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An Electrical PD Location Method Applied to a Continuous Disc Type Transformer Winding

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Abstract: A 6.6kV continuous disc type winding of a distribution transformer is used to investigate the propagation of partial discharges (PD) with the aim of location. The winding was modelled, as multiconductor transmission lines with each turn represented by a transmission line. This approach results in the model being valid up to a few MHz in frequency. The validity of the model was confirmed by impedance measurements on the winding. The transfer functions calculated between probable PD source locations to winding terminals showed that the troughs (or zeros) change in frequency with the location of PD source and hence can be used for the location of PD. Transfer functions obtained experimentally using a discharge calibrator as the PD source, showed very good agreement with the calculations.

INTRODUCTION

Dielectric breakdown in transformers are most frequently preceded by partial discharge (PD). There can be many causes of partial discharge: defects in insulation, loose connections, floating metallic objects arcing under oil, are a few [1]. In operating transformers, online condition monitoring is performed to measure the PD. Unless, action is taken to detect, quantify and remedy the situation at an early stage of PD development, catastrophic failures can occur resulting in outages and further secondary losses. Depending upon the severity of the PD, diagnosis and maintenance of the transformer may be required and for the maintenance, the location of the PD source is important.

The PD signals, which originate inside a transformer, can only be measured at a limited number of places due to the structural design of the transformer. The PD signal gets distorted as it travels from the site of origin to the measuring terminals. Therefore, it is imperative to understand the propagation mechanism of the PD for the location of its site of origin.

A recent study [2] has shown that by modelling each double section of a winding as a lumped element a model valid up to a few hundreds of kHz can be obtained. With this model, the troughs of the transfer functions calculated between probable PD sites to the measuring terminals could be used to locate the PD. The aim of this paper is to devise a transformer model valid for even higher frequencies (a few MHz), and use it to locate the PD. Hence each turn of the winding was modelled by a transmission line with distributed parameters. The validity of this model up to 10MHz was confirmed by impedance measurements on the winding.

The paper presents an extension of the work described in a previous paper [3], which was not convincingly validated due to the impact of noise and the low A/D resolution of the signal conditioning equipment used [4]. The experimental results shown in this paper, obtained using a higher A/D resolution oscilloscope, agrees well with the simulation results from the model. This paper also presents some features of signals measured at a transformer winding terminals that can be used to locate a PD.

COMPUTER SIMULATIONS

The design data of the 6.6kV transformer used in the model are listed below:

Transformer Design Data

Number of sections = 22
Number of turns per section = 13
Conductor dimensions = 2.5mm× 13.75mm
Single-sided inter turn insulation thickness = 0.2mm
Inter-section distance = 4.5mm
Outer radius of the LV winding = 203.3mm
Inner radius of the HV winding = 230mm
Outer radius of the HV winding = 267.7mm

Transformer Winding Model

The model used for the transformer winding, based on the multiconductor transmission line theory [5] assumes the parameters to be uniformly distributed along the line. Each transmission line can be regarded as made up of a cascade of identical cells of infinitesimal length, as shown in Fig. 1. L, R, C and G denote the series inductance, series resistance, parallel capacitance and conductance, all per unit length and calculated per turn basis so that each turn of the winding is considered as equivalent to a 'transmission line'. The winding can then be represented as in Fig. 2, where the subscript '$_S$' denotes sending end and '$_R$' denotes the receiving end. The number of transmission lines in the model, n equals to 286 (22 sections × 13 turns).

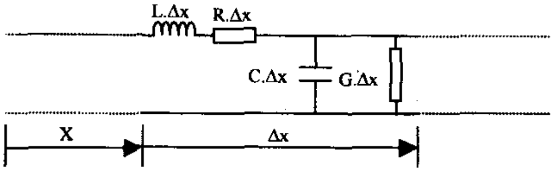


Fig. 1. One cell of distributed parameter model

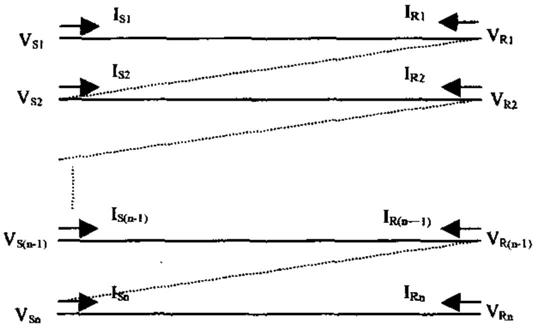


Fig. 2. Transformer winding represented by multiconductor transmission line model

The voltage and current distribution along these transmission lines can be described by wave equations [6], (1) and (2):

$$\frac{d^2V}{dx^2} = [Z][Y]V = [P^2]V \qquad (1)$$

$$\frac{d^2I}{dx^2} = [Y][Z]I = [P_t^2]I \qquad (2)$$

where [Z] and [Y] are the impedance and admittance matrices for the winding given by

$$[Z] = [R] + j\omega[L] \qquad (3)$$

$$[Y] = [G] + j\omega[C] \qquad (4)$$

and $[P^2] = [Z][Y]$ and $[P_t^2] = [Y][Z]$.

The solution of (1) and (2) can be expressed in classical form as a summation of two waves one travelling in the positive (or forward) direction and the other travelling in the negative (or reverse) direction.

$$V_x = V_1 e^{(-[P]x)} + V_2 e^{([P]x)} \qquad (5)$$

$$I_x = Y_O (V_1 e^{(-[P]x)} - V_2 e^{([P]\ x)}) \qquad (6)$$

Y_O in (6) is the characteristic admittance matrix given by $[Y_O] = [Z]^{-1}[P] = [Y][P]^{-1}$.

With terminal conditions applied at the sending and receiving ends it is possible to express the currents in Fig. 2 in terms of voltages as given by (7). Further simplification of (7) is possible using the eigenvalues (γ) and eigenvectors (Q) of [P]. Equation (7) then simplifies into the form of (8), where $[A] = [Y][Q][\gamma]^{-1}\coth([\gamma]l)[Q]^{-1}$ and $[B] = [Y][Q][\gamma]^{-1}\operatorname{cosech}([\gamma]l)[Q]^{-1}$ are n × n matrices, and 'n' is the number of conductors in the model.. Equation (8) expresses 2n equations of sending and receiving end currents in terms of sending-end and receiving-end voltages.

$$\begin{pmatrix} I_S \\ I_R \end{pmatrix} = Y_O \begin{pmatrix} \coth([P]l) & \cos ech([P]l) \\ \cos ech([P]l) & \coth([P]l) \end{pmatrix} \begin{pmatrix} V_S \\ V_R \end{pmatrix} \qquad (7)$$

$$\begin{pmatrix} I_S \\ I_R \end{pmatrix} = \begin{pmatrix} [A] & -[B] \\ -[B] & [A] \end{pmatrix} \begin{pmatrix} V_S \\ V_R \end{pmatrix} \qquad (8)$$

Fig. 2 shows that the transmission line model has the following terminal conditions:

$$I_S(i+1) = -I_R(i) \quad \text{for } i=1 \text{ to } n-1 \qquad (9)$$

$$V_S(i+1) = V_R(i) \quad \text{for } i=1 \text{ to } n-1 \qquad (10)$$

Using these terminal conditions, the matrix in (8) can be reduced from (2n × 2n) to a (n+1) × (n+1) matrix.

PD injection: If a PD current signal, I_{PD}, is injected to the kth turn of the winding, (9) will get modified for i = k-1 as

$$I_S(k) + I_R(k-1) = I_{PD} \qquad (11)$$

The voltage-current distribution along the winding can now be expressed by (12).

$$\begin{pmatrix} I_S(1) \\ 0 \\ . \\ 0 \\ I_{PD} \\ 0 \\ . \\ . \\ 0 \\ I_R(n) \end{pmatrix} = \Bigg(\qquad [Y] \qquad \Bigg) \begin{pmatrix} V_S(1) \\ V_S(2) \\ . \\ . \\ V_S(k) \\ . \\ . \\ . \\ V_S(n) \\ V_R(n) \end{pmatrix} \qquad (12)$$

The terminal conditions of the winding have to be incorporated into the calculations. If the line-end is connected to a bushing (as is the usual case) having a capacitance C_B, the line-end current can be expressed as

$$I_S(1) = -j\omega C_B V_S(1) \qquad (13)$$

If the neutral-end is solidly earthed,

$$V_R(n) = 0 \qquad (14)$$

Transfer functions can now be calculated between the PD current and the line ($I_S(1)/I_{PD}$) and the neutral currents ($I_R(n)/I_{PD}$). Fig. 3 and Fig. 4 show such transfer functions calculated for various positions of the PD current along the winding. The ranges of frequencies used were from 1 kHz to 2 MHz. Calculations were performed for every other section starting from the 2nd section. Hence the position of the PD signal source is in multiples of 26 turns (2 sections =2×13 turns).

Some salient features of these transfer functions are:

(i) The crests (or poles) always occur at fixed frequencies.

(ii) The troughs (or zeros) change in frequency with the position of the PD current source. The troughs at the line-end transfer functions increase in frequency as the PD source is moved away from that end whereas the troughs at the neutral end transfer functions decrease in frequency as the PD source is moved towards that end.

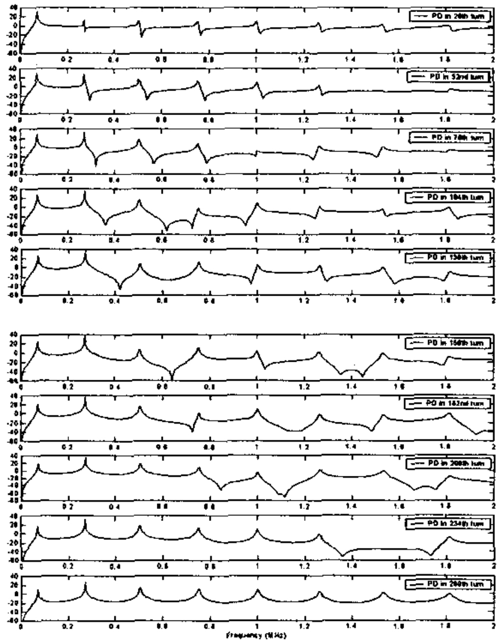


Fig. 3. Transfer functions (in dB) between PD source and line-end

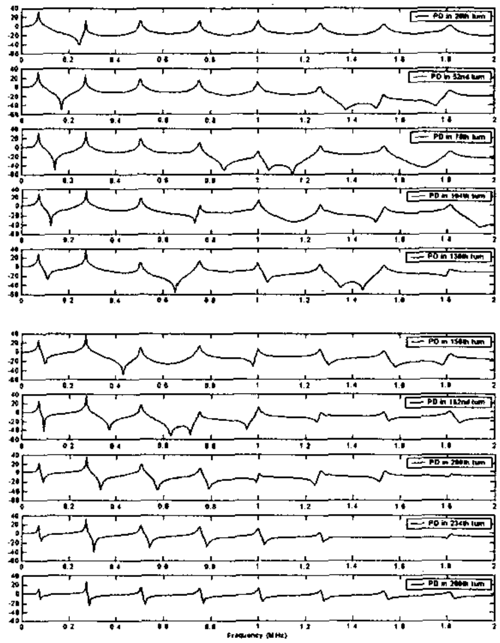
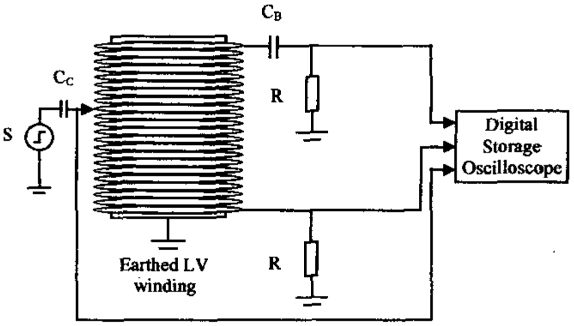


Fig. 4. Transfer functions (in dB) between PD source and neutral-end

EXPERIMENTAL INVESTIGATION

The experimental test setup used to investigate the PD propagation along the winding is shown in Fig. 5. The PD signal was generated using a calibrator consisting of a step wave voltage generator (S) and a coupling capacitor (C_C) of 10pF. The capacitance of the transformer bushing was represented by a capacitor (C_B) with a value of 220pF. Two 50 Ω resistors were used to measure the line-end and neutral-end signals generated across the winding terminals. The oscilloscope (DSO) used has a 12-bit vertical resolution with a maximum sampling rate of 2GS/s on a single channel.



S = step wave generator, C_C = coupling capacitor (10pF)
C_B = bushing capacitance (220pF), R = measuring resistors (50 Ω)

Fig. 5. Experimental test set up

The calibrator was used to inject a PD signal pulse of 200pC to alternate sections along the winding starting from the 2nd section. This included sections 2, 4, 6, 8, 10, 12, 14, 16, 18 and 20 from the line-end. In terms of turn numbers these were: 26, 52, 78, 104, 130, 156, 182, 208, 234 and 260 turns. The responses at the terminals as well as the injected signal were measured simultaneously using three channels of the DSO.

Each signal measured by the DSO had a memory length of 500 data points. In the DSO, the vertical resolution was set to 12 bits and the sampling rate to 10MS/s and the bandwidth to 20MHz. The spectra of the terminal signals were obtained after augmenting the data points with zeros up to a total of 8000 points to increase the frequency resolution, and then applying the Fast Fourier Transform (FFT) algorithm in Matlab®. These spectra are shown in Fig. 6 and Fig. 7.

In comparing the spectra from the line-end responses in Fig. 6 with the corresponding results from the simulations in Fig. 3, one can see the similarity of pole-zero pattern clearly. There are two poles before the first zero for a PD signal in the top half of the winding (i. e. up to turn numbers 130), and this pattern diminishes as the PD source is moved further down the winding. When the PD source is closer to the neutral-end, the zeros at the line-end terminal spectra are undetectable for this range of frequencies (1 kHz ~2 MHz).

The spectra of the neutral-end responses from the measurement and the simulations (Fig. 7 and Fig. 4) show that there is only one pole before the first zero and as the PD signal moves away from the neutral-end terminal, apart from the first zero, other zeros become undetectable.

The two measuring terminals, line and neutral ends, only differ by the capacitance of the bushing, C_B, connected at the line-end terminal. That is, if C_B were not there line-end and neutral-end spectra would have given similar characteristics for PD signals at equal distances from their measuring terminals.

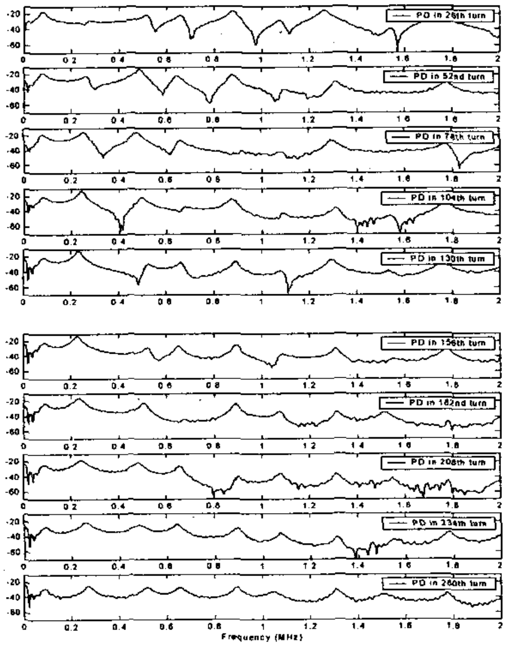


Fig. 6. Frequency spectra of measured line-end signals (in dB)

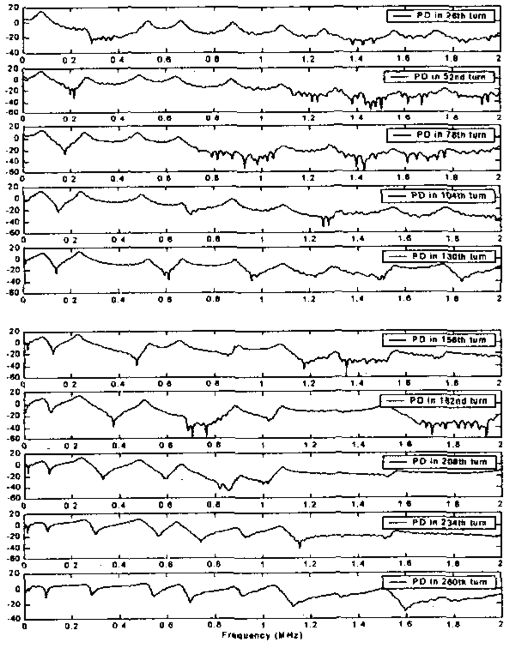


Fig. 7. Frequency spectra of measured neutral-end signals (in dB)

Another feature noticeable in the measured signal spectra is that the crests and troughs are not as sharp as in the simulations. This is due to the high damping effect of the losses in the winding, which is not adequately represented by the simulation model. In the simulation model the calculated resistance and the conductance only consider the skin effect and the dissipation factor.

PD LOCATION

To locate the position of a PD along the winding, one has to obtain the frequency spectra of the measured terminal signals and compare them with the simulation results of transfer functions. The frequency of the first-zero from measurements has to be compared with the first-zero from simulations. If frequencies match closely, the location of the PD source along the winding can be approximated by the location of the PD source in the simulation.

CONCLUSION

The frequency spectra of signals measured at the terminals of a continuous-disc type transformer-winding can give useful information with regard to the location of any partial discharge. The spectra of terminal signals show that troughs increase in frequency as the PD source is moved away from the measuring terminal. Simulated transfer functions from probable PD source locations to the terminals can be compared with the measured terminal signal spectra to match the frequencies of the first-zero. If a close match is found, the location of the PD can be approximated by the location of the simulated PD.

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