MODELING LIGHTNING SURGES IN POWER TRANSFORMERS

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Abstract **– Using FEM, the self and mutual inductances of all the windings of a three phase power autotransformer and their partial capacitances are determined and used to explain the early observed lighting over voltages on the free end of regulating winding.**

1. INTRODUCTION

High voltage (HV) and high power (HP) transformer / autotransformer stressing with impulse voltage or high frequency (HF) oscillating voltages is a complex phenomenon depending mainly on the intrinsic characteristics of the windings and on their connections.

At impulse voltage as well as when applying some HF oscillating voltages the windings behave as a complex R-L-C network the elements of which are frequency dependent reason why the voltages appearing in different points of the windings have wave shapes completely different from the ones of the applied voltages, even their peak values being affected. Consequently, on the regulating taps and on on-load tap changer plots important overvoltages can appear and their maximum values greatly exceed the maximum value of the incident voltage.

L – C model study of the processes taking place in transformer winding during voltage impulse testing renders evident the model possibility to identify constructive parameter influence on the level of the voltage impulse generated stresses.

2. INFLUENCE OF SHORT-CIRCUITED TERTIARY WINDING

Denoting by $\hat{\mathbf{I}}$ the amplitude of the current in the **w** turns winding, by $\boldsymbol{\Phi}$ the magnetic flux in the core, by **r** and $\mathbf{x = \omega w^2 \Lambda_s}$ the resistance and the leakage reactance of tertiary winding, by $\omega=2\pi f$ frequency of magnetic field and $\boldsymbol{\Lambda_s}$ the leakage permeance, the magnetic impedance of the transformer core with short-circuited tertiary winding will be:

$$Z_{sc} = \frac{w\hat{I}}{\Phi} = R_{sc} + j\,X_{sc}$$

$$R_{sc} = \frac{\omega\, w^2\, x}{r^2 + x^2} \qquad (1)$$

$$X_{sc} = \frac{\omega\, w^2\, r}{r^2 + x^2}$$

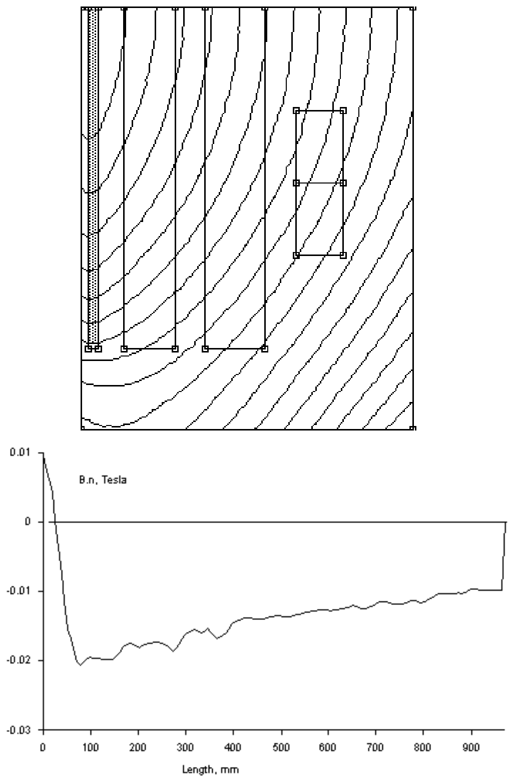

Figure 1: Axisymmetric solution for short-circuited tertiary winding (FEMM)

Mesh size 20, 3128 nodes, 6024 elements
Current density 0.8 A/mm2
Total current 25600 A
Magnetic field energy 678.6 J
Leakage inductance 12.08 mH
$\Lambda_S \approx 1\ \mu\mathrm{H}$

The permeance of the S - cross-section core-with open winding is given by the average relative permeability μ of the core:

$$\Lambda_0 = \frac{\mu_0 \, \mu S}{l_{fe}} \qquad (2)$$

The equivalent permeance of the core with short-circuited winding at frequency ω results from the equation:

$$\frac{1}{\Lambda_e} = \frac{1}{\Lambda_0} + R_{sc} \quad \Rightarrow$$

$$\Lambda_e = \Lambda_s \frac{1+u^2}{1+\frac{\Lambda_s}{\Lambda_0}\left(1+u^2\right)} \qquad (3)$$

where $u = \frac{r}{x}$.

In particular, for high frequency and large core cross-section, u as well as $\mathbf{\Lambda_s/\Lambda_0}$ tend to zero and the equivalent permeance approaches the leakage permeance $\mathbf{\Lambda_s}$. This leakage permeance can be determined using the magnetic field energy or directly magnetic flux linkage, obtained by solving the magnetic field in the transformer window and in frontal part of the winding.

In our case r = 0.31 Ω at 14 kHz , x = 1100 Ω, Λ_s = 1 μH, Λ_o=90 μH for μ = 1000.

This means that practically all the magnetic flux avoid the core and closes in air. The same is thru for the magnetic flux produced by all the currents in other windings. Each current in a winding produces an eddy current in the short-circuited tertiary winding, reducing practically to zero the magnetic flux thru the core. All the self and mutual inductances will be calculated in these conditions.

3. SELF AND MUTUAL INDUCTANCES FOR SHORT-CIRCUITED TERTIARY WINDING

The self and mutually inductances was calculated using the solved by FMM magnetic field in the transformer window in the case of short-circuited (and grounded) tertiary winding. The results obtained for external part of the windings, taking into account the ferromagnetic tank, are very close to them and no showed.The two inductances are given by the equations:

$$L_1 = \frac{\iiint\limits_{S_1} A\, j_1 \,\mathrm{d}V}{{I_1}^2}; \qquad M_{12} = w_2 \frac{\iiint\limits_{S_2} A \mathrm{d}V}{I_1} \qquad (4)$$

where A is the vector potential of the magnetic field, j_1 and I_1 the current density in coil 1 cross-section S_1 and the current in the coil 1, w_2 and S_2 the turns density and the cross-section of the coil 2.

Using the turns density from Table 1, the results obtained for self and mutually inductances are showns in Table 2, 3 and 4.

Turns density	T	LV	HV	R
W[m^{-2}]	1688	2183	2769	5076

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Table 1: Turns density of the windings

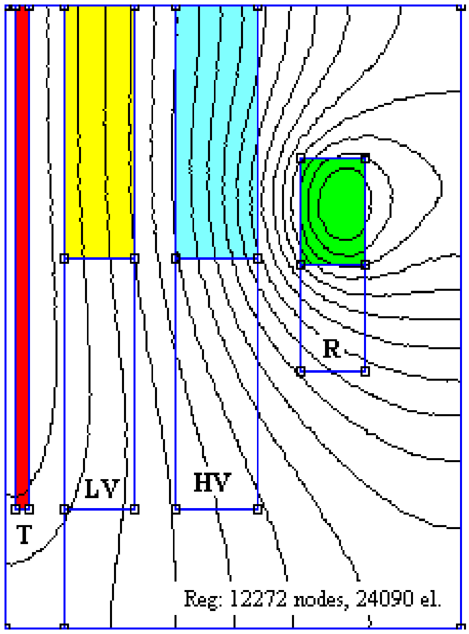

Figure 2: Magnetic field pattern for current injected in upper half of regulating winding

Current	A	290
Ampere turns	kA	43.8
Current densities	A/mm^2	1.47; -1.37
$\iiint\limits_{R/2} A\, j \,\mathrm{d}V$	J	10208
$\iiint\limits_{HV/2} A \mathrm{d}V$	mWb·m^2	9.34
$\iiint\limits_{LV/2} A \mathrm{d}V$	mWb·m2	2.53
$L_{R/2}$	mH	122
$M_{R/2\text{-}HV/2}$	mH	137
$M_{R/2\text{-}LV/2}$	mH	19

Tabel 2: Calculated parameters and their values for current injected in upper half of regulating winding

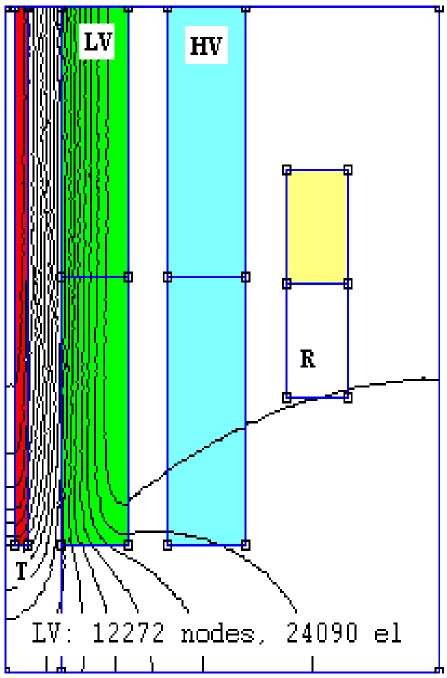

Figure 3: Magnetic field pattern for current injected in low voltage winding

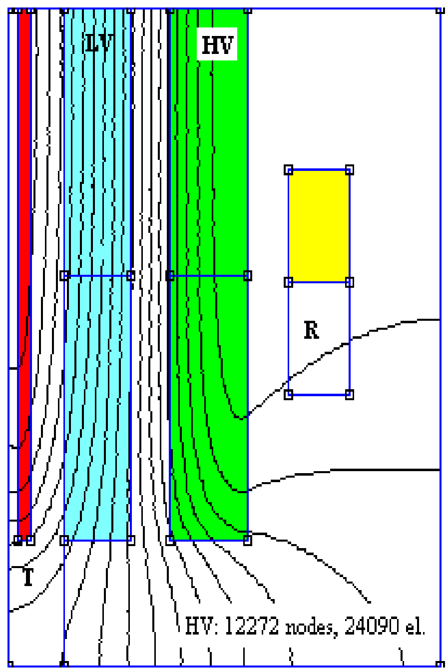

Figure 4: Magnetic field pattern for current injected in high voltage winding

Current	A	578
Ampere turns	kA	189.3
Current densities	A/mm^2	1.262; -5.914
$\iiint\limits_{LV} A\,j\,dV$	J	23295
$\iiint\limits_{R/2} A dV$	mWb·m^2	4.29
$\iiint\limits_{HV} A dV$	mWb·m^2	24.82
L_{LV}	mH	69.76
$M_{LV\text{-}R/2}$	mH	37.6
$M_{HV\text{-}LV}$	mH	118.9

Table 3: Calculated parameters and their values for current injected in low voltage winding

Current	A	289
Ampere turns	kA	138.4
Current densities	A/mm^2	0.8 ; -4.325
$\iiint\limits_{HV} A\,j\,dV$	J	39835
$\iiint\limits_{R/2} A dV$	mWb·m^2	9.417
$\iiint\limits_{LV} A dV$	mWb·m^2	17.244
L_{HV}	mH	477
$M_{HV\text{-}R/2}$	mH	165.4
$M_{HV\text{-}LV}$	mH	130

Table 4: Calculated parameters and their values for current injected in high voltage winding

4. CAPACITANCE OF A PAIR OF INTERLINKED WINDING DISKS

Denoting by C the capacitance between two adjacent turns, the equivalent capacitance of two disks with 2n turns (n turns of each disk) results from the equality of electric energies stocked in wires capacitances and the equivalent capacitance of the two

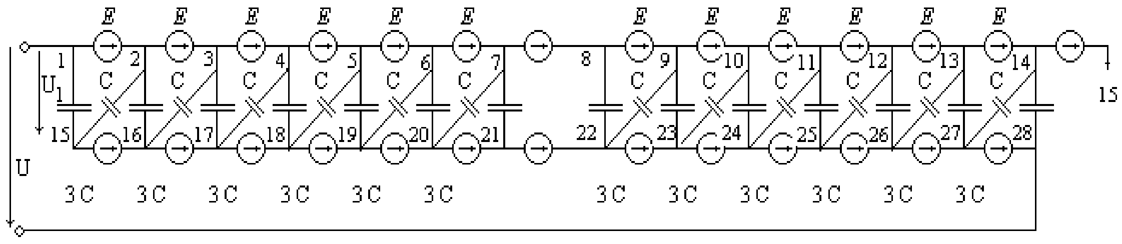

Figure 5: Wires capacitances for n = 14

disks (fig. 5):

$$\left[3nU_1^2+(n-2)U_2^2\right]\frac{C}{2}=C_{\mathrm{e}}\frac{U^2}{2}$$

$$U_1=\frac{n}{2n-1}U \qquad (5)$$

$$U_2=\frac{n-1}{2n-1}U$$

The equivalent capacitance of two disks will be:

$$C_{\mathrm{e}}=\frac{2n^2-n+2}{2n-1}C$$

$$C=\varepsilon_0\,\varepsilon_{\mathrm{p}}\,\pi\,D_{\mathrm{m}}\frac{h_{\mathrm{c}}}{\delta_{\mathrm{i}}} \qquad (6)$$

where $\varepsilon_{\mathrm{p}}\approx 3.8$

Here δ_i is the conductor insulation double thickness, ε_p is the transformer paper relative dielectric permittivity, h_c – the conductor height.

For a winding with N disks the equivalent axial capacitance will be:

$$C_{\mathrm{e}N}=\frac{2}{N}C_{\mathrm{e}}=\frac{2(2\,n^2-n+2)}{(2n-1)\,N}C \qquad (7)$$

The longitudinal winding capacitances, determined with above formula, considering only the adjacent wires capacitances and neglecting the capacitances between the wires situated in different disks, are the following:

High voltage winding	Low voltage winding	Regulating winding
1050 m·pF	537 m·pF	183 m·pF

Table 5: Specific longitudinal equivalent wires capacitances

5. SIMPLE SCHEME FOR LIGHTING SURGE EVALUATION ON FREE END OF REGULATING WINDING

We can neglect, in first approximation, the mutual inductances between the regulating winding and low voltage winding, because of relatively low value (2 x 19 mH) and of the screening effect of the high voltage winding, situated between them. We will neglect also the mutual inductance between high and low voltage windings. In these conditions, we can consider a very simple scheme Simp3 from the fig. 6, which was analyzed with ATP program. The theoretical results are given in fig. 7.

In the next table is given the comparison with experimental data. The large differences are probably the result of the assumptions.

	u_{max}	u_{min}	$(u_1-u_2)_{max}$	t_{min}
Experim.	40 V	-220 V	340 V	34.5 μs
Calc.	29 V	-162 V	290 V	30.0 μs

Table 6: Experimental and calculated results

6. CONCLUSIONS

1. The characteristic length of the lumped elements necessary for consideration is of the order of 20-50 cm.
2. The simplified scheme can be used to identify the influence of the constructive parameters of the autotransformer on the level and the frequency of lighting surges.

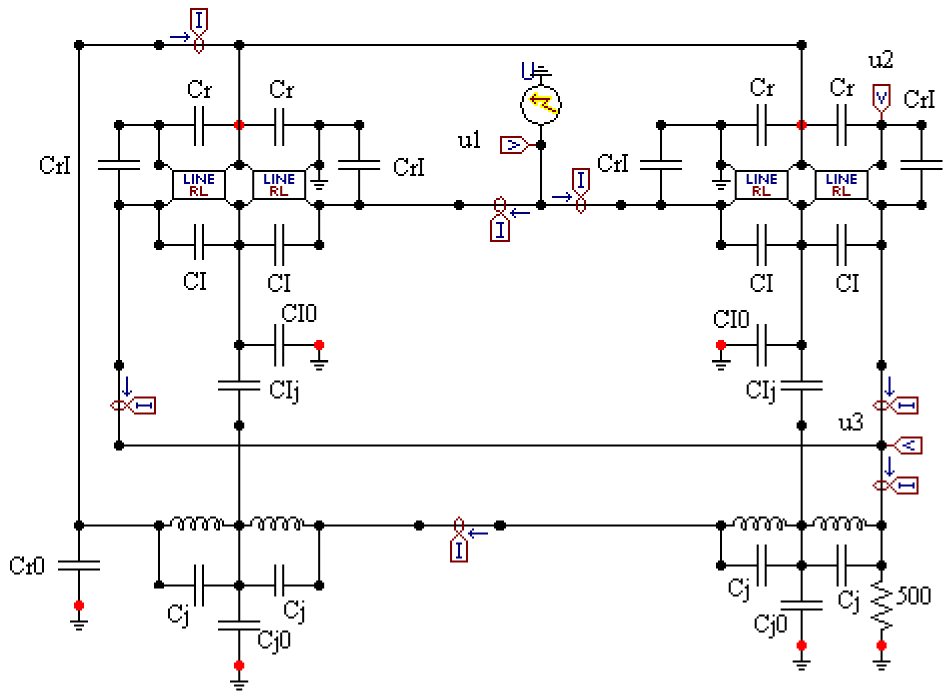

Figure 6: Simplified scheme of transformer windings

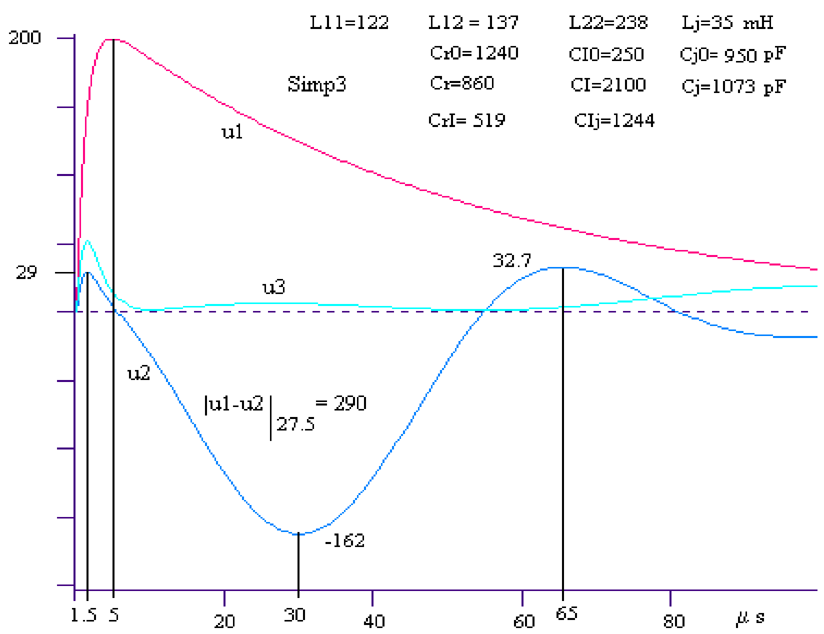

Figure 7: Lighting surge in free end of regulating winding and in the common terminal A_2 (u_2 point and respectively u_3 point from simplified scheme).

References

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