right)w_c(t)} & \text{if } t \geq 0 \\ \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

where β is the damping factor, w_c is the center frequency of the wavelet, and C is the scaling factor. The frequency w_c defines the oscillation of the wavelet and factor β allows to control the decay rate of the exponential function, in the time domain. Both WL parameters β and w_c will be defined by the PD signals obtained in the calibration process, before computing the WT, these parameters define the PD signal waveform. Once the WT is computed, the obtained coefficients must be represented as follows:

$$WT(a,b) = A(t)e^{j\theta(t)} \tag{5}$$

where $\theta(t)$ is the phase and $A(t)$ is the instantaneous envelope, also known as the envelope wavelet transform (EWT) [20], given by:

$$A(t) = EWT = \sqrt{ \left\{ Re[WT(a,b)] \right\}^2 + \left\{ Im[WT(a,b)] \right\}^2 } \tag{6}$$

EWT obtained by the WT will be used to determine the PD position along the transformer winding, as can be seen in (6), due to the similarity between the original signal $x(t)$ and the WL function.

According to (4), the WL parameters to be determined are C, w_c and β. Where, C is a random constant value fixed to 1 to represent the normalized amplitude of WL. C takes a value from 0 to 1, which represent the maximum value of the normalized amplitude of WL. The parameters w_c and β are defined by the following equations:

$$w_c = \frac{w_c^{min} + w_c^{max}}{2}$$
$$\beta = \frac{\beta(w_c^{min}) + \beta(w_c^{max})}{2} \tag{7}$$

where w_c^{min} and w_c^{max} are the minimum and maximum value of the central frequency respectively, which already depends on the correlation coefficient (k) [21], these parameters define the minimum and maximum resonant frequencies into the transformer winding. w_c and β are calculated according to the bank filter theory. Therefore, the maximum value of k will detect the combinations of w_c and β which provide the optimal WL.

$$k = \sqrt{2} \frac{\left| \langle \psi_{a,b}(t), x(t) \rangle \right|}{\left\| \psi_{a,b}(t) \right\| \left\| x(t) \right\|} \tag{8}$$

To obtain k the WL will be correlated with the PD reference signal, varying the central frequency and the damping factors. Then k will take multiple values, giving as a result a matrix M with dimensions (p, q), the number of damping factors defines p and the number of central frequency values defines q. The relevant

correlation coefficient is the highest value of M indicating greater similarity between the PD signal and the WL. Finally, the optimal WL is applied to obtain the PD location along winding sections and between them.

5. Partial discharges location algorithm

5.1. WL parameters

The RLC model presented in Fig. 1 was implemented into the EMTP Software ATP® [13]. PD signals were obtained along each section of the winding using a sample frequency of 10 MHz. The center frequency takes values from 60 kHz up to 500 kHz with increments of 1 kHz, since a measuring frequency of 500 kHz is acceptable in real applications [22]. Further, the damping factor takes values in the range of 0.01 and 0.5 with increments of 0.01. Finally, each PD reference signal is correlated with the WL function to obtain the correlation coefficients in the range of the parameters. The output voltage and current signals will be used to determine the correlation coefficient.

In Table 1 the maximum k is shown for each section with the corresponding WL parameters (w_c and β). From the results it is also possible to conclude that the highest excited frequency is the central frequency obtained when there is a PD in a section of the winding, i.e. if there is a PD at section 1 of the winding, the highest excited frequency is 68 kHz using the current signals.

For PD between winding sections, the results k are shown in Table 2. Besides the WL parameters (w_c and β) between winding sections, it is possible to conclude that PDs between winding sections cause higher resonant frequencies. Moreover, the minimum central frequency value appears when there is a PD near to the high voltage terminal (section 1) and the maximum central frequency is obtained when there is a PD near to the neutral terminal (section

Table 1
WL parameters for PD along winding sections.

Section	Current signals			Voltage signals		
	Parameters		k	Parameters		k
	w_c(kHz)	β		w_c(kHz)	β	
1	68	0.07	0.3220	68	0.07	0.3366
2	279	0.02	0.4261	279	0.02	0.4254
3	165	0.03	0.4575	165	0.03	0.4599
4	101	0.05	0.4624	101	0.05	0.4644
5	100	0.05	0.4479	100	0.05	0.4502
6	97	0.07	0.3483	98	0.06	0.3498
7	165	0.03	0.4650	165	0.03	0.4686
8	226	0.03	0.4502	226	0.02	0.4527
9	277	0.02	0.4391	277	0.02	0.4402
10	403	0.07	0.5233	409	0.06	0.5111

Table 2
WL parameters for PD between winding sections.

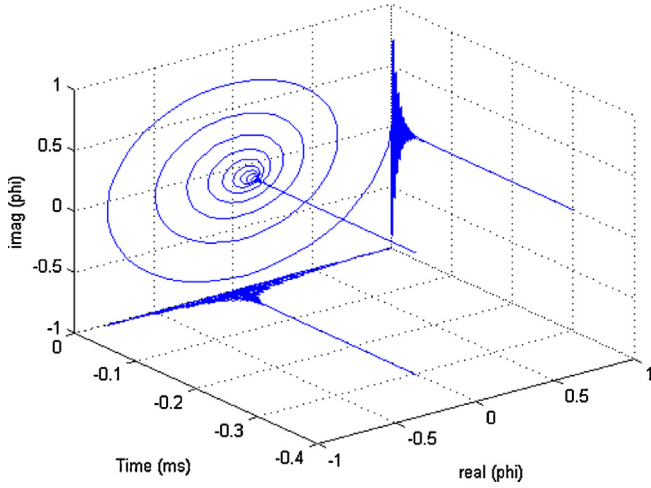| Sections	Current signals			Voltage signals		
	Parameters		k	Parameters		k
	w_c(kHz)	β		w_c (kHz)	β	
1–2	325	0.01	0.4363	279	0.02	0.4350
2–3	363	0.01	0.5289	363	0.01	0.5279
3–4	394	0.01	0.5286	394	0.01	0.5255
4–5	411	0.01	0.5019	411	0.01	0.4978
5–6	364	0.01	0.5422	364	0.01	0.5410
6–7	391	0.01	0.5690	390	0.01	0.5659
7–8	396	0.01	0.5611	396	0.01	0.5576
8–9	407	0.01	0.5751	407	0.01	0.5708
9–10	412	0.03	0.6407	412	0.03	0.6324
10–11	418	0.07	0.7474	419	0.06	0.7338

Fig. 5. Wavelet Laplace function for PD along winding sections.

N). According to the results, the optimal WL parameters will be defined by PD reference signals (currents or voltages) given by the first and last sections of the winding.

For PD location along sections of the winding, the optimal WL parameters are $W_c = 235.5$ kHz and $\beta = 0.07$ (using the PD current signals), the corresponding WL function is shown in Fig. 5. In the same way, for PD between winding sections, the optimal WL parameters are $w_c = 371.5$ kHz and $\beta_c = 0.04$.

5.2. PD location

PD location is carried out using the optimal WL, which is utilized to compute the WT. For all PD reference signals along the winding sections, the WT is computed to each PD reference signal and its EWT coefficients will replace it. The obtained EWT coefficients are shown in Fig. 6, which will be used to obtain the minimum Hellinger distance which define the PD location.

The Hellinger distance H_d is used to quantify the similarity between two probability distributions, it is a type of f-divergence [23,24], and is given by:

$$H_d(p, q) = \sqrt{1 - BC(p, q)}$$
$$BC(p, q) = \sum_n \sqrt{p(n)q(n)} \qquad (9)$$

where q is the probability mass distributions defined by EWT coefficients in each section and p is the distribution defined by the EWT coefficients, when there is a PD signal along any section of the winding (real PD). Those distributions are determined by their respective EWT coefficients as follows:

$$q(n) = \frac{EWT_{PD}^j(n)}{\sum_n EWT_{PD}^j(n)}; n = 1, 2, \ldots, m \qquad (10)$$

where m is the number of samples, and j is the PD reference signal at each section. Then, PD location in the transformer winding will be defined by the smallest Hellinger distance. The proposed methodology can be summarized in the following steps:

- Load PD reference signals (along sections and between them).
- Use PD references of the section 1 and section N to determine optimal WL parameters (using (8) and (7)).
- Determine the EWT for each PD reference signal using (3) and (6).
- If there is a PD signal in the winding, compute its EWT.
- Compute the Hellinger distance (9) regarding to each PD reference.
- Use the minimum Hellinger distance to define the PD location.

A flowchart with the algorithm is presented on Fig. 7, which represent the proposed methodology.
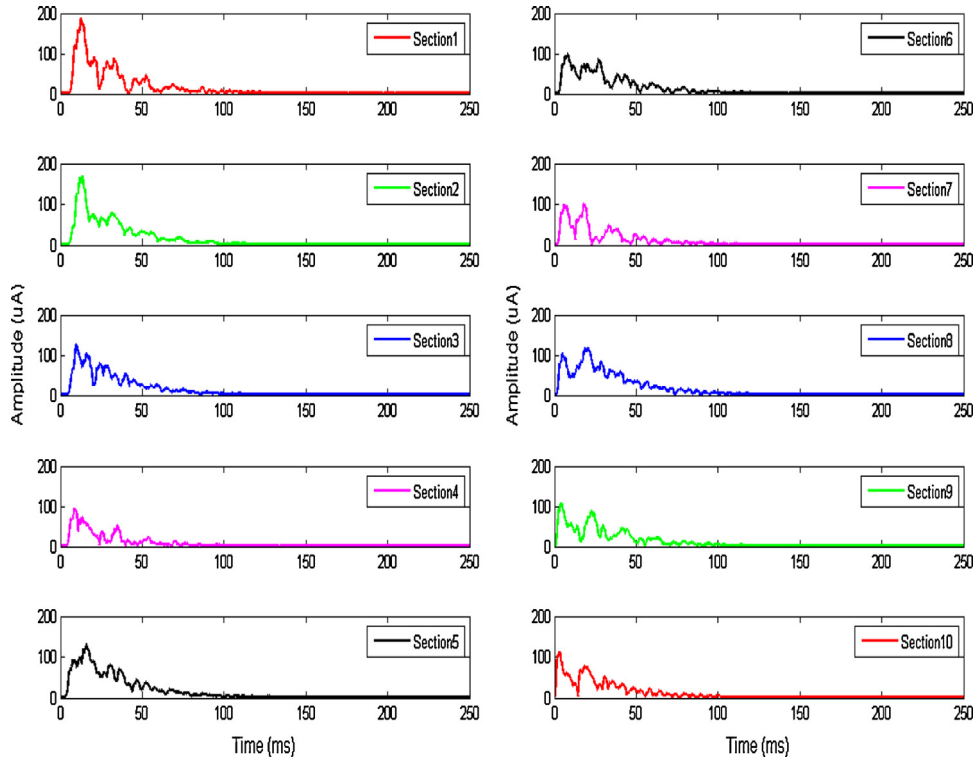

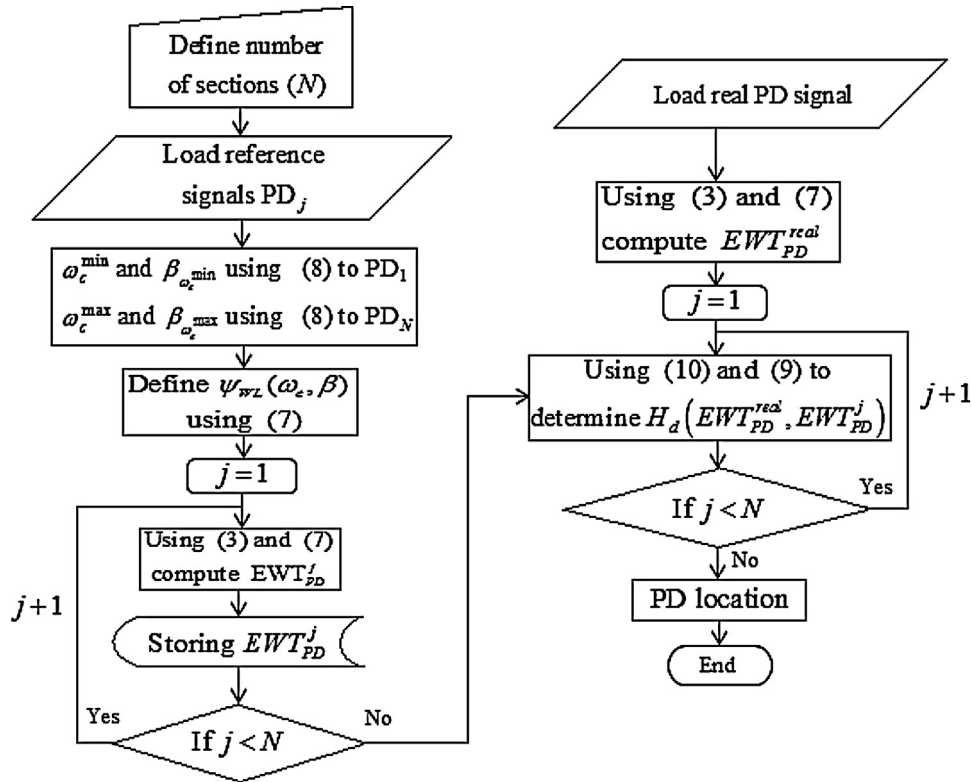**Fig. 6.** EWT coefficients for each section.

Fig. 7. Algorithm for PDs location.

6. Results and discussion

The proposed method to PD location in transformer windings is tested with different PD signals injected along each section of the winding, and between winding sections. In Table 3 the obtained results for PD signals injected along the sections of the winding are shown. Each column has the Hellinger distance value (H_d) between PD signals (injected at a specific position) and each PD reference signal. For instance, when the PD signal is injected at section 2, its corresponding distance values are in column 2, the minimum Hellinger distance value is 0.0275 indicating that there is a PD at section 2. Besides, if there is a PD signal at section 7 of the winding, the minimum Hellinger distance is 0.0661, element (7, 7), this means that there is a PD signal at section 7 of the transformer winding. With these results it is possible to conclude about the accuracy of the proposed algorithm.

In Table 4 the corresponding results for PD between winding sections is shown. This results are obtained using a central frequency of 371.5 *kHz*, given that PD signals injected between sections excite higher resonant frequencies in the transformer winding, e.g. when there is a PD between sections 5 and 6, its location will be estimated using the minimum Hellinger distance, i.e. the Hellinger distance value is 0.0503, it means that there is a PD signal between sections 5 and 6. Moreover, If there is a PD signal between sections 9 and 10, its corresponding Hellinger distance value is 0.0378, indicating a PD signal between sections 9 and 10, this numerical result is associated to the length of the winding, in this case correspond to 10% of the winding length with respect to the neutral point of the transformer. It was also included in Table 4 a comparison with the methodology proposed by [25], which is an statistical correlation. Both results produce normalized values, so that, different magnitude pulses can be evaluated and its accuracy

Table 3
Results for PD along winding sections.

PD reference at section	PD signal injected at section "j"									
	1	2	3	4	5	6	7	8	9	10
	Hellinger distance regarding to each PD reference									
1	**0.0689**	0.1887	0.2329	0.2522	0.2201	0.3049	0.3301	0.3152	0.3852	0.3864
2	0.1774	**0.0275**	0.1415	0.2389	0.1608	0.2569	0.3226	0.2629	0.3350	0.3522
3	0.2152	0.1395	**0.0372**	0.2275	0.1531	0.1923	0.2978	0.2410	0.3029	0.3261
4	0.2356	0.2344	0.2220	**0.0720**	0.1916	0.2486	0.2338	0.2702	0.3335	0.3299
5	0.2111	0.1642	0.1604	0.1916	**0.0381**	0.1799	0.2253	0.1702	0.2670	0.2806
6	0.3060	0.2628	0.2050	0.2547	0.1814	**0.0471**	0.2469	0.1831	0.2175	0.2624
7	0.3332	0.3295	0.3104	0.2359	0.2361	0.2581	**0.0661**	0.2184	0.2868	0.2558
8	0.3116	0.2653	0.2470	0.2750	0.1762	0.1822	0.2182	**0.0373**	0.1759	0.1997
9	0.3907	0.3473	0.3175	0.3472	0.2848	0.2270	0.3014	0.1867	**0.0548**	0.1996
10	0.3862	0.3561	0.3348	0.3369	0.2875	0.2725	0.2656	0.2057	0.1882	**0.0576**

The bold values correspond to the minimum Hellinger distance.

Table 4
Results for PD between winding sections.

PD reference between sections	PD signal injected between sections "j and k"									
	Hellinger distance									
	1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10	10–11
1–2	**0.0320**	0.1587	0.1319	0.2252	0.2856	0.2406	0.3434	0.3494	0.3298	0.4115
2–3	0.1528	**0.0550**	0.1561	0.2297	0.2597	0.2433	0.3311	0.3316	0.3317	0.4062
3–4	0.1315	0.1675	**0.0358**	0.2217	0.2475	0.2113	0.3193	0.3173	0.3110	0.4054
4–5	0.2218	0.2379	0.2234	**0.0453**	0.2277	0.1893	0.2562	0.2881	0.2628	0.3589
5–6	0.2808	0.2512	0.2394	0.2308	**0.0503**	0.2253	0.3241	0.2751	0.3263	0.4061
6–7	0.2395	0.2435	0.2110	0.1832	0.2251	**0.0376**	0.2228	0.2258	0.2229	0.3177
7–8	0.3437	0.3398	0.3219	0.2553	0.3268	0.2330	**0.0486**	0.2158	0.2017	0.2720
8–9	0.3453	0.3272	0.3112	0.2856	0.2729	0.2229	0.1981	**0.0492**	0.2052	0.2983
9–10	0.3339	0.3411	0.3162	0.2662	0.3299	0.2239	0.1926	0.2178	**0.0378**	0.2025
10–11	0.4176	0.4191	0.4136	0.3663	0.4143	0.3277	0.2689	0.3140	0.2208	**0.0509**
	Statistical correlation									
1–2	**0.8679**	−0.6573	−0.0851	0.0862	−0.0171	0.0382	−0.0154	0.0178	−0.0041	0.0040
2–3	−0.6638	**0.9038**	−0.3627	−0.1682	0.1334	−0.0592	0.0352	−0.0237	0.0108	−0.0058
3–4	−0.0294	−0.3922	**0.8970**	−0.3645	−0.1912	0.1743	−0.1196	0.0857	−0.0135	−0.0077
4–5	0.0578	−0.1217	−0.3869	**0.8956**	−0.3572	−0.1900	0.1662	−0.1081	0.0918	−0.0625
5–6	−0.0031	0.0762	−0.1614	−0.3883	**0.8950**	−0.3523	−0.2059	0.1547	−0.0884	0.0582
6–7	0.0221	−0.0138	0.1455	−0.1699	−0.3913	**0.8946**	−0.3581	−0.1929	0.1579	−0.0709
7–8	−0.0134	0.0207	−0.0621	0.1403	−0.1627	−0.3809	**0.8950**	−0.3561	−0.1945	0.1182
8–9	0.0160	−0.0187	0.0250	−0.0911	0.1428	−0.1711	−0.3935	**0.8955**	−0.3672	−0.1635
9–10	−0.0044	0.0128	0.0022	0.0805	−0.0878	0.1237	−0.1453	−0.4163	**0.8936**	−0.3004
10–11	0.0021	−0.0022	−0.0115	−0.0168	0.0518	−0.0500	0.0905	−0.1121	−0.3536	**0.9083**

The bold values correspond to the minimum Hellinger distance.

is not affected, reaching an accuracy of 100% for PD along sections of the winding and among them.

The proposed algorithm also provides the instantaneous frequency amplitude (EWT), reducing the data dispersion in the time domain, improving and diminishing the limitations into PD location. Results showed that WL is an appropriated tool to PD location in transformer windings. Furthermore, the proposed algorithm uses the complete frequency spectrum contained into the EWT, which is an advantage with respect to other wavelet applications, e.g. wavelet packages for PD location presented in [5], in which results may be affected by the decomposition level. Furthermore, WL can be used to determine the principal oscillations when there is a PD along sections of the winding.

7. Conclusions

A new methodology to PD location in transformer winding using the wavelet Laplace is proposed. The algorithm is assessed for PD along the winding sections, and between them. Results allow to conclude about the feasibility of the methodology and its advantages. The use of WL reduces the data dispersion in the time domain. Using a Laplace function as the mother wavelet represent an improvement into the PD area, it is possible to conclude that wavelet Laplace is a powerful tool to PD location in transformer windings. Besides, the wavelet Laplace can be used to know the more excited resonant frequencies, when a PD is in a defined position. Furthermore, the use of the Hellinger function, enhances the error in PD location, with respect to actual proposed methods found in literature. Finally, a measure of the insulation condition into power transformer windings can be obtained implementing this methodology as an *off-line* application, due to the incorporation of real signal inputs into the proposed algorithm.

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