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INVESTIGATING THE DYNAMIC PERFORMANCE OF A WYE CONNECTED 18 COIL SECTION TRANSFORMER MODEL WINDING DUE TO LIGHTNING VOLTAGE SURGES

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ABSTRACT

A lightning voltage impulse is a very fast rising unidirectional transient overvoltage with magnitude of the order of several million volts and when gets in touch with the windings of a high voltage power transformer, the winding insulation will be overstressed and may get damage. This failure event incurs a heavy loss to the electric utility and is mainly responsible for transformer outages and thereby effecting the normal functioning of an electric power system. Hence a better knowledge of highly nonlinear electric stresses developed due to lightning impulses is necessary to safeguard the inner winding insulation of high voltage power transformers. In this paper, simulation analysis on a three phase wye-connected 18 coil section transformer model winding is being carried out to examine its dynamic behaviour under the influence of a standard lightning impulse and chopped impulse voltages.

Keywords: transformer model winding, wye-connected, dynamic behaviour, lightning impulse voltage, inner winding insulation.

INTRODUCTION

Power transformers are one of the major essential equipments used in electric ac power transmission systems. During service transformer windings are exposed to various transient over voltages like lightning surges, switching surges etc. Lightning surges have steep wave fronts and relatively longer tails and perhaps being the most hazardous abnormal voltages and when hit the transformer windings may breakdown the insulation and produce heavy damage [1-3]. In this paper, the power transformer high tension winding is modeled by a three phase wye-connected 18-coil section and is simulated to study its dynamic performance under standard lightning impulse voltage and chopped impulse voltage surges. The mutual inductance among the 18 coil sections is reflected in the analysis for better accuracy. The present work paves a way for the research scholars to design and install a suitable low cost effective protective device for insulation protection of high voltage power transformer windings against high voltage surges.

COMPUTATION OF COMPLETE INDUCTANCE MATRIX FOR A WYE-CONNECTED 18 COIL SECTION TRANSFORMER MODEL WINDING

In this paper the high tension winding is represented by a three phase wye-connected 18 coil section transformer model winding with resistance of each coil and mutual inductance coupling among the different coils is being considered.

Calculation of self-inductance of each coil (Ls)

Self inductance L_s of each coil section is determined using the Nagaoka's inductance formula for circular cross section [6] given by:

$$Ls=0.002\pi^2 a\,(2a/b)\,N^2 k\ \mu H \tag{1}$$

Where a = mean radius of the coil
b = length of the winding
k = factor that takes account of the effect of the ends and is a function of the shape ratio (2a/b)
N = number of turns
$Ls = 0.002\pi^2 a\,(2a/b)\,N^2 k\quad \mu H$

Where a = mean radius of the coil
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N = number of turns

Calculation of mutual inductances between the eighteen coil sections (L_{jk})

Mutual inductances between the different coil sections of a model winding, is found using the formula

$$Ljk=0.002\pi^2 a^2 n_1 n_2\,(r_1B_1 - r_2B_2 - r_3B_3 + r_4B_4)\quad \mu H$$

Where n_1 and n_2 are winding densities and the functions B_n depend upon the parameters $\rho^2_n = A^2/r^2_n$ and are obtained by interpolation [6] and [7].

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The complete inductance matrix for the wye-connected 18 coil section transformer model winding is build up.

ANALYSIS

In the analysis, the high tension winding of a power transformer is represented by a 3-Φ wye-connected 18-coil section model as shown in figure-1and is simulated to assess its dynamic performance under standard lightning impulse voltage 1.2/50μs and chopped impulse voltage surges impressed on phase 'a' and phases 'b' and 'c' subjected to normal power frequency sine waveforms. The mutual inductance among the 18 coil sections is also reflected in the analysis for better accuracy.

Here $\alpha=\sqrt{Cg/Cs}$ where,
Cg is ground capacitance and
Cs is the series capacitance of the winding.

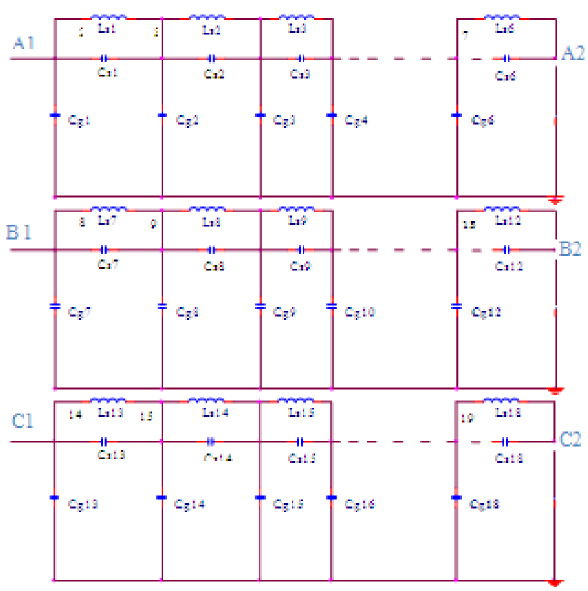

Figure-1. A three phase wye-connected 18 coil section transformer model winding.

Wye-connected 18-coil section model winding, phase 'a' impulsed with a 5 pu standard lightning voltage surge for α =10

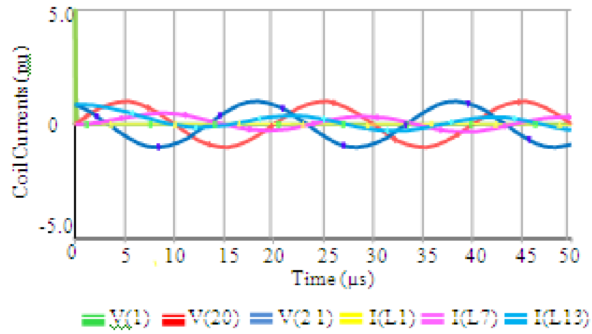

Figure-2. Coil current waveforms for Phase 'a' impulsed with a 5 pu lightning voltage surge and phases 'b' and 'c' subjected to normal power frequency sine waveforms.

From Figure-2 it can be seen that the current through the first coil section I(L1) of phase 'a' is zero where a lightning impulse voltage of 5 pu is pressed upon, that is, the first coil section of phase 'a' behaves like a pure capacitive circuit. The current through the second and third coil section of phases 'b' and 'c' I(L7) and I(L13) respectively is sinusoidal where power frequency sine waveforms are applied and these two coil sections behave as an inductive circuit.

In Figure-3 the objective is to study the impact of voltage stresses on 2nd and 3rd coil sections of phases 'b' and 'c' of the wye-connected 18 coil section transformer model winding due to a lightning impulse voltage on phase 'a' for α = 10. The voltage across the first coil section v (3) rise very fast to a peak value of 6.28pu in about 6.346 μs and contains positive decaying oscillations.

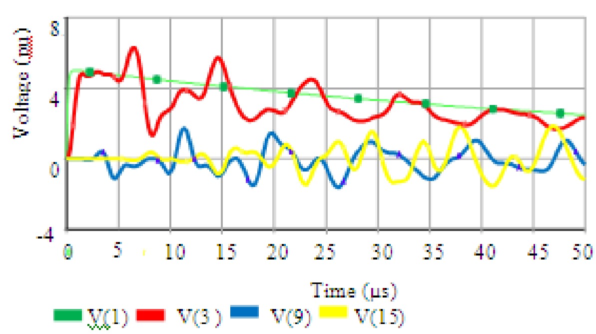

Figure-3. Transient node voltages at different coil sections with respect to ground when Phase 'a' impulsed with a 5 pu lightning voltage surge and phases 'b' and 'c' subjected to normal power frequency sine waveforms.

The voltages across the second coil section v (9) reaches a peak value of 1.75pu around 11.32μs and contain several positive and negative oscillations. It is to be noted that the voltage across the third coil section v(15) is oscillatory with increasing amplitude.

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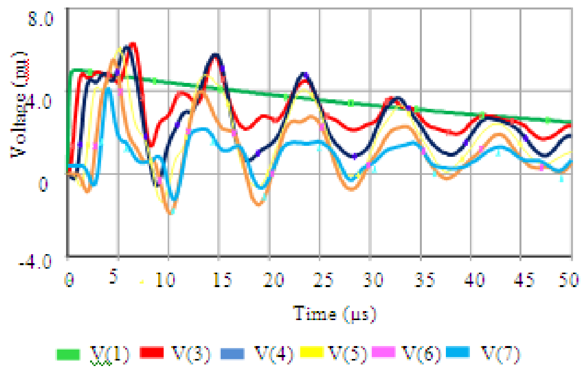

Figure-4. Oscillatory node voltages at 6 coils of the first coil section of phase ‘a’ with respect to ground when Phase ‘a’ impulsed with a 5 pu lightning voltage surge and phases ‘b’ and ‘c’ subjected to normal power frequency sine waveforms for α = 10.

It is interesting to observe from Figure-4 that the node voltages at the end of the first coil section v(7), v(6), v(5), v(4), reaches their peak values ahead of node voltage of first coil v(3).

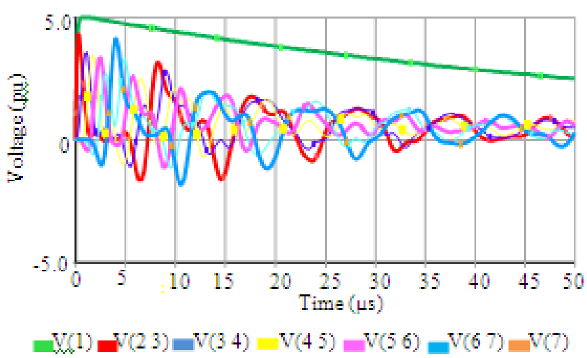

Figure-5. Oscillatory node voltages across the first coil V(2 3), second coil V(3 4), third coil V(4 5), fourth coil V(5 6), fifth coil V(6 7), sixth coil V(7 0) of the first coil section for Phase ‘a’ impulsed with a 5 pu lightning surge and phases ‘b’ and ‘c’ subjected to normal power frequency sine waveforms for α = 10.

In Figure-5, the voltage stress across the first coil V (2 3), that is, the winding turns close to the transformer line terminal is 4.29 pu peak value and rises very fast in about 0.266 μs(very steep rise) and then follows the subsequent coil voltages. However the voltage stress across the sixth coil V (7 0) of the first coil section is 4.12 pu peak value, which should be taken notice of.

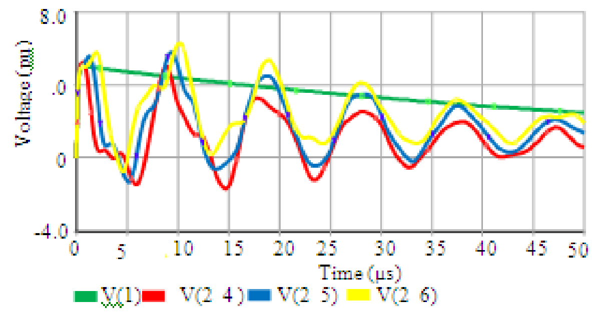

Figure-6. Voltage stresses across i) 11.11% of coil turns V(2 4), ii)16.66% of coil turns V(2 5) and iii)22.22% of coil turns V(2 6), of the first coil section for Phase ‘a’ impulsed with a 5 pu lightning voltage surge and phases ‘b’ and ‘c’ subjected to normal power frequency sine waveforms for α = 10

Referring Figure-6, the voltage stress across 11.11% of the 18 coil section wye connected transformer model winding V(2 4) is 5.25pu peak that rises very fast in 0.586 μs (very steep rise) and voltage stress across 16.66% of winding V (2 5) is 5.575pu peak occurring at 1.24 μs and voltage stress across 22.22% of winding V (2 6) is 5.8pu peak occurring at 1.923 μs with a large number of oscillations.

Wye-connected 18-coil section model winding, phase ‘a’ impulsed with a 5 pu standard lightning voltage surge for α =20

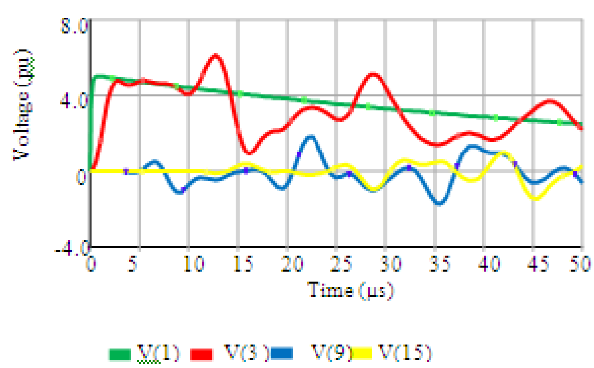

Figure-7. Transient node voltages at different coil sections with respect to ground for Phase ‘a’ impulse d with a 5 pu lightning voltage surge and phases ‘b’ and ‘c’ subjected to normal power frequency sine waveforms for α = 20.

Figure-7 shows the impact of voltage stresses on 2nd and 3rd coil sections of wye-connected 18 coil section transformer model winding due to a lightning impulse voltage on phase ‘a’ for α = 20.The result is same as that of for α = 10, but the incidence of the occurrences of peak values of the node voltages are deferred.

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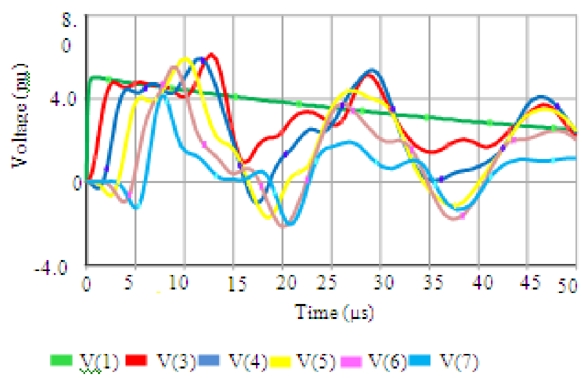

Figure-8. Oscillatory node voltages at 6 coils of the first coil section with respect to ground for Phase 'a' impulse d with a 5 pu lightning voltage surge and phases 'b' and 'c' subjected to normal power frequency sine waveforms for α = 20.

For α = 20 it can be seen from Figure-8 that the node voltages contain large number of oscillations with their peak values incidence occurrence deferred as compared to α = 10.

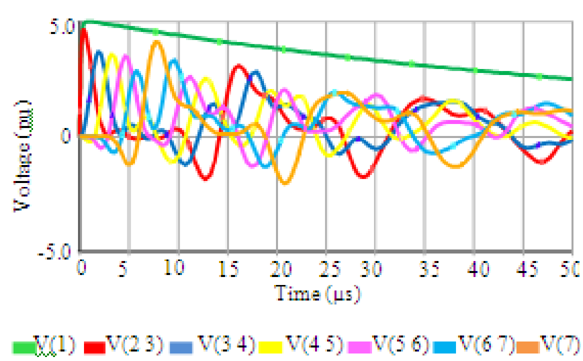

Figure-9. Oscillatory node voltages across the first coil V(2 3), second coil V(3 4), third coil V(4 5), fourth coil V(5 6), fifth coil V(6, 7), sixth coil V(7 0) of the first coil section for Phase 'a' impulse d with a 5 pu lightning voltage surge and phases 'b' and 'c' subjected to normal power frequency sine waveforms for α = 20.

For α = 20 the voltage stress across the first coil V (2 3) is 4.66 pu peak value and rises in about 0.427 µs as compared to 4.29 pu peak value and rise time of 0.266 µs for α = 10. However the voltage stresses contain a large number of oscillations.

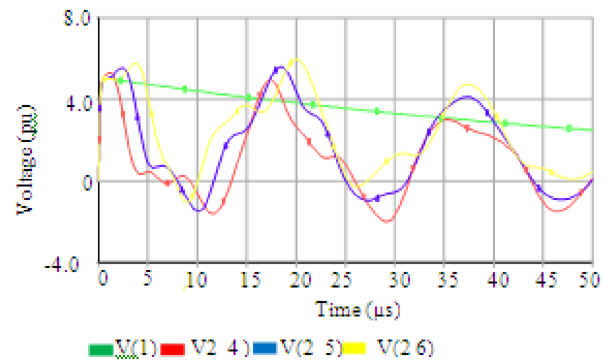

Figure-10. Voltage stresses across i) 11.11% of coil turns V(2 4), ii)16.66% of coil turns V(2 5) and iii) 22.22% of coil turns V(2 6), of the first coil section for Phase 'a' impulse d with a 5 pu lightning voltage surge and phases 'b' and 'c' subjected to normal power frequency sine waveforms for α = 20.

In Figure-10, the peak value of the voltage stresses across 11.11%, 16.66% and 22.22% of the 18 coil section wye connected transformer model winding are same as that for α =10 but their peak value incidence is belated.

Special case: To study the effect on other two coil sections of phases 'b' and 'c' of a wye connected 18 coil section transformer model winding due to a chopped lightning voltage surge impulsed at phase 'a' for α =10

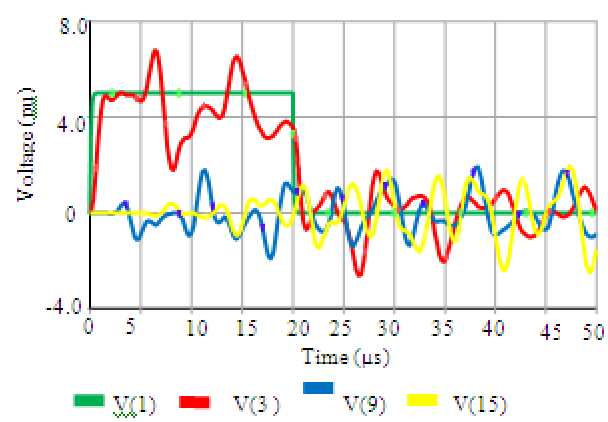

Figure-11. Transient node voltages at different coil sections with respect to ground for Phase 'a' impressed with a 5 pu lightning voltage impulse chopped at tail wave and phases 'b' and 'c' with normal power frequency sine waveforms for α = 10

In Figure-11 the objective is to study the impact on 2nd and 3rd coil sections of phases 'b' and 'c' of a wye-connected 18 coil section transformer model winding due to a chopped tail wave impulse voltage on phase 'a' for α = 10.The voltage across the first coil section v (3) reaches to a peak value of 6.78pu and the moment the surge is chopped at 20 µs the voltage falls to -0.712pu with positive and negative excursions. However the voltages across the second and third coil section contain quite a lot of positive and negative oscillations.

CONCLUSIONS

PSpice Simulation was carried out on the transformer model winding consisting of 18 coil sections, wye connected by using the designed model winding parameters.

On analyzing the dynamic performance of a three phase wye-connected 18 coil section transformer model winding with phase 'a' impulsed with a 5 pu standard lightning voltage and phases 'b' and 'c' impressed with normal power frequency sine waveforms with 1 pu peak value for α=10, it was concluded that the voltage stresses in the first coil section reach suddenly large peak values of up to 6.28pu which may probably damage the winding insulation of the costliest high voltage power transformers. The peak voltage magnitudes on the second and third coil sections are not of much significance but are very oscillating in nature and are dangerous to the winding insulation of high voltage power transformers as these transient frequencies may match with the natural frequency of the transformer, leading to internal resonance problems.

For the winding constant α = 20, the magnitude of the coil voltages were almost same as that for α = 10, but the coil voltages contain large number of oscillations with their peak values incidence occurrence deferred as compared to α = 10.

When a chopped tail wave impulse voltage was applied on phase 'a' for α = 10 of a wye-connected 18 coil section transformer model winding, it was found that the voltage across the first coil section reaches to a peak value of 6.78pu and the moment the surge is chopped at 20 µs the voltage falls to -0.712 pu with positive and negative excursions. The voltages across the second and third coil section contain quite a lot of positive and negative oscillations.

The authors finally conclude that these peak voltage stresses either due to lightning impulse or chopped impulses are hazardous to the winding insulation of the high voltage power transformers and need to be brought down to a tolerable value using a reasonable and effective defensive device. The present work paves a way for the research scholars to design and install an effective low cost protective device that can bring down these peak voltage stresses to a minimal especially at the initial portion close to the line terminal and centre portion of the windings and hence safeguard the insulation of high voltage power transformer windings against high voltage surges.

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