

Research Article

A Simplified High Frequency Model of Interleaved Transformer Winding

K. Usha and S. Usa

Division of High Voltage Engineering, College of Engineering Guindy, Anna University,
Chennai-600025, Tamil Nadu, India

Abstract: Disconnecter 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.

Corresponding Author: K. Usha, Division of High Voltage Engineering, College of Engineering Guindy, Anna University, Chennai-600025, Tamil Nadu, India

This work is licensed under a Creative Commons Attribution 4.0 International License (URL: <http://creativecommons.org/licenses/by/4.0/>).

Table 1: Constants of 22 kV interleaved winding

Sections per coil	40
Turns per sections	12
Size of conductor	4.5*1
Mean diameter	319.5
Height of section axial	313
Depth of windings (radial)	19.5
Axial and radial spacing	3
Section clearance	3
Dielectric constant of insulation (ϵ_r)	2.08
Conductor conductivity (σ)	5×10^7 S/m
Inductance per turn	0.8264 μ H
Total series capacitance	40.645 pF
Total stray capacitance	467 pF
G.I. sheet is placed inside the windings to act as a core.	
All dimensions are in mm	

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:

$$C_0 = C_r \frac{n-2}{2} \quad (1)$$

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_s and a ground capacitance C_g .

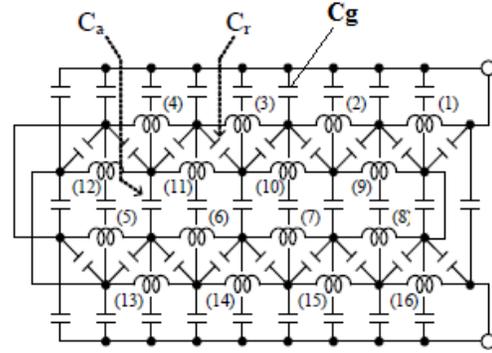


Fig. 1: Detailed circuit-model A (Okabe *et al.*, 2011)

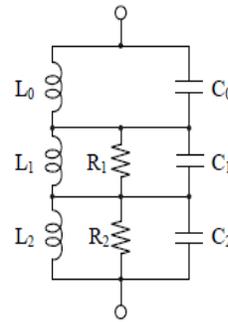


Fig. 2: High frequency model up to 2nd order-model C (Okabe *et al.*, 2011)

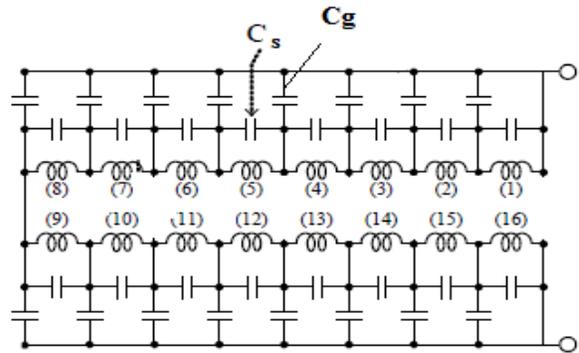


Fig. 3: RLC ladder network model-model B (Hosseini *et al.*, 2008)

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

$$C_s = E^2 * C_t * \frac{(n-1)}{4N} \quad (2)$$

where,

E = Order of interleaving

C_t = 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:

$$C = (n - 1)\epsilon\epsilon_0\pi D b/d \tag{3}$$

where,

- ϵ = Relative permittivity of the turn-to-turn insulation
- ϵ_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:

$$L = \frac{n}{2} \epsilon\epsilon_0\mu_0\pi D d/b \tag{4}$$

where,

- μ_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:

$$T = 2\sqrt{LC} = 2\pi n D \sqrt{\frac{\epsilon\epsilon_0\mu_0}{2} \left(1 - \frac{1}{n}\right)} \tag{5}$$

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:

$$f_1 = \frac{1}{2\sqrt{LC}} = \frac{1}{2\pi\sqrt{L_1C_1}} \tag{6}$$

$$\text{Hence, } L_1 = \frac{L}{\pi}; C_1 = \frac{C}{\pi} \tag{7}$$

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.

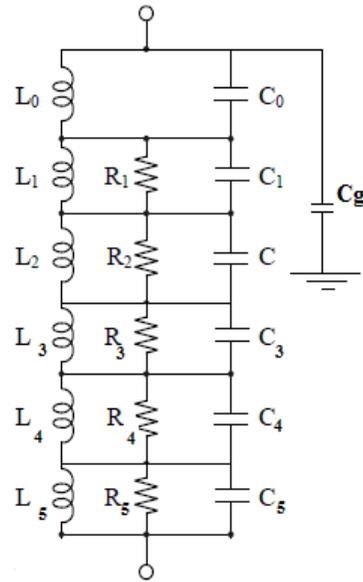


Fig. 4: High frequency model up to 5th order with Cg-model D

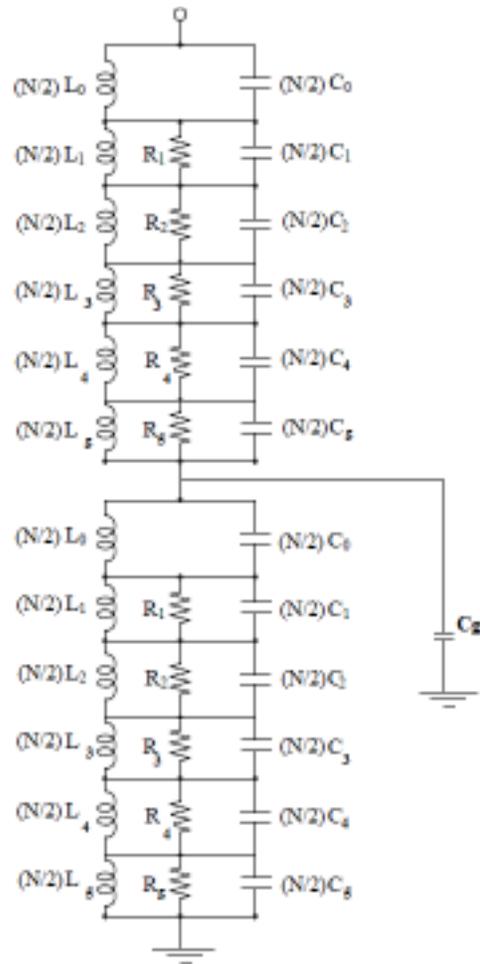


Fig. 5: Lumped high frequency model up to 5th order with Cg-model E

Parallel resistors are connected in the second and third stage LC circuits. The damping resistance of this high frequency wave is expressed as $k * (L/C)^{1/2}$ 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:

$$L_3 = \frac{L_1}{3}; C_3 = \frac{C_1}{3} \text{ and } L_4 = \frac{L_1}{4}; C_4 = \frac{C_1}{4}$$

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 winding. 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 wavefront duration is in nano second range, the section to section voltage

Table 2: Comparison of various models based on nodal requirement

Model	Nodes required for time domain simulations
	For 40 disc sections
Model A	400
Model B	360
Model C	80
Model D	140
Model E	13

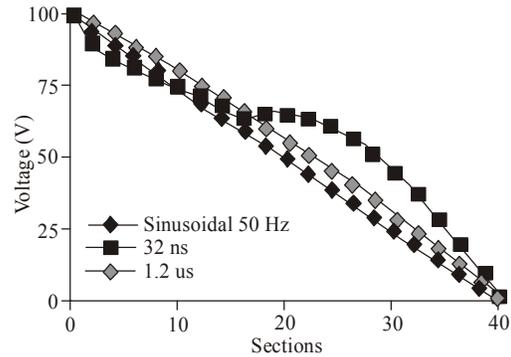


Fig. 6: Voltage distribution of 22 kV interleaved transformer winding

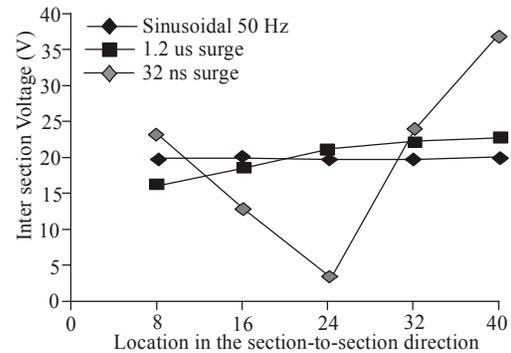


Fig. 7: Relationship between location in the section-to-section direction and inter-section voltage

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 conforming 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

Resonant frequency (MHz)				Difference in resonant frequency (%)		
SFRA measurement	Model C	Model D	Model E	Model C	Model D	Model E
0.24327	0.379	0.3789	0.261	-55.80	-55.76	-7.29
2.95800	2.924	2.9700	2.960	1.15	-0.41	-0.07
3.89900	4.054	4.0500	4.017	-3.98	-3.88	-3.03
6.18000	6.251	6.2100	6.210	-1.15	-0.49	-0.49
8.05400	8.128	8.0900	8.016	-0.92	-0.45	0.48
9.57200	-	9.7700	9.638	-	-2.07	-0.69
11.91300	-	12.1600	12.050	-	-2.08	-1.16
12.76500	-	14.1200	13.960	-	-10.62	-9.37
16.64000	-	16.2900	16.220	-	2.11	2.53
18.66500	-	18.4500	18.320	-	1.16	1.85
21.43000	-	20.5100	20.420	-	4.30	4.72

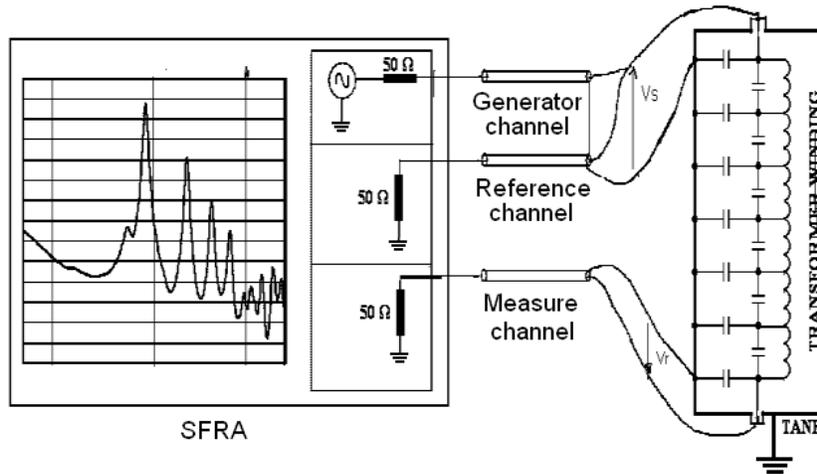


Fig. 8: Experimental set up for SFRA measurement on a transformer winding

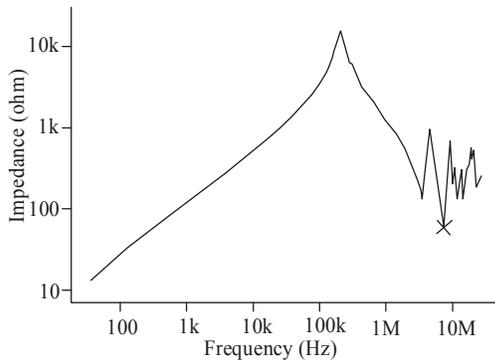


Fig. 9: Measured impedance-frequency response

compared for deviations which indicate core movements, winding deformations and displacements, faulty core grounds and partial winding collapse etc. Impedance characteristics of winding is analyzed by FRAX 101 Sweep Frequency Response Analyzer (SFRA), Megger make. The instrument comprises of a sweep frequency voltage source of 10 V peak-to-peak. The experimental set up to carry out sweep frequency measurements is shown in Fig. 8. The impedance-frequency characteristics for the winding obtained through SFRA is shown in Fig. 9.

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

model (Model E) of 2.8% and also reduces the complexity of the model.

REFERENCES

- Hosseini, S.M.H., M. Vakilian and G.B. Gharehpetian, 2008. Comparison of transformer detailed models for fast and very fast transient studies. *IEEE T. Power Deliver.*, 23(2): 733-741.
- Matsumara, S. and T. Nitta, 1981. Surge propagation in gas insulated substation. *IEEE T. Power Ap. Syst.*, 100(6): 3047-3054.
- Meppelink, J., K. Diederich, K. Feser and D.W. Pfaff, 1989. Very fast transients in GIS. *IEEE T. Power Deliver.*, 4(1): 223-233.
- Naidu, M.S., 2008. *Gas Insulated Substations*. I.K. International Publishing House Pvt. Ltd.
- Okabe, S., M. Koto, G. Ueta, T. Saida and S. Yamada, 2011. Development of high frequency circuit model for oil-immersed power transformers and its application for lightning surge analysis. *IEEE T. Dielect. El. In.*, 18(2): 541-552.
- Okabe, S., M. Koto, T. Teranishi, M. Ishikawa, T. Kobayashi and T. Saida, 1999. An electric model of gas-insulated shunt reactor and analysis of re-ignition surge voltages. *IEEE T. Power Deliver.*, 14(2).
- Pedersen, A., 1963. On the response of interleaved transformer windings to surge voltages. *IEEE T. Power Ap. Syst.*, 66: 349-356.
- Shibuya, Y., S. Fujita and N. Hosokawa, 1997. Analysis of very fast transient overvoltage in transformer winding. *IEE P-Gener. Transm. D.*, 144(5).