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Simulation Study of Voltage Surge Distribution in a Transformer Winding

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Abstract: **In this paper simulation study of voltage surge distribution in a transformer winding using P-Spice Orcad is presented. A model based on ladder network for representing HV side of the transformer winding is used.The surge behavior of the transformer winding is studied for lightning and VFTO surge voltages. The study is carried out for continuous disc type winding and interleaved winding for the cases of without skin effect, with skin effect and mutual coupling.**

Keywords: Disc winding, Interleaved winding, Modeling, Surge performance, Transformer.

I. INTRODUCTION

Power transformers play a very important role in power system. Transformers operating in power grid or in industrial environment are subjected to lightning, switching and very fast transient overvoltages (VFTO) phenomenon. Surge voltages whether they be system generated or those that occur due to natural phenomenon have detrimental effects on transformer windings unless protective measures are put in place. Detailed knowledge of surge voltage distribution along the transformer winding helps in the design of appropriate winding structure and insulation co-ordination for transformers[1]. Switching operations in a gas insulated substation (GIS) and lightning impulses are known to produce VFTO's which are dangerous for the transformer and motor insulation. Also in medium voltage systems where vacuum circuit breakers are used reignition causes high-frequency oscillations which can be dangerous because of their short rise time. Under special circumstances the terminal overvoltages can arise close to the transformer basic impulse level (BIL). These overvoltages are characterized by a very short rise time. The experience shows that VFTO's within GIS can be expected to have even a rise time of 0.1 µs and an amplitude of about 2.5 p.u. The inter-turn insulation is particularly vulnerable to high-frequency oscillation and therefore the study of the distribution of inter turn over-voltages is of essential interest [2]. As a first step in this direction distribution of over voltages for inter sections is presented in this paper.

II. PROBLEM DEFINITION

The present paper discuses the study of voltage distribution of a power transformer winding when it is subjected to lightning and VFTO surges. The studies have been made on an electromagnetic analogue model of one HV winding limb of a 11kV/33kV, 3MVA DY_n 50Hz power transformer. Surge analysis is carried out for continous disc winding and interleaved winding for the cases of without skin effect, with skin effect and with mutual coupling effect, assuming that the response of a well constructed model is farely in good agreement with that of the original. For this purpose the HV winding of the transformer and the different generators are modeled in P-Spice [3].

III. P-SPICE MODEL FOR SURGE ANALYSIS

Fast and very fast front transient in transformers are commonly analyzed using internal models, which can take into account the distribution of the incident surge along the windings. These models are described either by distributed parameters using the transmission line theory or as a ladder connection of lumped parameter segments. The latter model is used wherein the transformer as been modeled by a network of distributed parameters of individual turns [4].

A) Transformer Parameters: The transformer model used for the purpose of study is a 11/33 kV, 3MVA DYn continuous disk type whose details are as follows [3].

- Outer diameter of each 33kV winding=0.524m
- Inner diameter of each 33kV winding=0.424m
- Axial length of each 33kV and 11kV winding=0.77m
- Number of discs in each 33kV winding=80
- Axial length of each 33kV and 11kV disc= 0.0066m
- Average number of turns/ 33 kV disc= 19
- Outer diameter of each 11kV winding=0.38m
- Axial length of bare conductor for each 33 kV disc= 0.006m
- Gap between two adjacent discs of each 33kV winding= 0.00288m
- Diameter of tank axially halved= 0.595m
- Inner diameter of the 10^{th} turn = 0.4714m

B) Winding details used in the present study

For the purpose of simulation continuous disc winding and interleaved winding are considered.

a) Continuous disc winding :

The continuous disc windings are primarily used, in high capacity transformers. These coils are initially Wound in the ordinary manner, beginning from the cylinder and outward, and then these coils are transposed in the reverse order The conductors are slackened somewhat in order to Make the reversing easier and the conductor running from the drum is again tensioned. This facilitates the continuous inter connection of coils without any soldered joints. A typical continuous disc winding is shown in Fig. 1

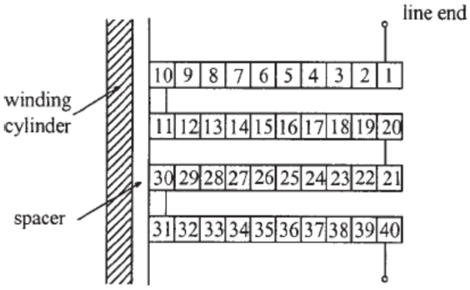

Fig. 1. Continuous Disc Winding

b) Interleaved Winding :

The inherent disadvantage of low series capacitance of the continuous disc winding was over come by electro static shielding till the advent of the interleaved winding. The original interleaved winding was introduced and patented by G F. Stearn in 1950. A simple disposition of turns in some particular ways increases the series capacitance of the interleaved winding to such an extent that a near uniform initial voltage distribution can be obtained. A typical interleaved winding is shown in Fig 2[5].

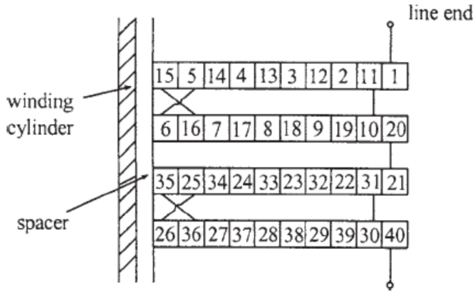

Fig 2. Interleaved Winding

c) Parameter Calculations for Disc & Interleaved winding:

Winding parameters and their calculation for the transformer considered are discussed below.

i) Self-inductance Li of the disc coil

The self inductance of the 33kV disc coil is calculated from the following equation [6]

$$L_o=4\pi * 10^{-7} * RN_1^2\{\ln\left({}^{SR}/{}_{R_1}\right) - 2\} \text{ H} \qquad (1)$$

ii) Capacitance to earth (C_g)

A delta connected transformer winding with its side limb winding impulsed, will have two components of C_g.

a) Capacitance between impulsed HV winding and earthned LV winding (C_1) which can be calculated using co-axial cylinder formula.

$$C_1 = \frac{2\pi\epsilon}{ln\frac{b}{a}} \quad \text{F} \qquad (2)$$

b) Capacitance between impulse side limb HV winding and transformer tank (C_2), which can be calculated by considering the tank as a co-axially halved cylinder

$$C_2 = \frac{\pi\epsilon}{ln\frac{b}{a}} \quad \text{F} \qquad (3)$$

The total ground capacitance for disc is,

$$C_g=C_1+C_2. \quad \text{F} \qquad (4)$$

iii) Series capacitance(C_{si})

Series capacitance of a disc coil has two components

a) Inter-turn capacitance(Ct)

This capacitance is calculated using the expression for the capacitance between two axial cylindrical electrodes

$$C_t=\frac{2\pi\epsilon}{ln\frac{b}{a}} \quad \text{F} \qquad (5)$$

b) Inter-disc capacitance(C_d)

For calculating C_d the adjacent discs are considered as two parallel plate electrodes.

$$C_d=\frac{\epsilon A}{d} \quad \text{F} \qquad (6)$$

The total series capacitance of a disc

$$Cs=(C_t/N_1)+(4/3\ C_d) \quad \text{F} \qquad (7)$$

Where, N1= No of turns per disc.

The calculated values of Self inductance of disc coil (L_i), Capacitance to earth (C_g) & Series capacitance are shown in Table1

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Table1: Parameters of hv winding

Parameters	Continues Disc winding	Interleaved winding
Self inductance of disc coil	1.294x 10^{-3}H/Section	1.294x 10^{-3}H/section
Capacitance to earth	66.28 pF /section	66.28 pF /section
Series capacitance	233.65pF/section	700.96pF/section

iv) Calculation of Mutual Inductance

Maxwell obtained an expression for the Mutual inductance between two Co-axial circle in the form of converging series which is often more convenient to use than the eleptical integral formula and when the circles are nearly of the same radii and relatively near each other, the value given is generally sufficiently exact [6].

$M_0 = 4\pi a[log\frac{8a}{d}(1+\frac{3d^2}{16a^2})]$ Neglecting higher order terms (8)

a=Radius of the coil
d=Distance between the coils

$$M_0 = 4\pi * 23.54[\log(\frac{8*23.54}{1.288})\{1+\frac{3*0.288^2}{16*23.54^2}\}] \quad (9)$$

=832.86cms

$$M_{12} = n^2 * M_0 = 19^2 * 832.86 = 0.3m \quad (10)$$

Similarly mutual inductance values for other sections are calculated.

The completed model of one limb of HV winding for PSPICE simulation is shown in Fig.3

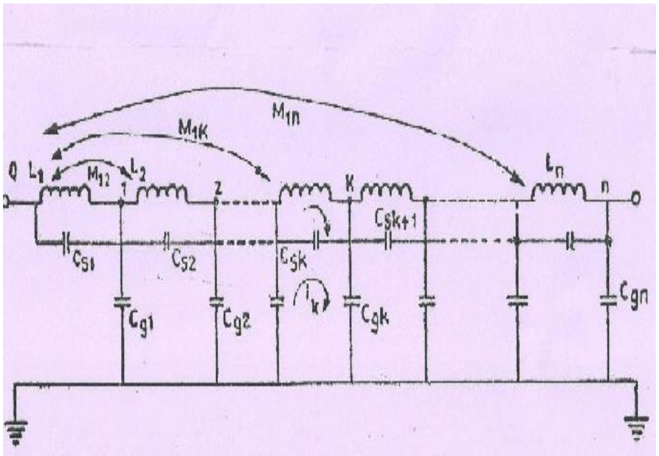
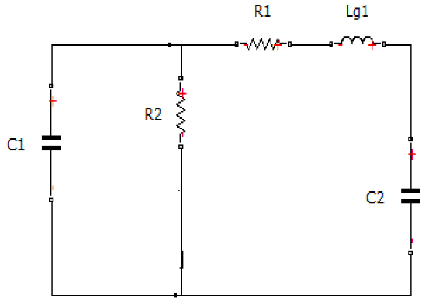


Fig.3. Simulated model of HV winding.

V) Modeling of lightning impulse generator

The circuit diagram of lightning impulse generator with the calculated values of parameters is as shown in Fig 4.



C1=0.01µF

C2=1nF

R1=400Ω

R2=7kΩ

Lg1=1nH

Fig.4. Lightning impulse generator

The simulated waveform of the output of the generator is shown in Fig 5.

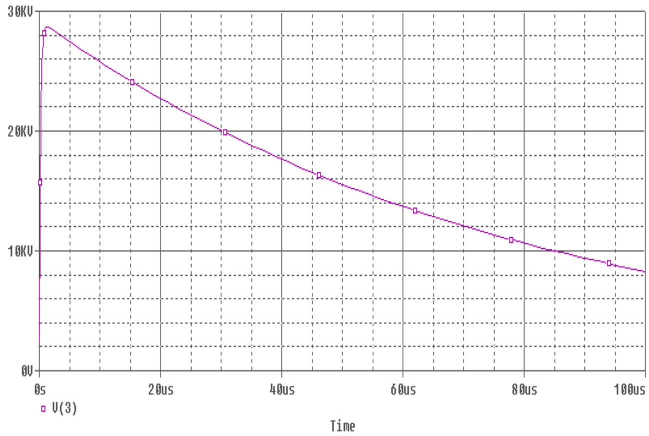
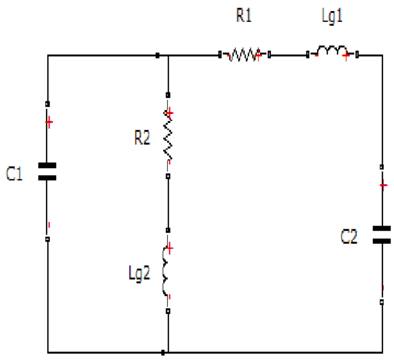


Fig.5. Output voltage of the Lightning generator

From the output waveform it is found that the value of front time of 1µs and fall time of 50µs which is in agreement with the standard specification 1.2/50µs±30%/±20%.

VI) Modeling of VFTO generator



C1=0.01µF

C2=1000pF

R2=70Ω

R1=40Ω

Lg1=0.048mH

Lg2=0.047mH

Fig.6. VFTO Generator

The circuit diagram of VFTO generator with the calculated values of the parameters is shown in Fig 6.

The simulated waveform of the output of the VFTO generator is shown in Fig 7.

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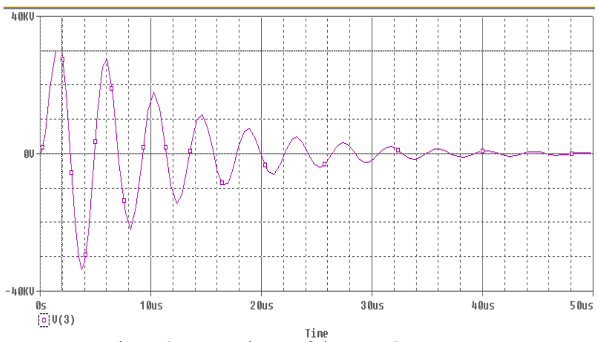

Fig.7. Output voltage of the VFTO generator

From the output waveform the measured time period is 1.67µs and hence the frequency is 598kHz which is in agreement with [7].

VII) Skin effect calculations

The resistance of the winding taking skin effect into consideration is calculated for both lightning and VFTO inputs which is shown in table 2.

Table2: Resistance values

Type of surge voltage	Resistance values with skin effect
Lightning impulse	0.0325Ω
VFTO	0.0487Ω

IV. RESULTS AND DISCUSSIONS

The simulation of the model is carried out by connecting the HV winding to the VFTO generator. The voltage at different nodes in disc type winding for VFTO input is shown in Fig 8.

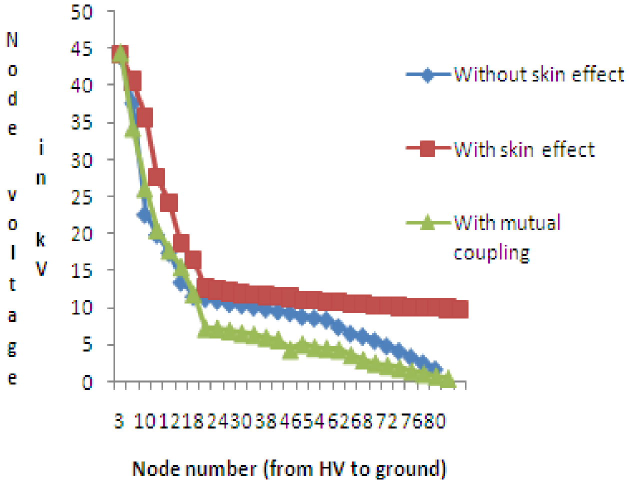

Fig.8 Voltage Distribution in Disc type winding for VFTO input.

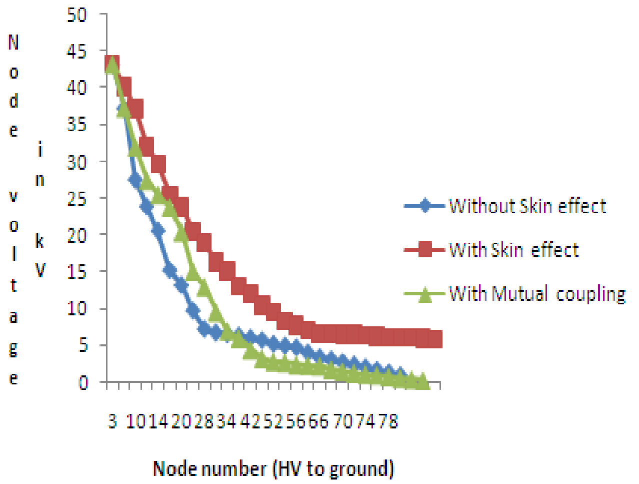

Fig.9. Voltage surge distribution in interleaved winding for VFTO input

Fig 8 and 9 shows voltage distribution at different nodes due to VFTO input on a Disc type winding and interleaved winding. From the graphs it is observed that the voltage distribution is almost uniform when skin effect is taken into consideration.

The simulation of the model is carried out by connecting the HV winding to the Lightning impulse generator. The voltages measured at various nodes for the cases of without, with Skin effect and mutual coupling effect are shown in Fig 10 and 11.

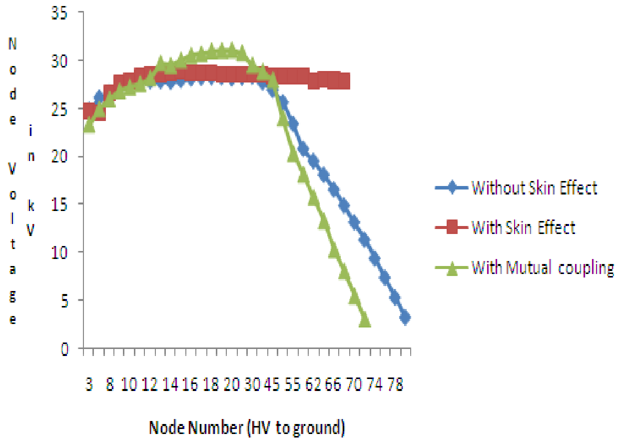

Fig.10. Voltage Distribution in disc type winding for Lightning input

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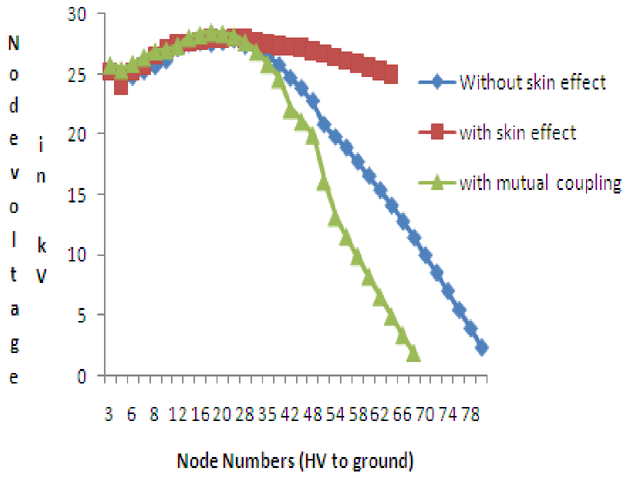

Fig.11. Voltage Distribution in inter leaved winding for Lightning input

Fig.10 and 11 shows voltage distribution at different nodes due to lightning impulse input on a Disc type and interleaved type winding. Here also it is evident that voltage distribution is almost uniform when skin effect taken into consideration.

V. CONCLUSIONS

In the present paper extensive observation study on voltage distribution have been made on surge model of a 3MVA,33/11kV,3phase,50Hz,DY_n Transformer. The studies cover voltage distribution in the winding when it is subjected to VFTO and Lightning impulse surges. These studies are carried out for the cases of without skin effect, with skin effect and with mutual coupling. For design engineer it is very important to analyse the effect of transients on the voltage distributions of power transformers to develop reliable insulation designs at low cost [8].

- The results have led us to the conclusion that the voltage peak occurs at the initials sections than at the end
- Time taken to reach peak values at different sections is different when the modules of the transformers are studied for the cases of without skin effect and with skin effect.
- Almost uniform distribution of voltage is observed when skin effect is taken into account.

A possible direction for extension of this research is to analyse the model for switching impulse and also taking end shield into consideration.

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