A Simplified High Frequency Model of Interleaved Transformer Winding

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Abstract: Disconnector or breaker switching operations generates Very Fast Transient Overvoltages (VFTO) in Gas Insulated Substations (GIS). These VFTO have their rise-times in the range of a few nanoseconds and is followed by high frequency oscillations which can endanger the insulation of transformer winding. Hence it is necessary to develop appropriate models to study these transients. In this study, a simplified transformer circuit model capable of simulating the high frequency range from 100 kHz to several MHz is proposed to simulate the high frequency surge over voltages generated in an actual system. A 22 kV interleaved transformer winding is considered for the analysis. Resonant frequencies for different transformer models are obtained in circuit simulation package and compared with measured frequencies obtained from Sweep Frequency Response Analyser (SFRA). The results of the proposed model demonstrate better agreement with the measured values.

Keywords: Circuit model, gas insulated substations, impedance characteristics, sweep frequency response analysis, very fast transient overvoltages

INTRODUCTION

Gas Insulated Substations has gained a wide range of acceptance in power system for its compactness, high reliability and low maintenance (Matsumara and Nitta, 1981). GIS units with sulphur hexafluoride as the insulating gas, has been functioning for more than 30 years (Naidu, 2008). In spite of these merits GIS has its unique problems, among which the susceptibility of the insulation system under VFTO is of major concern. These VFTO’s stress the equipment in GIS as well as the secondary equipment (Meppelink et al., 1989). Due to very short rise time, VFTO can cause an unbalance in voltage distribution in transformer windings (Shibuya et al., 1997). Under these circumstances, the turn-to-turn voltage can arise close to the transformer BIL. Another problem is the occurrence of resonance in transformer winding when the frequencies of the incoming VFTO match some of the resonance frequencies of the transformer. Most of the time, resonant overvoltages can cause a flashover from the windings to the core or between the turns leading to insulation failure of Transformer. Hence, there is a need to estimate the magnitudes of VFTO generated at the Transformer terminal during switching operations in GIS.

Often, the transformer is simulated by a single lumped capacitance called a surge intrusion capacitance. Since high frequency surge overvoltages which ranges from several kHz to several MHz are generated in an actual system, the development of a new transformer model for the frequency range of several KHz to MHz is desirable (Okabe et al., 2011). A simple high frequency electric model is used for the analysis of the re-ignition surges at interruptions of the reactor of a model substation (Okabe et al., 1999). To precisely simulate the winding up to the high frequency range, a detailed equivalent circuit is required that provides the inductance and capacitance for each turn of the conductor. However, such a detailed model is far too complicated for the whole transformer if its purpose is not to clarify the electric potential distribution within a winding but to obtain the voltage generated at the transformer terminal through surge analysis of the substation or overall system. In this study a simplified and lumped high frequency circuit model is developed for an interleaved transformer winding. The efficacy of the model is verified by comparing the resonant frequencies with the measurement values.

METHODOLOGY

Materials:
Winding under study: A prototype 22 kV interleaved transformer winding is considered for analysis. The winding comprises of 40 sections with 12 turns/section. The main parameters and constants of the winding are shown in Table 1. The values of inductance and capacitance for different models are calculated from the physical parameters.
Methods: The different circuit models for an interleaved transformer winding are considered for analysis. The resonant frequencies obtained for various models using PSpice are compared with measured frequencies through SFRA.

Detailed models: Two discs constitute a single structural unit, which comprise the whole winding when collectively stacked (Okabe et al., 2011). The detailed transformer models are used to predetermine the over voltages, to study the resonance behaviour of transformer winding and the distribution of electrical stresses along the transformer winding. Detailed model (Okabe et al., 2011) and RLC Ladder network model (Hosseini et al., 2008) referred as model A and B respectively are discussed in this section.

Figure 1 shows the Detailed model (Model A) for an interleaved double disc coil. Each turn is expressed by one inductance element. \( C_a \) represents the section-to-section capacitance, \( C_r \) represents the turn-to-turn capacitance and \( C_g \) represents the ground capacitance per turn whose values are obtained from the finite element method simulation of the actual transformer winding with the accurate physical dimensions.

To simulate a single double disc interleaved winding with circuit Model A, the number of nodes required is 20. This circuit model can be simplified which holds in the low frequency range with the parallel combination of \( L_0 \) and \( C_0 \). Here, \( L_0 \) is the self inductance of the whole coil with \( 2n \) turns, which is about \((2n)^2\) times the value of the inductance per turn. The series capacitance of an interleaved disc winding can be obtained using the stored energy method and is given by equation:

\[
C_0 = C_r \frac{n^2 - 2}{2}
\]  

(1)

where, \( C_0 \) in equation is given as the capacitance for two sections in Fig. 2 to structure the circuit of the whole winding.

Figure 3 shows the RLC ladder network model (Hosseini et al., 2008) Model B for an interleaved double disc coil. Each turn is expressed by one inductance element and a series capacitance \( C_r \) and a ground capacitance \( C_g \).

The series capacitance comprises of inter turn capacitance alone and is given by equation:

\[
C_s = E^2 \cdot C_r \cdot \frac{(n-1)}{4N}
\]  

(2)

where,

\( E \) = Order of interleaving
\( C_r \) = Inter turn capacitance
\( N \) = Number of discs
\( n \) = Number of turns per section

Similarly, to simulate a single double disc interleaved winding with circuit Model B, number of nodes required is 18.
**High frequency circuit model:** When the wave front time of the voltage applied to the winding is short relative to the charging time of the inter turn capacitance, the potential of the turns in the section is not linearly distributed and so the capacitance obtained by the stored energy method is not applicable.

Pedersen (1963) has assumed each section of an interleaved disc winding to be a spirally wound parallel plane capacitor and considered that the winding responded to steep front waves like a transmission line of capacitance \( C \) and inductance \( L \) per section. Here, \( C \) is given by equation:

\[
C = (n - 1) \varepsilon \varepsilon_0 \pi D b / d
\]  
(3)

where,
- \( \varepsilon \) = Relative permittivity of the turn-to-turn insulation
- \( \varepsilon_0 \) = Vacuum permittivity
- \( D \) = Average winding diameter
- \( b \) = Axial conductor width
- \( d \) = Turn-to-turn insulation thickness

The value \( L \) is given by the inductance of the parallel conductors consisting of the conductors in Groups A and B with the length of the parallel conductor in one section equivalent to \( n/2 \) turns. Inductance \( L \) is given by equation:

\[
L = \frac{n}{2} \varepsilon \varepsilon_0 \mu_0 \pi D d / b
\]  
(4)

where,
- \( \mu_0 \) = Vacuum magnetic permeability

When a surge reflects at that part of a section which extends on the inner side to the next section, oscillation of a frequency corresponding to the reciprocating time of the section occurs and its fundamental oscillation frequency is given by:

\[
T = 2\sqrt{LC} = 2\pi n D \sqrt{\frac{\varepsilon \varepsilon_0 \mu_0}{2}} \left(1 - \frac{1}{n}\right)
\]  
(5)

In order to express an oscillation circuit of resonance frequency \( f_1 \) identical to this oscillation using the LC parallel circuit with a lumped constant, its inductance \( L_1 \) and capacitance \( C_1 \) is given by:

\[
f_1 = \frac{1}{2\sqrt{LC}} = \frac{1}{2\pi \sqrt{L_1 C_1}}
\]  
(6)

Hence, \( L_1 = \frac{L}{\pi} \); \( C_1 = \frac{C}{\pi} \)  
(7)

The \( L_1C_1 \) parallel circuit, consisting of the inductance \( L_1 \) and capacitance \( C_1 \) is serially connected to the \( L_0C_0 \) parallel circuit. This circuit has a parallel resonance point at frequency \( f_1 \). To simulate higher order resonance frequencies up to the second order, the \( L_2C_2 \) parallel circuit given by equation \( L_2 = L_1/L_2 \) and \( C_2 = \frac{C_1}{2} \) is connected.

![Fig. 4: High frequency model up to 5th order with Cg-model D](image1)

![Fig. 5: Lumped high frequency model up to 5th order with Cg-model E](image2)
Parallel resistors are connected in the second and third stage LC circuits. The damping resistance of this high frequency wave is expressed as \( k^* \left( \frac{L}{C} \right)^{1/2} \) and the value of \( k \) is approximately equal to 10. The high frequency circuit model comprises of three stages of LC parallel circuit is shown in Fig. 2. In this case, the number of nodes reduces to 7. The number of three stages of LC parallel circuit equals the number of double disc coil in the entire winding.

High frequency circuit model up to fifth order models the high frequency oscillations in addition to the fundamental component. The circuit model is same as that of three stage LC circuit with another three stages cascaded to it accounting for the higher frequencies as shown in Fig. 4. Inclusion of Capacitance to ground \( C_g \) is necessary since it has a predominant effect in the higher frequency range in the range of MHz. The cascaded LC parallel circuits are the integral multiples of the \( L_1C_1 \) parallel circuit given by equations:

\[
L_3 = \frac{L_1}{3} \quad C_3 = \frac{C_1}{3} \quad \text{and} \quad L_4 = \frac{L_1}{4} \quad C_4 = \frac{C_1}{4}
\]

**Proposed high frequency model:** The proposed circuit model (Model E) comprises of two sections of fifth order high frequency model with \( C_g \) as shown in Fig. 5 which models the entire winding. Model E is obtained from Model D, where the distributed high frequency sections for each and every double disc is converted into only two high frequency sections representing the entire winding. The stray capacitance of the winding is connected in between the two sections. The major advantage of this model is that, the complexity of the model is reduced by reducing the number of nodes required for the whole winding to 13 irrespective of the number of sections, turns and dimensions of the winding.

**RESULTS AND DISCUSSION**

Initially, the entire 22 kV interleaved winding is modeled for analyzing the voltage distribution of the inducting. Input source is taken as sinusoidal source (50 Hz), lightning impulse and steep wave front 32 nsec surge for voltage distribution studies, as these sources cover the wide frequency range from kHz to several MHz. Figure 6 shows the voltage distribution along the winding for different source voltages. The voltage distribution is not linear when the input surge is of very high frequency range (several MHz). A graph showing intersection voltage along Y axis and corresponding sections along X axis is plotted is shown in Fig. 7. The section to section voltage difference is found as constant for sinusoidal supply and a small deviation is seen for lightning impulse. If the waveform duration is in nano second range, the section to section voltage difference is not constant. A deviation occurs at the earth terminal and in the middle sections of the winding. Hence, a single transformer model cannot be used for the whole frequency range to obtain the overvoltage at the transformer terminal.

A comparison of various models on the basis of nodal requirement is given in Table 2. Model E requires minimal number of nodes for modelling the transformer winding for a wide range of frequencies when compared to other transformer models, thereby conforms the model validity. With AC sweep analysis through PSpice, the resonant frequencies for Model C, D and E of the transformer winding are obtained.

**Measurement using SFRA:** SFRA is designed to detect winding displacements in power transformers or faults in the magnetic core based on the comparison of their resonant frequencies with that of the frequencies corresponding to the healthy winding. The system provides attenuation signature curves that can easily be
Table 3: Comparison of resonant frequencies for different models of 22 kV interleaved winding

<table>
<thead>
<tr>
<th>Resonant frequency (MHz)</th>
<th>SFRA measurement</th>
<th>Model C</th>
<th>Model D</th>
<th>Model E</th>
<th>Difference in resonant frequency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.24327</td>
<td>0.379</td>
<td>0.3789</td>
<td>0.261</td>
<td>-55.80</td>
<td></td>
</tr>
<tr>
<td>2.95800</td>
<td>2.924</td>
<td>2.9700</td>
<td>2.960</td>
<td>1.15</td>
<td>-0.41 -0.07</td>
</tr>
<tr>
<td>3.89900</td>
<td>4.054</td>
<td>4.0500</td>
<td>4.017</td>
<td>-3.98</td>
<td>-3.88 -3.03</td>
</tr>
<tr>
<td>6.18000</td>
<td>6.251</td>
<td>6.2100</td>
<td>6.210</td>
<td>-1.15</td>
<td>-0.49 -0.49</td>
</tr>
<tr>
<td>8.05400</td>
<td>8.128</td>
<td>8.0900</td>
<td>8.016</td>
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<td>-0.45 0.48</td>
</tr>
<tr>
<td>9.57200</td>
<td>-</td>
<td>9.7700</td>
<td>9.638</td>
<td>-</td>
<td>-2.07 -0.69</td>
</tr>
<tr>
<td>11.91300</td>
<td>-</td>
<td>12.1600</td>
<td>12.050</td>
<td>-</td>
<td>-2.08 -1.16</td>
</tr>
<tr>
<td>16.64000</td>
<td>-</td>
<td>16.2900</td>
<td>16.220</td>
<td>-</td>
<td>2.11 2.53</td>
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<tr>
<td>18.66500</td>
<td>-</td>
<td>18.4500</td>
<td>18.320</td>
<td>-</td>
<td>1.16 1.85</td>
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<td>21.43000</td>
<td>-</td>
<td>20.5100</td>
<td>20.420</td>
<td>-</td>
<td>4.30 4.72</td>
</tr>
</tbody>
</table>

Fig. 8: Experimental set up for SFRA measurement on a transformer winding

Model E yields number of resonant frequencies which are in good agreement with the measured resonant frequencies. The difference in resonant frequencies with respect to measurement frequencies is calculated and shown in Table 3. This illustrates that percentage difference in resonant frequency with measured frequencies is less for the Model E when compared to that of other models.

**CONCLUSION**

For accurate analysis of estimation of overvoltages generated at the transformer terminal in an actual system, the transformer has to be modelled as high frequency model instead of single lumped capacitance for electromagnetic transient simulations. In this study, a 22 kV interleaved transformer winding has been modelled using detailed and high frequency models. Resonant frequencies for these models are obtained using circuit simulation package and are compared with measured frequencies obtained from SFRA. The proposed high frequency model adequately simulates the impedance characteristics of the winding at frequencies up to 25 MHz with the average difference in resonant frequencies for simplified high frequency models.
model (Model E) of 2.8% and also reduces the complexity of the model.

REFERENCES


