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A Measurements-based Discharge Location Algorithm for Plain Disc Winding Power Transformers

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ABSTRACT

A measurements-based electrical method for locating partial discharges (PD) in transformers is described in the paper. This location method relies on the series resonance frequencies of the signals produced at the transformer terminals by a discharge on the winding. Based on the equivalent circuit of plain disc type winding which consists of series inductance (L), series capacitance (K) and shunt capacitance to earth (C) of the winding, an analytical location algorithm is derived which gives the relationship between the location of a discharge and its terminal response's series resonance frequencies. LKC parameters of the equivalent circuit can be estimated using the series resonance frequencies of a calibration signal measured at the bushing tap during PD calibration. The PD location algorithm was tested on 11 kV transformer winding using signals produced by a discharge simulator and real discharges, and the results confirm its validity with a location accuracy of better than 10% of the winding length. However, blind area where this location algorithm is not applicable does exist near the neutral of the winding and far away from the measuring terminal. Since this location algorithm uses the series resonance frequencies below 500 kHz, it can be implemented with conventional PD measuring circuitry and instruments to detect and locate discharges in power transformers.

Index Terms — **Partial discharges, power transformers, propagation, windings, bushing tap, location algorithm.**

1 INTRODUCTION

PARTIAL discharges can cause incipient insulation faults, if allowed to develop over time, may lead the insulation to a total breakdown and result in catastrophic failure of power transformers. As an important entity of power plant, loss of a power transformer in operation can lead to economic penalties due to loss of power supply and the capital expenditure for replacement. PD monitoring therefore forms an important part of online condition monitoring and is used as a diagnostic tool for quality of insulation. If during the monitoring process an excessive amount of discharge activity has been detected, the location of discharge needs to be sought in aid of making the decision of either taking the transformer out of service for further investigation or keeping it in operation with increased monitoring.

Non-electric PD location methods include the acoustic location technique which uses acoustic emissions from a discharge and the time differences for it to travel to acoustic sensors. Although the acoustic location method is popularly used on site and the IEEE transformer committee is drafting a guide for acoustic PD detection and location; the location results could be sometimes misleading especially when there is solid insulation between the discharge source and the sensor. The transmission losses in different media and their interface [1] and the reduced sensitivity to a discharge buried within windings [2] are the concerns when using the acoustic PD location techniques.

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Electrical PD detection method [3] measures apparent charge quantity using conventional PD measuring circuitry and instruments with an effective frequency bandwidth of less than 500kHz. Ultra high frequency (UHF) PD detection utilizes the frequency components of a discharge signal in the range of 300 MHz − 3 GHz for detecting discharges in power transformers [4]. Since electrical methods of PD detection are more sensitive, electrical location techniques are preferable for PD online monitoring. Recent developments in electrical location methods [5−9] are based on the fact that while a discharge signal propagates from the location to the measuring terminals, the terminal response acquires the information on the location of the PD source.

The method developed in [5−7] requires computer-based simulations. Transformer windings are modeled using either a lumped element model [5] or a distributed parameter multi-conductor transmission line model [6]. To locate a discharge, simulated transfer functions from probable positions of the discharge to the terminals are recorded and compared with those obtained from measurements of a real discharge. One drawback with this method is that it requires detailed transformer construction data which may not be available for most operating transformers. Further methods developed in [8−9] are based on evaluating the sectional winding transfer functions (SWTFs) from the probable PD locations to the winding terminals, and use those for the location with the measured discharge responses at line and neutral-ends.

In this paper a location algorithm is developed based on an analytical solution which is derived from the equivalent circuit of a plain disc winding power transformer. This location method relies on the series resonance frequencies of the signals produced at the transformer terminal by a discharge on the winding. Using this location algorithm, PD location can be found through standard measurements known as PD calibration and PD detection, performed with conventional PD measuring instruments. Consequently the technique developed here overcomes the problems exhibited in [5−9] for plain disc-winding transformers.

2 ANALYTICAL SOLUTION

As shown in Figure 1, the equivalent circuit of a single winding at high frequencies consists of multiple stages of LKC unit, where L is the series inductance, K is the series capacitance and C is the shunt capacitance to earth of the winding. A bushing capacitance C_B is connected at the line-end and the neutral is grounded. Discharge signals can be measured at the line-end as the line-end current i_l at the bushing tap, or at the earthed neutral point as the neutral-end current i_n.

The voltage and current distribution along the winding are given by equations (1) and (2) [10]:

$$u(x, j\omega) = A\cosh(rx) + B\sinh(rx) \quad (1)$$

$$i(x, j\omega) = \frac{1}{Z}\left[A\sinh(rx) + B\cosh(rx)\right] \quad (2)$$

where,

$$r^2 = \frac{-LC\omega^2}{1 - LK\omega^2} \quad (3)$$

and

$$Z = \sqrt{\frac{L}{C(1 - LK\omega^2)}} \quad (4)$$

Taking the total length of the winding as unit length, when a PD current, i_{pd}, occurs at a distance x_0, from the line-end, the voltage and current distribution along the winding due to the PD source will be described as similar to equations (1) and (2), except that the constants A and B are different for the two parts of the winding, one between the line-end and PD source location, and the other between the PD location and earthed neutral. Therefore, the voltage and current distribution can be written as:

$$u_1(x, j\omega) = A_1\cosh(r(x_0 - x)) + B_1\sinh(r(x_0 - x)) \quad \text{for } 0 \le x \le x_0 \quad (5)$$

$$i_1(x, j\omega) = \frac{1}{Z}\left[A_1\sinh(r(x_0 - x)) + B_1\cosh(r(x_0 - x))\right] \quad \text{for } 0 \le x \le x_0 \quad (6)$$

$$u_2(x, j\omega) = A_2\cosh(r(x - x_0)) + B_2\sinh(r(x - x_0)) \quad \text{for } x_0 \le x \le 1 \quad (7)$$

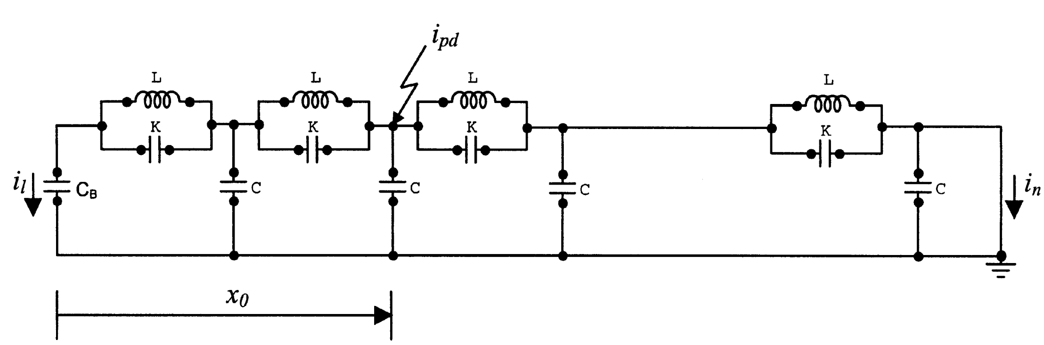

Figure 1. LKC equivalent circuit of a single transformer winding at high frequencies.

$$i_2(x, j\omega) = \frac{1}{Z}\left[A_2 \sinh\left(r(x - x_0)\right) + B_2 \cosh\left(r(x - x_0)\right)\right] \; for\, x_0 \le x \le 1 \tag{8}$$

The constants A_1, B_1, A_2 and B_2 can be determined by the boundary conditions of the winding given by

$$i_1(0, j\omega) = j\omega C_B \cdot u_1(0, j\omega) \tag{9}$$

$$i_{pd} = i_1(x_0, j\omega) + i_2(x_0, j\omega) \tag{10}$$

$$u_2(1, j\omega) = 0 \tag{11}$$

An analytical solution for the line-end current can be obtained by equations solving (5) to (8) with the boundary conditions in equations (9) to (11). The transfer function of the line-end discharge signal is given by

$$i_l(j\omega) = \frac{\frac{C_B}{C} r \sinh\left(r(1 - x_0)\right)}{-\cosh(r) + \frac{C_B}{C} r \sinh(r)} \cdot i_{pd} \tag{12}$$

Equation (12) shows that the line-end response of the discharge signal, not only contains the information of the discharge itself i_{pd}, but also its location x_0.

3 PD LOCATION ALGORITHM

The location information is reflected as series resonances on the line-end response of the discharge signal, i_l, since x_0 only appears in the numerator of equation (12). Whereas parallel resonances, governed by the denominator of equation (12), are fixed and only related to the whole winding, as the total length of the winding is regarded as unit length when deriving the equations above. The series resonance frequencies of the line-end current are given by

$$\frac{C_B}{C} r \sinh\left(r(1 - x_0)\right) = 0 \tag{13}$$

where either $r = 0$ or $\sinh(r(1 - x_0)) = 0$. The only value of ω giving $r = 0$ is when $\omega = 0$ and this is of no interest for this study, and so,

$$\sinh\left(r(1 - x_0)\right) = 0 \tag{14}$$

is the only solution required.

Since r has an imaginary value,

$$\sinh\left(\mathrm{r}(1 - x_0)\right) = -j \sin\left(jr(1 - x_0)\right) = 0 \tag{15}$$

$$\sin\left(jr(1 - x_0)\right) = \sin(n\pi) = 0, \qquad \text{for } n = 0, \pm 1, \pm 2, \ldots \tag{16}$$

$$jr(1 - x_0) = n\pi \qquad \text{for} \qquad n = 0, \pm 1, \pm 2, \ldots \tag{17}$$

In equation (17), $n = 1, 2, 3, \ldots$ correspond to the order of the resonance. The series resonance frequencies of the line-end current due to a discharge on the winding change with the location of the discharge. Therefore, such series resonances measured at the line-end can be used for locating the PD.

Squaring equation (17) on both sides and substituting equation (3) for r^2, the following equation is obtained:

$$(1 - x_0)^2 = -\left(\frac{n\pi}{r}\right)^2 \qquad \text{for} \qquad n = 0, \pm 1, \pm 2, \ldots \tag{18}$$

$$x_0 = 1 - \frac{n}{2f}\sqrt{\frac{1 - 4\pi^2 f^2 LK}{LC}} \tag{19}$$

Equation (19) can be used to calculate the location of the PD source when the frequency of a series resonance of the line-end discharge signal (f) and its order (n) is known, provided that LC and LK values of the equivalent circuit of winding are also known.

4 PROPOSED PD LOCATION METHOD

LC and LK values of the equivalent circuit of a winding can be found by carrying out PD calibration on the transformer. In conventional PD measurements, to obtain the apparent charge quantity PD calibration is performed by injecting an artificial discharge signal at the line-end and measuring the response at the bushing tap. PD calibration assumes the discharge source at the line-end, i.e. $x_0 = 0$, and therefore equation (19) simplifies to

$$LC + n^2\pi^2 LK = \left(\frac{n}{2f}\right)^2 \tag{20}$$

Equation (20) shows that if two series resonances f_1 and f_2, can be obtained corresponding to n_1 and n_2, then LC and LK can be found for the equivalent circuit of the winding and are given by

$$LC = \frac{(n_1 n_2)^2}{4\left(n_2^2 - n_1^2\right)}\left(\frac{1}{f_1^2} - \frac{1}{f_2^2}\right) \tag{21}$$

$$LK = \frac{1}{4\pi^2\left(n_2^2 - n_1^2\right)}\left[\left(\frac{n_2}{f_2}\right)^2 - \left(\frac{n_1}{f_1}\right)^2\right] \tag{22}$$

The proposed location method can be depicted by a flow chart in Figure 2, showing the stages of measurements needed for PD location.

5 APPLICATION OF PD LOCATION ALGORITHM

5.1 TESTS ON 11 KV WINDING WITH PD SIMULATOR

The proposed PD location method was applied to 11 kV plain-disc distribution transformer winding containing 72 discs. The winding was constructed out of two parallel conductors each having cross sectional dimensions of 6×2 mm, with single side insulation thickness of 0.25 mm. The inner radius of the HV winding was 251.5 mm and the outer radius 292.5 mm. Figure 3 shows the experimental set-up used for verifying the PD location algorithm on the 11 kV winding. The discharge signals, produced by a PD simulator which is normally used for PD calibration, were

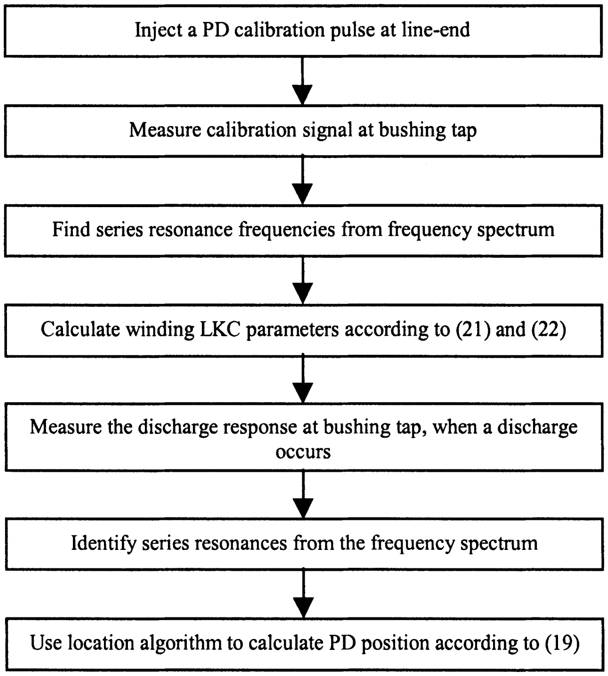

Figure 2. PD Location method.

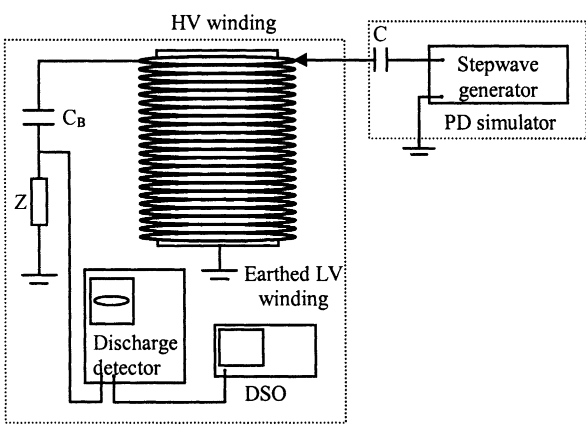

Figure 3. Experimental set-up used for discharge detection on 11kV winding.

injected at the line-end of the winding, and also at discs 8, 16, 24, 32, 40, 48, 56, 64 and 72, numbered down from the line-end. The measuring impedance Z was connected underneath the bushing capacitance (C_B = 220 pF) and the discharge signal was fed into a Robinson DD5 discharge detector. The discharge detector has a gain-adjustable amplifier and a band pass filter of 10 kHz to 300 kHz. Signals were taken from the discharge detector to a digital storage oscilloscope (DSO) which has a 12-bit A/D converter and 20 MHz analog bandwidth.

The partial discharge signals measured at the line-end for the simulated discharge source at various locations on the winding were saved on the DSO, the frequency spectra of these responses were obtained using fast Fourier transform (FFT) and were used to find the series reso-

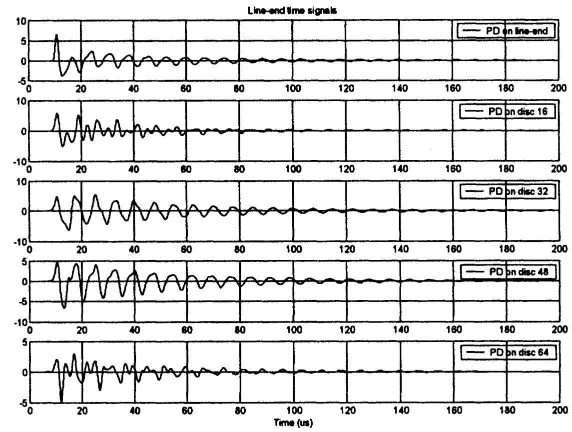

Figure 4. Measured discharge signals at line-end terminal in mV.

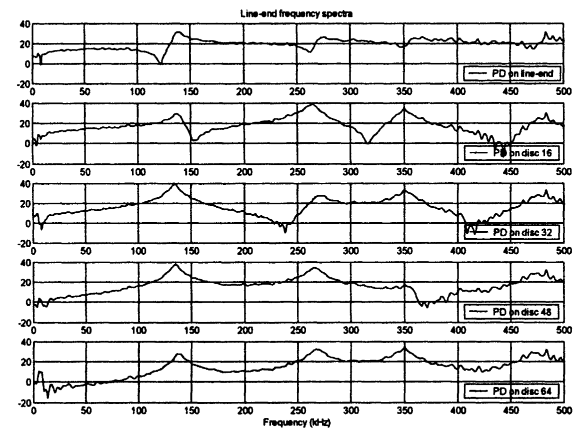

Figure 5. Frequency spectra of measured line-end discharge signals in dB.

nance frequencies of the signals. Out of these discharge locations, only signals measured at the line-end produced by discharges at the line-end, and at discs 16, 32, 48 and 64 are shown in Figure 4. Their frequency spectra are shown in Figure 5.

Figure 4 shows that the measured signals at bushing tap are oscillatory due to the propagation along the winding. Figure 5 shows that the frequencies of parallel resonances, which correspond to crests in the spectra, are independent of the PD location on the winding and are approximately at 140 kHz, 270 kHz and 350 kHz. On the other hand, the frequencies of series resonances corresponding to troughs in the spectra change with the location of the discharge, and therefore can be used for PD location [5].

Table 1 shows the series resonance frequencies obtained for various positions of the discharge on the winding. Only discharges located from the line-end down to disc 48 produce series resonance frequencies at the line-end signals, and below disc 48 no observable series resonance frequency is produced on the line-end signals. This region of the winding for which no series resonance fre-

Table 1. Series resonance frequencies (kHz) of line-end discharge signals.

Discharge position (disc number)	f_1	f_2	f_3
Line-end	122	262	347
8	133	289	375
16	153	316	443
24	183	346	–
32	238	409	–
40	289	–	–
48	371	–	–

Table 3. Comparison between actual and estimated PD location (disc number).

Actual PD position	Estimated PD position using f_1	Estimated PD position using f_2	Estimated PD position using f_3
8	−6	9	9
16	5	16	29
24	17	24	–
32	31	37	–
40	40	–	–
48	51	–	–

quencies are obtained at the line-end signals is called a *blind area* for this location algorithm. If no series resonances are available in the line-end signal, the source of discharge could therefore be estimated as in the region closer to the neutral-end of the winding.

If the 1st and 2nd series resonance frequencies (f_1 = 122 kHz and f_2 = 262 kHz) of the line-end PD calibration signal are used to calculate LKC parameters of equivalent circuit using equations (21) and (22), the values obtained for LC and LK are LC = 1.7539×10^{-11} and LK = -7.5270×10^{-14}. Assuming a discharge occurs at the positions listed in Table 1, these LC and LK values are used with the series resonance frequency of the measured line-end signal to calculate the PD location. The estimated PD positions by the location algorithm in equation (19) are given in Table 2.

LK appears as a negative value in the above calculation due to $(n_2/f_2)<(n_1/f_1)$ in equation (22), which reflects the simplicity of the equivalent circuit of the winding in which mutual inductance and resistive and dielectric losses are not considered. Nevertheless the algorithm derived from this simplified equivalent circuit gives reasonable estimation of PD location when the calculated negative LK value is accepted.

In Table 2, PD location estimated using f_2 could only be obtained up to disc 32, due to the natural fading of the 2nd series resonance frequency beyond disc 32 (see Table 1). Similarly, PD location estimated using f_3 could only be obtained for discs 8 and 16.

Comparing the values in Table 2, it can be seen that PD positions estimated using f_1 are closer to the actual PD positions compared to those estimated using f_2 or f_3. LC and LK values calculated using f_1 and f_2 of the line-end PD calibration signal give more accurate results when used with f_1 values in Table 1; the maximum location error being 3 out of 72 discs. The negative disc number of estimated PD locations using f_3 indicates that there are significant errors when the location algorithm uses f_3 of measured discharge signals with LC and LK values obtained through f_1 and f_2 of PD calibration signals.

Table 2. Comparison between actual and estimated PD location (disc number).

Actual PD position	Estimated PD position using f_1	Estimated PD position using f_2	Estimated PD position using f_3
8	6	6	−10
16	14	10	−1
24	23	14	–
32	33	20	–
40	39	–	–
48	45	–	–

If the 2nd and 3rd resonance frequencies (f_2 = 262 kHz and f_3 = 347 kHz) of the line-end PD calibration signal are used to calculate LC and LK, LC = 1.1273×10^{-11} and LK = 8.3456×10^{-14} are obtained. If these two values are used to estimate the PD location using the series resonance values in Table 1, the estimated PD locations in Table 3 are obtained.

By inspecting the values in Table 3, it can be seen that PD positions estimated using f_2 are closer to the actual PD position than in other cases. The maximum location error is 5 out of 72 discs. This again shows that LC and LK values calculated using f_2 and f_3 of a PD calibration signal give more accurate results when used with f_2 values of Table 1.

5.2 TESTS ON 11KV WINDING WITH REAL DISCHARGES

The PD location algorithm was also verified using a real discharge model in place of the PD simulator. Such an experimental set-up is shown in Figure 6. The corona model, made up of a sharp electrode pointed to the insulated conductor of the winding with an air gap, was energized by 11 kV supply and the bushing capacitance was 330 pF. The series resonance frequencies of the measured line-end signals produced by the corona discharge at discs 2, 8, 16, 24, 32, 40, 48, 56, 64 and 70 are shown in Table 4. No series resonance frequencies are obtained from the line-end signals for PD positions beyond disc 48 in the blind area.

If the values of series resonances in Table 4 are used to estimate the PD position using LC = 1.7539×10^{-11} and LK = -7.5270×10^{-14}, obtained using f_1 and f_2 from PD calibration, the estimated PD locations are given in Table 5. The results in Table 5 reinforces what was found

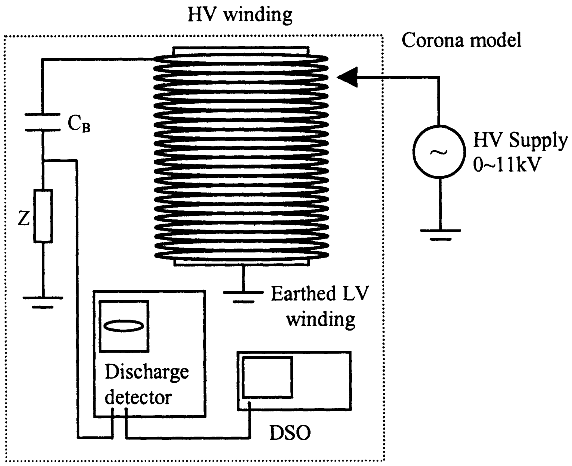

Figure 6. Experimental set-up with a real discharge on 11kV winding.

Table 4. Series resonance frequencies (kHz) of line-end discharge signals.

Disc number	f_1	f_2	f_3
2	124	268	356
8	135	287	375
16	165	319	–
24	216	344	–
32	250	–	–
40	287	–	–
48	337	–	–
56	–	–	–
64	–	–	–
70	–	–	–

previously with the simulated discharge sources, i.e. PD location estimated using f_1 is closer to the actual position than those estimated using f_2 or f_3.

Table 5 shows a maximum error of 6 discs when the actual PD position is at disc 24. This corresponds to an error of approximately 8% of the total winding length.

If the values of series resonances in Table 4 are used to estimate the PD position using $LC = 1.1273 \times 10^{-11}$ and $LK = 8.3456 \times 10^{-14}$, obtained using f_2 and f_3 from PD calibration, the estimated PD locations are given in Table 6.

Table 5. Comparison between actual and estimated PD location (disc number).

Actual PD position	Estimated PD position using f_1	Estimated PD position using f_2	Estimated PD position using f_3
2	1	1	−13
8	7	5	−10
16	18	11	–
24	30	14	–
32	35	–	–
40	39	–	–
48	43	–	–

Table 6. Comparison between actual and estimated PD location (disc number).

Actual PD position	Estimated PD position using f_1	Estimated PD position using f_2	Estimated PD position using f_3
2	−12	2	3
8	−5	8	9
16	10	17	–
24	26	24	–
32	34	–	–
40	40	–	–
48	47	–	–

Table 6 shows that PD locations estimated using f_2 values are closer to the actual PD positions and the maximum error is 1 out of 72 discs.

In using the series resonance frequencies of a PD calibration signal to obtain LC and LK values it is important to consider the order of these resonance frequencies. If the first and second resonance frequencies of a PD calibration signal are used in calculating LC and LK, the first series resonance frequency of the measured line-end signal due to the discharge has to be used in locating the PD source. If the second and third resonance frequencies are used to calculate LC and LK, then the second resonance frequency of the line-end discharge signal has to be used. Therefore, in locating a PD using the algorithm, an 'order-matching' series resonance frequency to those used in calculating LC and LK is preferred and this produces more accurate results. When order-matching series resonance frequencies are used, it achieves a location accuracy of better than 10% of the winding length.

6 CONCLUSIONS

A measurements-based electrical method for locating partial discharges in plain disc type transformers is presented. This location method relies on the series resonance frequencies of the line-end signals produced by a discharge on the winding. The analytical solution for PD location is derived based on the equivalent circuit of the winding which consists of series inductance (L), series capacitance (K) and shunt capacitance to earth (C). LKC parameters can be derived in the form of LC and LK using series resonance frequencies of line-end signals obtained during PD calibration, where a PD simulator is connected at the line-end and the discharge signal is measured at bushing tap with the conventional PD measuring instruments.

In using the series resonance frequencies of a PD calibration signal to obtain LC and LK values, at least two frequencies are required and the order of these frequencies should match with that of the resonance of the measured discharge signal used for location. The 'order-matching' series resonance frequencies are preferred in this location method and produce more accurate locating results. The algorithm was tested on 11 kV plain disc type transformer winding using a PD simulator and real discharges. The estimated discharge locations showed good agreement with the real positions and the maximum error in PD location was less than 10% of winding length when order-matching series resonance frequencies are used.

Since this location algorithm relies on the series resonance frequencies, which are profound for plain disc type transformer windings and are normally within the range of frequencies below 500 kHz, it can be easily implemented by conventional PD measuring instruments with oscilloscopes for partial discharge detection and location in power transformers.

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