

Lumped Parameter Model for High Frequency Partial Discharge Estimation in High Voltage Transformer

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Abstract: - Lumped Parameter Model is well known in solving high frequency signal propagation in high voltage transformer windings. At Southampton University, the modelling technique has been improvised and employed to solve partial discharge (PD) problem occurred within deep inside transformer windings. Firstly, a lumped capacitive parameter model was considered and secondly a transmission line lumped parameter approach developed. A technique of split winding analysis is introduced for both types of model. The derivation of the capacitive network considers the source location of a PD by defining the PD signal propagation in two directions. At the source, the currents are equal in magnitude and are attenuated as they flow in each direction. This provides information for a fixed distribution model equation. Under transmission line lumped parameter models, split winding analysis explains the development of accumulated harmonic waveforms of the PD propagation signal towards the neutral and bushing tap-point. Results have shown a better way to estimate the level of PDs occur within deep inside of transformer windings.

Key-Words:- Partial Discharge Estimation, Transformer Windings, Partial Discharge Propagation.

1 Introduction

A transformer winding may be represented as a large coil consisting of several elements. Fundamentally, the transformer consists of insulation materials and copper windings placed around a laminated core. The transformer can be described using a simple equivalent circuit which results in a lumped circuit parameter model [1-3]. Typically, insulation is modelled using an equivalent capacitor, the coil windings

represented by an equivalent inductor and the losses represented as equivalent resistors.

Different winding types will produce different responses and therefore have different equivalent circuit configurations [4]. This can be seen clearly when comparing the typical plain winding type with the interleaved winding type. The winding arrangement for both types is almost similar except the connection between the coils of the coil pairs.

The choice of connection affects the interturn capacitance between coils and the interleaved winding has a higher series capacitance [5]. Thus in the case of estimating the magnitudes and locating a partial discharge source within the winding it is necessary to consider the detailed construction of the transformer. A good model should give an initial indication of the voltage distribution resulting from any partial discharge within the transformer through the use of transient analysis.

2 Lumped Capacitive Model with Current Divergence

At any instant in time, if an arbitrary input signal is applied at a point x' along the transformer winding, a current in the transformer winding will flow away from the source in two directions as shown in Figure 1.

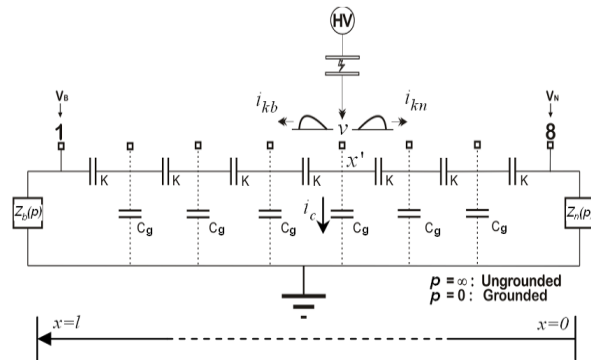


Fig 1. Current divergence for capacitive distribution network

With reference to Figure 1 i_{kn} is the transmitted signal in the direction towards neutral line (ground connection) and i_{kb} is the transmitted signal in the direction towards bushing terminal. Considering the direction towards the neutral line to be positive, the divergence of current according to Kirchoff's Current Law (KCL) can be solved by:

$$\nabla \cdot i = 0 \tag{1}$$

Hence solving Equation (1) for all currents, with the following current definitions:

$$i_k = K \frac{\partial^2 v}{\partial x \partial t} \tag{2}$$

$$i_c = C_g \frac{\partial v}{\partial t} \tag{3}$$

the following partial differential equation (PDE) is developed:

$$\frac{\partial^2 v}{\partial x^2} - \alpha^2 v = 0 \tag{4}$$

where i_k is the current flowing in series capacitance (K), i_c is the current flowing in shunt capacitance to ground (C_g) and α is a fixed distribution constant [1] with the following definition:

$$\alpha = \sqrt{\frac{C_g}{K}} \tag{5}$$

With reference to Figure 1, v_b is the voltage distribution along transformer winding towards bushing and v_n is the voltage distribution towards neutral to ground connection. Hence the terms v_b and v_n corresponds to the two different directions of current flow along the winding with respect to i_{kb} and i_{kn} respectively, i.e.

$$\begin{aligned} v_b &: & x' \leq x \leq l \\ v_n &: & 0 \leq x \leq x' \end{aligned} \tag{6}$$

The solution to the PDE in equation (4) will have the following boundary conditions:

$$\begin{aligned} v_b &= V_B & \text{at } x = l \\ v_n &= V_N & \text{at } x = 0 \end{aligned} \tag{7}$$

and

$$\begin{aligned} v_b &= v_n & \text{at } x = x' \\ \frac{dv_b}{dx} &= \frac{dv_n}{dx} & \text{at } x = x' \end{aligned} \tag{8}$$

Where V_B and V_N are measurable voltage level at bushing and neutral respectively.

3 The PDE

As an alternative solution to the PDEs from Equation (4), the presence of inductive elements can cause oscillations in the circuit. This is due to energy storage excited by the current-carrying conductor which tends to resist changes in the current. Figure 2 shows an alternative circuit solution for current propagation including the influence of inductive elements.

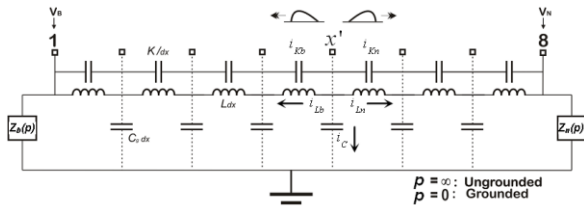


Fig 2. Current divergence LCK circuit network

Based on the divergence of the current in opposite directions, the following equation is derived [1]:

$$LK \frac{\partial^4 v}{\partial x^2 \partial t^2} - LC_g \frac{\partial^2 v}{\partial t^2} + \frac{\partial^2 v}{\partial x^2} = 0 \quad (9)$$

3.1 Split Winding Analysis

Equation (9) describes signal propagation towards the neutral and bushing tap point. The solution of the PDE is in the form of standing wave solution for both waves travelling towards bushing and neutral to ground connection. By considering losses and attenuation, a full lumped parameter model has to be considered by introducing core loss, ground conductance and iron loss. This can be found in [6-8]

The split winding analysis introduces two different solutions corresponds to two different waves propagate in opposite direction. To obtain a solution towards neutral, assumption made that the initial conditions are that the initial inductance current is zero which satisfies the following:

$$\frac{\partial^2 v_n}{\partial x^2} - \alpha^2 v_n = 0 \quad \text{and} \quad \frac{\partial \psi_n(x,t)}{\partial t} = 0 \quad (10)$$

and with boundary conditions:

$$\psi_n(l,t) = V_B(t) \quad \text{and} \quad \psi_n(0,t) = 0 \quad (11)$$

Where $\psi_n(x,t)$ is the standing wave solution at any point x towards neutral. Similarly for the solution toward bushing, must also satisfies the following conditions:

$$\frac{\partial^2 v_b}{\partial x^2} - \alpha^2 v_b = 0 \quad \text{and} \quad \frac{\partial \psi_b(x,t)}{\partial t} = 0 \quad (12)$$

and with boundary conditions:

$$\psi_b(l,t) = V_B(t) \quad \text{and} \quad \psi_b(0,t) = 0 \quad (13)$$

Where $\psi_b(x,t)$ is the standing wave solution at any point x towards bushing.

3 Results and Discussion

The results presented are based on both experimental and simulation. The experiment were carried out for the injection of infinite rectangular and real PD waves onto interleaved winding and plain winding with 7 disc sections, where $x' = 0/7$ is the measurement for the source at neutral and $x' = 7/7$ is the measurement for the source at bushing tap point.

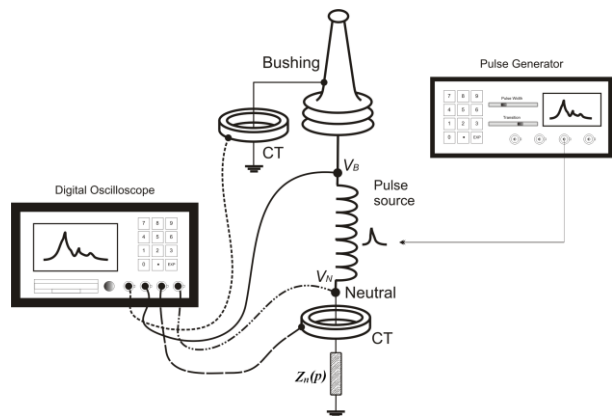


Fig3. Measurement for infinite rectangular waves injection.

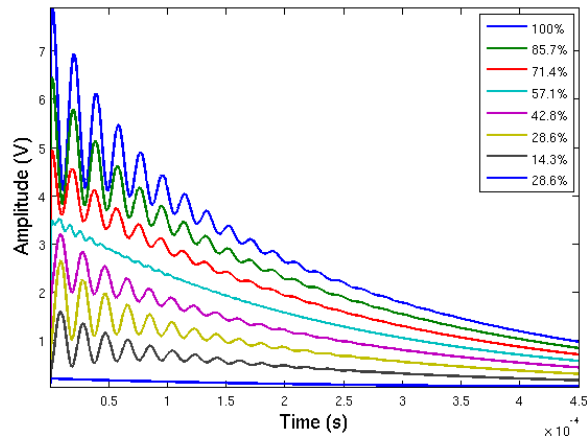
3.1 Results of Split Winding Analysis

The fundamental of PD signal modeling lies in the split winding analysis and its parameter estimation solution [1]. To demonstrate the split winding analysis, a simple experiment was carried out using an infinite rectangular wave as a source of PD. Figure 3 shows the experimental arrangement.

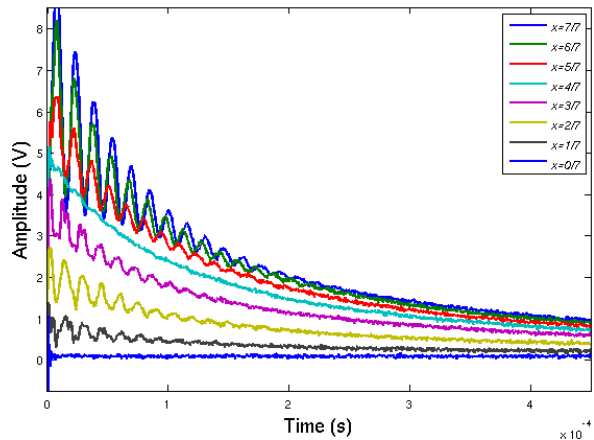
The infinite rectangular waves were injected at different position, x' , along transformer windings. The responses were measured at bushing and neutral terminal. The corresponding currents were verified with the high frequency current transition in time domain from the current transformer (CT) measurements.

Figure 4 shows the experimental and the model simulation results for interleaved winding. The model was taken by considering the fixed distribution constant, α equals to 0.35. Noted that, the split wave originated from source x' oscillate as the waves travels further away from each other. At any point x , the voltage level was measured and estimated using the derived model based on the PDE of Equation (9) with losses.

Figure 5 shows the experimental and the model simulation results for plain winding. The simulated model was by considering the fixed distribution constant, α equals to 0.7. Through observation, it is obvious that both windings have a very similar pattern for travelling waves. There is very good agreement between

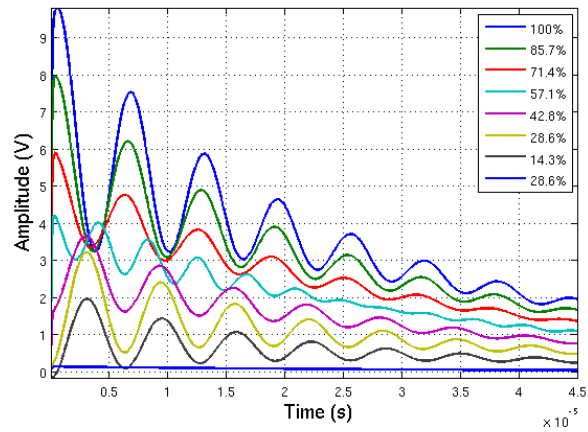


(a) Model Simulation

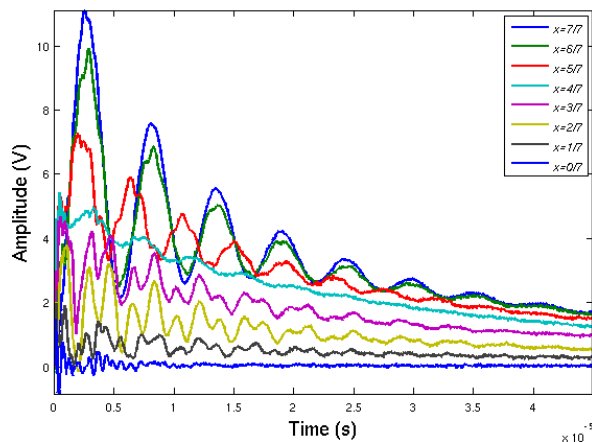


(b) Experimental Result

Fig4. Time domain response to infinite rectangular wave measured at different x' for interleaved winding



(a) Model Simulation



(b) Experimental Result

Fig5. Time domain response to infinite rectangular wave measured at different x' for plain winding

measurement and simulation results for both type of windings by means of its oscillation patterns

3.1 Results of Capacitive Network with PD

To demonstrate the capacitive lumped parameter model, an experimental setup as shown in Figure 6 was carried out using real PD measurement. The experiment used five RFCTs to measure PD current propagation along the transformer windings.

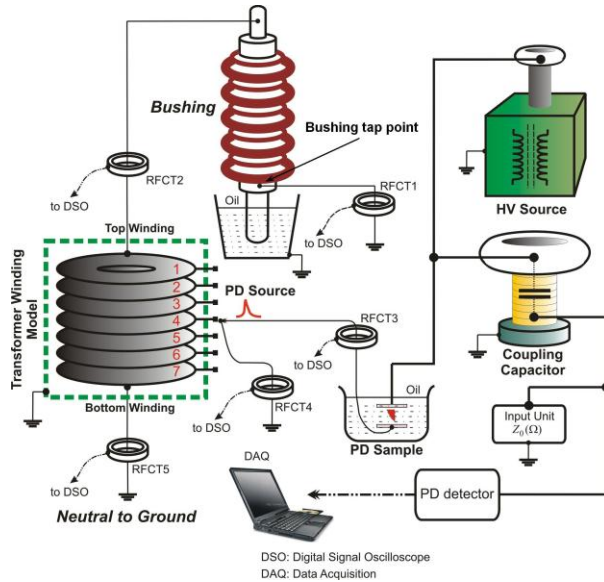
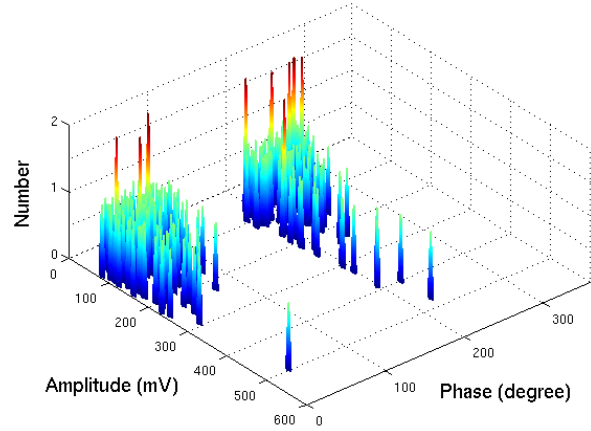


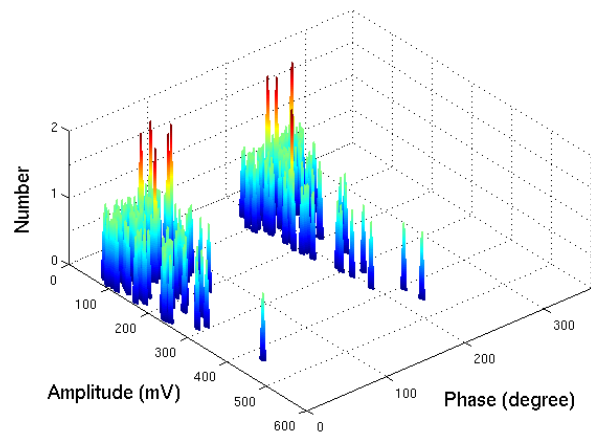
Fig6. Schematic diagram for PD measurement with five RFCTs

RFCT1 is used to measure the PD response from bushing to ground connection, RFCT2 is to measure PD current at the top of the winding, RFCT3 is to measure the PD current at source or before entering the winding, RFCT4 is to measure current due to the influence of the winding configuration at the source point x' and RFCT5 is to measure the PD current to the ground connection.

For sake of modeling and experiment, only RFCT2, RFCT4 and RFCT5 were considered. Therefore the current capacitive model will now take place for the modeling part. The full derivation of the current capacitive model can be found in [1]. However all the RFCTs were measured in mV scale which has been calibrated to real PD measurement to be 5mV to 20pC for void PD and 3mV to 9pC for surface discharge.



(a) Measured at $x' = 5/7$



(b) Model estimation at $x' = 5/7$

Fig7: PD from void pattern measured and estimated, filtered at $f_L = 7\text{MHz}$, $f_U = 90\text{MHz}$, injection at $x' = 5/7$ on plain winding. 50 cycles of data

The objective of the experiment was to estimate the PD magnitudes with ϕ - q - n pattern at RFCT4 based on terminal end measurements from RFCT2 (bushing) and RFCT5 (neutral).

Figure 7 shows the comparison of the measured ϕ - q - n PD pattern and the model estimation ϕ - q - n pattern of the PD signal at $x' = 5/7$ of plain winding. The data was recorded on the DSO using sampling rate at 200MHz, with total recorded data 100MS, equivalent to 0.5s or 25 cycles of applied voltage.

The experiment continued with higher sampling rate at 1GHz. A surface discharge source was injected into the plain winding at $x' = 2/7$.

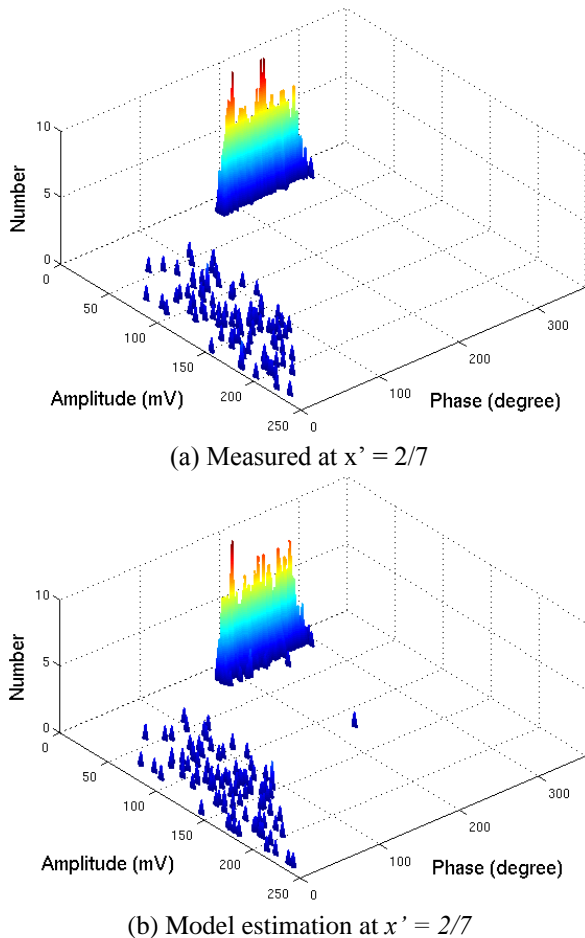


Fig8: Surface discharge pattern measured and estimated, filtered at $f_L = 7\text{MHz}$, $f_U = 150\text{MHz}$, injection at $x' = 2/7$ on plain winding. 10 cycles of data

Figure 8 shows the results with close agreement of the ϕ - q - n patterns between measurement and model estimation for a wider frequency range with higher frequencies above 100MHz.

4 Conclusion

Modelling techniques for PD estimation based on the lumped capacitive and LCK network models have been presented. With similar analysis to the capacitive network for a voltage distribution, the solution based on the current derivation is needed to provide an analytical model solution for real PD current propagation. The split winding analysis has proven to be able to model high frequency signal transition in time domain in order to model the PD propagation. Both model

equations consider the source position at x' for the source to ground connection. This has facilitate in finding a new way to estimate the PD magnitudes and location within transformer windings.

References:

- [1] R. Mohamed, "Partial Discharge Signal Propagation, Modelling and Estimation in High Voltage Transformer Windings". *Doctor of philosophy*, School of Electrical and Computer Science, University of Southampton, SO17 1BJ, Sept 2010.
- [2] L. V. Bewley, "Transient oscillations in distributed circuits with special reference to transformer windings," *Transactions of the American Institute of Electrical*, vol. 50, pp. 1215–1233, December 1931.
- [3] L. V. Bewley, "Equivalent circuits of transformers and reactors to switching surges", *Transactions of the American Institute of Electrical Engineers*, vol. 58, pp. 797–802, December 1939.
- [4] K. Pedersen, M. E. Lunow, J. Holboell, and M. Henriksen, "Detailed high frequency models of various winding types in power transformers," *International Conference on Power Systems Transients (IPST05), Montreal, Canada*, vol. Paper No. IPST05-100, 19-23 June 2005.
- [5] K. Karsai, D. Kerenyi, and L. Kiss, *Large Power Transformer*. Elsevier Science Ltd, Nov 1987.
- [6] L. V. Bewley, *Traveling Waves on Transmission Systems*. 180 Varick Street, New York 14, N.Y: Dover Publication, Inc, 2nd edition ed., 1951.
- [7] A. Akbari, P. Werle, H. Borsi, and E. Gockenbach, "A continuous parameter high frequency model based on travelling waves for transformer diagnostic purposes," *Conference Record of the 2002 IEEE International Symposium on Electrical Insulation*, pp. 154–157, April 7-10 2002.
- [8] A. Akbari, P. Werle, P. Borsi, and E. Gockenbach, "Transfer function based partial discharge localization in power transformer: A feasibility study," *IEEE Electrical Insulation Magazine*, vol. 18, pp. 22–32, Sept/Oct 2002.