Modelling of partial discharge pulse propagation in transformer windings using multi conductor transmission line modelling scheme

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Abstract. Power transformers are considered as an essential component in the electric power systems. They are placed in services in different circumstances like electrical, environmental and mechanical stresses, and through the progress of operation it can affect with various threats and hazards. Transformer failure should be diagnosed earlier in order to avoid its unsafe and unstable operation. The main reason for failure of insulation in power transformer is due to partial discharges. The partial discharge activity occurring in the transformer have to be identified earlier, afore it progresses into a complete discharge, otherwise it results in the maintenance of the device and causes loss of economic cost to the utilities. In this paper, multi conductor transmission line theory is used for the modelling of transformer windings and the partial discharge pulse propagation through the winding is simulated in the MATLAB Simulink. The effect of partial discharge on the windings are also discussed.

Keywords- Partial Discharge (PD), Transformer Winding Modelling, Pulse Propagation, Multiconductor Transmission Line (MTL), MATLAB Simulink

1. INTRODUCTION

Partial discharge can occur in the transformers due to degradation processes of the insulation systems and ageing. Several factors including thermal, mechanical and electrical overstressing are the reasons for the frequent occurrence of partial discharge activities in the transformer. This PD activity happening through primary stages of process can be due to the imperfections of design or processing during manufacture [1]. PD measurement is an authentic and efficient method and using this method the insulation condition of an electrical asset can be diagnosed at all times. Regular partial discharge measurements and continuous monitoring collects very sensitive information to efficiently identify the stresses and weak points occurring in the insulation structure. Systematic partial discharge measurement in the system can safeguard the reliable, efficient and long-term operation of electrical equipment without causing any economic loss to the utilities [2].

There are various methods available for partial discharge detection in transformer windings. The primary set contains studies about partial discharge measurement. It is divided into electric, audio and optical detection. The second type consist of data analysis measurement for identifying the kind of fault and its effect. The various technique employed for the analysis of data includes signal processing, statistical methods etc. Transformer winding models [3-4] are also very useful for partial discharge studies. For the analysis purpose, either the Lumped parameter or distributed parameter archetypal can be used. The MTL is very useful for the partial discharge studies. In MTL process, the winding is treated as parallel lines having the equivalent length. Each turns or winding of the
transformer can be modelled in terms of a transmission line. The propagation of partial discharge pulses taking place in the transformer windings can be effectively analysed using this method of modelling. This method can also be suitably used for frequency up to several MHz [5].

In this paper, pulse propagation due to partial discharge occurring in the windings of transformer is investigated. A transformer winding is designed and the parameters required for the studies are calculated. In section 2, the structure of the transformer winding, the design steps and obtained values of design parameters are presented. The MTL concept is used for the propagation study of PD pulse in the windings. The third section gives an idea about the MTL theory and description about circuit used in MATLAB Simulink model. The obtained results are presented in section 3.

2. DESIGN AND ESTIMATION OF PARAMETERS OF TRANSFORMER WINDING

2.1. Structure of the transformer winding

The transformer winding is modelled as an equivalent RLC circuit. The winding includes a series connection of resistance and inductance in parallel with a capacitance. A shunt capacitance or parallel capacitance is also connected to the ground. From the first winding to the last, the structure remains the same. The equivalent circuit of a 42-disc transformer winding model is depicted in Figure 1.

![Figure 1. Equivalent circuit of a 42 disc transformer winding model](image)

2.2. Design steps

The transformer winding modelling is a crucial part for the partial discharge propagation study. In the design part the specification of transformer is given. The specification of the transformer is 1 MVA, 11KV/415V, delta-star connected dry type transformer. The core circle diameter is initially assumed. The number and width of core steps are selected and the gross area is calculated. The low voltage and high voltage currents and voltages are subsequently calculated. The maximum and rated tap turns are also estimated. An initial current density is selected to compute the low voltage net area and cross sectional area. Then the actual current density is determined. Similarly, the high voltage winding cross-sectional area and conductor size is calculated.

After finding the low voltage and high voltage parameters the calculation of number of discs are calculated. Then the inside and outside diameter of both high voltage winding and low voltage winding is calculated. Based on these values the resistance, inductance and capacitance values of the windings are obtained. The values obtained from the design are given in Table 1.
Table 1: Specifications and design parameters of 1MVA,11KV/415V transformer

| Sl.No | Specifications             | Values     |
|-------|---------------------------|------------|
| 1     | KVA                       | 1000       |
| 2     | Phases                    | 3          |
| 3     | Frequency                 | 50 Hz      |
| 4     | Primary Volts             | 11,000 v   |
| 5     | Secondary Volts           | 415 v      |
| 6     | Percentage Impedance      | 5%         |
| 7     | Tap Range                 | ±5%        |
| 8     | Core Circle Diameter      | 266 mm     |
| 9     | Inside Diameter of LV     | 282 mm     |
| 10    | Outside Diameter of LV    | 371 mm     |
| 11    | Inside Diameter of HV     | 437 mm     |
| 12    | Outside Diameter of HV    | 545 mm     |
| 13    | HV rated tap turns        | 597 turns  |
| 14    | HV highest tap turns      | 627 turns  |
| 15    | Height of winding         | 800 mm     |
| 16    | No of Discs               | 42         |
| 17    | Flux Density              | 1.65 T     |

2.3. Parameters Calculation
For the parameters calculation a transformer winding having forty-two continuous disc type sections is designed. Each winding has a resistance, inductance, capacitance and conductance [9].

2.3.1. Resistance:
The resistance of the disc winding can be calculated using the following equations:

\[ R = \rho \frac{l}{A} \]  

Where ‘R’ is the resistance of the winding
‘l’ is the length
‘A’ is the area of the conductor
‘\( \rho \)’ is the resistivity

2.3.2. Inductance:
The inductance calculation is done by assuming that the winding comprises of loss-less multi-conductor transmission lines bounded via identical insulator. The inductance is given by:

\[ L = 0.001n^2a \rho \]  

Where ‘\( n^2 \)’ is the number of turns in each winding
‘\( \rho \)’ = b/c
‘b’ = width of the conductor
‘c’ = radial thickness of the disc.

### 2.3.3. Capacitance

Based on permittivity of the insulation and geometry of the winding the capacitance is calculated. Inter-turn capacitance (CIT), Disc-Disc capacitance (Cd) and Ground capacitance (Cg) are the main three capacitance used in the calculation. The CIT and Cd comprises the total series capacitance of the winding (Ct) [6].

**i) Capacitance between turns of winding (CIT)**

\[
\text{CIT} = 0.974 \frac{D_m}{e} \left( \frac{h+e}{e} \right) \\
\text{Where } D_m = \text{mean diameter of the conductor} \\
h = \text{Width of the bare conductor} \\
e = \text{insulation thickness between conductor}
\]

**ii) Capacitance between Discs (Cd):**

\[
C_d = D_m \left( \frac{B+t}{t+0.874e} \right) \\
\text{Where } D_m = \text{mean diameter of discs} \\
e = \text{insulation thickness} \\
B = \text{radial thickness of Disc} \\
t = \text{distance between two discs}
\]

**iii) Total series capacitance of Disc winding (Ct):**

\[
C_t = \frac{\text{CIT}}{N} + C_d \left( \frac{4}{3} \right) \\
\text{Where CIT- Capacitance between turns of disc winding} \\
C_d - \text{Capacitance between Discs}
\]

**iv) Ground Capacitance (Cg):**

\[
C_g = \frac{0.378}{\Delta-0.43t} \frac{(D_a+D_b)(L+\Delta)}{\Delta} \\
\text{Where } D_a = \text{outer diameter of low voltage winding} \\
D_b = \text{inner diameter of high voltage winding} \\
L = \text{winding height} \\
\Delta = \text{radial gap between windings} \\
t = \text{total insulation thickness between windings}
\]

### 2.3.4. Conductance

As a result of capacitive loss in the insulation conductance (Ga) occurs. The frequency f, capacitance C and the dissipation factor tan δ are the factors the conductance depends on.

\[
G_a = 2nf[C] \tan \delta' \\
\text{Where } G_a \text{ is the conductance} \\
\tan \delta' \text{ denotes the dissipation factor}
\]
The parameters of the winding are calculated using the equations (1-7) and the values are given in Table 2.

| Sl.No | Parameters                                | Values    |
|-------|-------------------------------------------|-----------|
| 1     | Resistance                                | 1.03 Ω    |
| 2     | Inductance                                | 1.3703 mH |
| 3     | Capacitance between turns                 | 1207.54 pF|
| 4     | Capacitance between Discs                | 711.031 pF|
| 5     | Total series capacitance                  | 976.8 pF  |
| 6     | Ground Capacitance                        | 754.168 pF|
| 7     | Conductance                               | 0.97087 S |

3. MODELLING OF PARTIAL DISCHARGE PULSE PROPAGATION IN TRANSFORMER WINDINGS

3.1 Multi Conductor Transmission Line Model

The primary phase of partial discharge identification is to develop a model that can be used in high frequencies to analyse and monitored precisely the behaviour of the transformer windings [7]. One of the best model for evaluating the PD studies and analysis is the MTL model. In the MTL model each turn or winding of the transformer is modelled as a transmission line.

The boundary conditions to realise the multi conductor transmission line theory given in equations (8) and (9) is illustrated in Figure 2:

\[
V_R(j) = V_S(j+1) \quad \text{for} \quad j = 1 \text{ to } p-1 \quad (8)
\]

\[
I_R(j) = -I_S(j+1) \quad \text{for} \quad j = 1 \text{ to } p-1 \quad (9)
\]

where \(V_S(j)\) and \(I_S(j)\) are sending end voltage and current of \(j^{th}\) transmission line. Similarly \(V_R(j)\) and \(I_R(j)\) are its receiving end voltage and current. The boundary conditions of equations (8) and (9) are applied to the wave equations, then the sending and receiving end current vectors can be defined in terms of voltage vectors [8].

\[
\begin{pmatrix}
I_S \\
I_R
\end{pmatrix}
= 
\begin{pmatrix}
Y_0 \coth([D]l) & -Y_0 \cosech([D]l) \\
-Y_0 \cosech([D]l) & Y_0 \coth([D]l)
\end{pmatrix}
\begin{pmatrix}
V_S \\
V_R
\end{pmatrix}
\quad (10)
\]

where \([D]^2 = [Z_a] [Y_a]\)

\[Y_0 = [Z_a]^{-1} \cdot [D]\]

\[Z_a = R \cdot [I] + j \cdot 2\pi f \cdot [L]\]

\[Y_a = [G_a] + j \cdot 2\pi f \cdot [C]\]
[\mathbf{Z}_a] and [\mathbf{Y}_a] are impedance and admittance matrices of the model respectively. The impedance and admittance matrix comprises of resistance, inductance, capacitance, conductance matrices, frequency (f) and the average length of the line (l) [8].

The matrix D have to be diagonalized using modal transform in order to find the value of \(\coth([D]l)\) and cosech([D]l). After dual phases of simplification and an inversion of matrix, expanding the first and last rows and applying the terminal conditions all the internal voltages needed for the PD localization can be computed [8].

\begin{equation}
\text{Pulse} = A_m (\exp^{-\alpha t} - \exp^{-\beta t})
\end{equation}

where ‘\(A_m\)’ is the amplitude of the wave and ‘t’ denotes the time instant.

The PD pulse is modelled using a signal builder, and a controlled current source. The pi network is used for modelling the MTL model of the transmission line. Fig 4 depicts the model of a single disc of a transformer winding. Similarly, 42 disc winding model is developed in Simulink. The input PD signal is generated in the signal builder block and is fed to the different discs of the winding through a current controlled source.

**Figure 2.** MTL model of Transmission Line

**Figure 3.** Simulink model of a 42 disc winding transformer
3.3. Results

In this paper, the PD pulse propagation through a 42 disc winding model is analysed. The input pulse is shown in Figure 4. The input partial discharge pulse generated from the signal builder is applied to the first disc winding of the transformer. As the PD pulse propagates along the transformer winding geometry, attenuation and distortion occurs and the magnitude of the pulse will be slightly small compared to the input. These pulses propagate through the whole winding of the transformer and on reaching the terminal the pulse magnitude will be very low.

![Figure 4](image)

**Figure 4.** Input partial discharge pulse

This input PD signal in the form of a current pulse is given as a source to the first disc winding. The magnitude of the input PD signal is 0.012. The output obtained from the discs 1 and 2 are shown in Figure 5. The magnitude of the pulses starts decreasing as it travels through each of the disc of the winding.

![Figure 5](image)

**Figure 5:** Output waveforms of propagated PD current pulses obtained from: (a) Disc 1 (b) Disc 2

Similarly, the outputs are obtained from discs 5 and 6 when the same input PD signal is given to the fifth disc winding are shown in Figure 6. Likewise, the same input can be applied to the different disc winding to find the characteristics of the PD pulse propagation.
Figure 6: Output waveforms of propagated PD current pulses obtained from:(a) Disc 5 (b) Disc 6

Table 3: Peak value, rise time and settling time of pulse propagates from disc 1

| Disc No | Peak Value (mA) | Rise Time (ns) | Tail Time (µs) |
|---------|-----------------|----------------|----------------|
| 1       | 1.1             | 2.08           | 2.28           |
| 2       | 1               | 1.89           | 2.05           |
| 3       | 0.9             | 1.73           | 1.84           |
| 4       | 0.8             | 1.58           | 1.65           |
| 5       | 0.7             | 1.45           | 1.49           |
| 6       | 0.63            | 1.34           | 1.33           |

Table 4: Peak value, rise time and settling time of pulse propagates from disc 5

| Disc No | Peak Value (mA) | Rise Time (ns) | Tail Time (µs) |
|---------|-----------------|----------------|----------------|
| 5       | 0.8             | 1.47           | 1.46           |
| 6       | 0.7             | 1.36           | 1.31           |
| 7       | 0.62            | 1.27           | 1.18           |
| 8       | 0.58            | 1.20           | 1.06           |
| 9       | 0.51            | 1.14           | 9.51           |
| 10      | 0.45            | 1.09           | 8.54           |

Comparing the results of Figure 5 and Figure 6 with Figure 4, it shows that the peak amplitude of PD pulse goes on decreasing while travelling through the whole disc of the transformer. The results of
time domain simulation of PD propagation when a PD signal is applied to disc number 1 is depicted in Table 3. The simulation of PD propagation when the PD signal is applied to disc number 5 is shown in table 4 for comparison. From Tables 3 and Table 4, it is clear that the peak value of pulse is decreasing while travelling through the whole disc. The rise time of the wave is also reduced when it propagates through the disc. The result shows that the peak time, rise time and tail time are reduced when the signal propagation from disc 5 is compared to the propagation from disc 1. The effect of partial discharge pulse occurring in the winding will be very high compared to that of other windings through which it propagates. This establishes that the proposed simulation method is a useful method for partial discharge analysis.

4. CONCLUSION

In this paper, the MTLM theory is used to find the partial discharge pulse occurring in the windings. A 1MVA, 11KV/415V transformer is designed and the parameters required for the simulation are calculated. An input PD signal is generated and is fed to the various disc of the windings. As it propagates through the discs the magnitude of the pulses is reduced. The peak value, rise time and tail time of the pulses are also calculated for the analysis purpose. When the pulse propagates through the whole windings of the transformer variations were occurred in the rise time, peak time and tail time of the pulse. These variations can be further analysed to develop suitable methods for the partial discharge source detection and localisation.

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