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Methods for Determining Dielectric Stresses in the Windings of a Transformer Subjected to Lightning Impulse

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Abstract— **In this paper there are presented two methods for determining the dielectric stresses occurring in the tap winding of a lightning pulse transformer. The first method is to implement the equivalent circuit using the ATP / EMTP program, and the second method consists in testing the transformer at a low voltage impulse before being put into the tank. The design of the transformer was done taking into account the results obtained with ATP / EMTP. This fact allowed the design of the winding structure as well as their location in space to obtain uniformly distributed overvoltages along the axial and radial direction of the coil assembly. The results of the laboratory tests performed on the transformer, validated the results obtained with ATP / EMTP.**

Keywords—transformer; lightning impulse; transient regime

I. INTRODUCTION

As the analytical approach to the determination of the response of the windings to the lightning impulse stress became complicated with the transition from uniform windings to interleaved windings, this problem was transferred for solving to numerical methods for solving differential equations that define electromagnetic phenomena in the transformer. At the same time it was passed from the theories of the standing waves, respectively, travelling waves applied to determine the response of transformer windings at surge stress to the simulation of the winding with circuits with lumped parameters. The analysis of such a network divided into a finite number of uniform sections, by using the Laplace transform was presented in [1].

The application of the Runge-Kutta method to solve the 2nd order differential equations for the purpose of determining the distribution of the voltage impulse along the winding of a transformer was given in [2].

In [3] is approached the equivalent network of a three-phase transformer which is characterized by a 2nd order equation with matrix coefficients. This equation is solved by the Milne method [4]. The same type of equation is solved in [5] and [6] by converting it into a system of two ordinal 1 equations, which in turn were solved by recursive integrations.

The MATLAB Program currently has a standard function, built to solve the 1st order systems [7]. If the equivalent circuit of the windings also contains mutual inductances, they are replaced by uncoupled elements by using the analytical relations presented in [8]. In this way the circuit can be analyzed by using the methods described above, because it is a purely resistive circuit.

The difficulty of achieving the equivalent circuit is given by the existence during the transient regime, of both the electric field and the variable magnetic one over time.

The two fields influence the value of capacitances, of the self-inductance and mutual inductance and of the resistance. In order to reduce the difficulty of solving partial differential equations, the analyzed winding is described by sections where the inductances and capacitances are represented by lumped parameters, and partial differential equations are approximated by ordinary differential equations that are resolved by numerical analysis.

One of the most accurate descriptions of the equivalent circuit is the description of the winding by the capacitance between the turns, resistances and the associated inductances [9].

Another proposed model [10], [11] consists in the representation of the transformer by two electromagnetic coupling circuits. In this model, the variable magnetic flux over time induces in the electrical circuit a voltage that establishes a level of the electrical current, which by the resulting current linkage constitutes in the magnetic circuit a source which, depending on the magnetic reluctances, establishes a new level of magnetic flux.

The models based on the inductance and self-capacitance of an area in the winding interfaced with a magnetic core model by using the duality principle are described in [12], [13], [14].

Based on the principle of electric and magnetic coupling circuits Dommel achieved the first variant of the ATP/EMTP program [15].

In the paper [16] a comparison is made between the results obtained by using a model of a phase of the transformer developed in the ATP/EMTP program and a model with distributed elements resulting from the telegrapher's equations applied to a transmission line, analyzed in the frequency domain. In order to obtain the results in the time domain, the NLT (Numerical Laplace Transform) program was applied.

The paper [17] uses the finite element method (FEM) to determine both self and mutual inductances and capacitances. For the purpose of placing them in the equivalent scheme of the tap winding for the determination of the surge transmitted at its free end. The representation of the surge transmitted and its parameters were obtained with the ATP/EMTP program.

ATP/EMTP (Alternative Transient Program – Electromagnetic Transient Program) is used worldwide for the analysis of the switching phenomena and the propagation of lightning wave on the lines of transmission or distribution of electricity, the coordination of the network insulation and the study of voltage oscillations, the modeling of relay protection, the study of harmonics and the quality of electricity [18], [19].

The ATP/EMTP program package is a very powerful software means for analysis of transient regimes in electrical networks of high voltages, which gives the user the possibility of modeling the polyphase networks of the extended networks [20], [21] as well as the investigation of faults in the electrical network [22], are associated with a high computing speed.

II. Theoretical Concepts

The test circuit with lightning impulse of the transformer is shown in Fig.1, and the layout of the tap coil relative to the tertiary (T), secondary (JT) and primary coils (IT) in Fig.2.

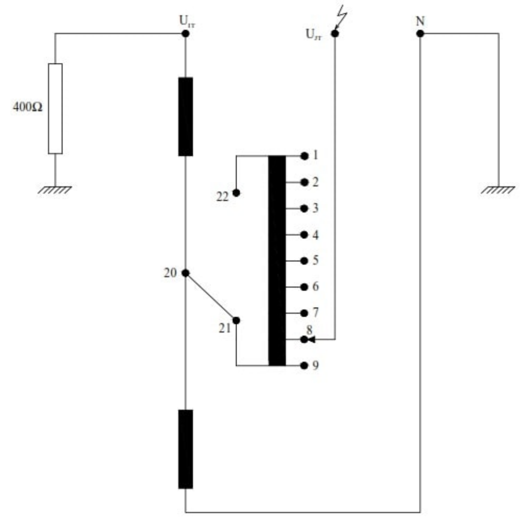

Fig. 1. Test circuit with lightning impulse

The tap winding is executed from the CTC (Continuously Transposed Conductor) conductor; the type of winding is continuous in two layers.

The CTC is used the most for the windings of power transformers. It consists of a set of enamel rectangular conductors, usually with PVF enamel, which are twisted to create a rectangular cable. In this set each wire takes successively and repeatedly every position possible within the cross section of the conductor.

The bulk wires are wrapped in pure cellulose paper strips. This conductor is used to manufacture low-loss windings for high-power transformers.

The increase of power of transformers has intensified the need for increased efficiency.

According to the "Ecodesign" European Directive it is necessary to drastically reduce the losses that occur at the operation of a transformer and the use of the CTC windings has improved this important feature of the construction of transformers.

The adoption of the CTC presents a great advantage by reducing the losses through eddy currents, especially at the end of the windings.

In addition, a considerable increase in the winding space factor is possible, due to the very small thickness of the insulation of separate conductors and it is possible to obtain a more uniform distribution of the temperature from one end to the other of the winding.

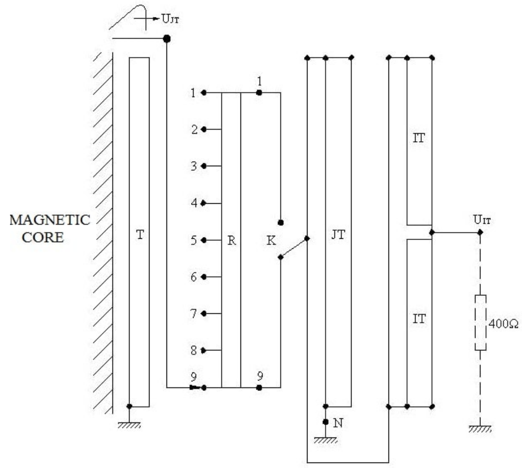

Fig. 2. Tap coil layout

A. Calculation of self-inductances

The inductance of the layer placed on the insulating cylinder of the coil:

$$4L_1 = \mu_0 \cdot N^2 \cdot \frac{\pi \cdot a_1}{l} \tag{1}$$

where: L_1- is the inductance of one of the four sections forming the first layer, $\mu_0\ H/m$ - magnetic permittivity, N - number of turns of the first layer, a_1 - mean radius of the coil, l- the length of the coil between two consecutive steps of the tap coil.

B. Calculation of capacitances to ground

Capacitance between the tap coil and the tertiary coil :

$$C_{R-T} = \frac{2 \cdot \pi \cdot \varepsilon_0 \cdot \varepsilon_{ru} \cdot l}{\ln(R_{ir} / R_{et})} \tag{2}$$

ε_0 - electric permittivity of vacuum, ε_{ru} - electric permittivity of oil, l - length of tap coil, R_{ir} - inner radius of tap coil, R_{et} - outer radius of tertiary coil.

C. Capacitance between tap coil and secondary coil (LV)

R_{iJT} - represent the inner radius of secondary coil and

R_{er} - outer radius of tap coil

$$C_{R-JT} = \frac{2 \cdot \pi \cdot \varepsilon_0 \cdot \varepsilon_{ru} \cdot l}{\ln R_{iJT} / R_{er}} \tag{3}$$

D. Calculation of capacitances between the two layers of the tap coil at the free end area

$$C_{1-9} = \frac{2 \cdot \pi \cdot \varepsilon_0 \cdot \varepsilon_{ru} \cdot l_r}{\ln R_{is2} / R_{es1}} \tag{4}$$

l_r - length of the segment in the coil of the tap winding containing its potential-free end.

Due to the fact that the first layer has 8 segments, each of 8 turns, $l_r = l/8$:

E. Calculation of series capacitance of tap winding

If the tap winding has 8 electric circuits with 8 turns on the circuit, we approximate that the voltage is evenly distributed along the 64 turns.

If we note with "U" the voltage applied at the end of the winding it results that the voltage on the turn is "U/64".

The energy stored in the tap winding has the following expression:

$$E_R = 8\left\{6 \cdot \left[\frac{1}{2} \cdot C \cdot \left(8 \cdot \frac{2U}{64}\right)^2\right] + \frac{1}{2} \cdot C \cdot \left(8 \cdot \frac{U}{64}\right)^2\right\} + 7 \cdot \left[\frac{1}{2} \cdot C \cdot \left(7 \cdot \frac{U}{64}\right)^2\right] \tag{5}$$

where: C represent the capacitance between two turns;

$1/2 \cdot C \cdot (8 \cdot 2U/64)^2$ - represents the energy stored in the capacitances between conductors that have the difference of potential equal to "U/64". For example, the capacitance between turns: 7b-8a on a control step.

$1/2 \cdot C \cdot (8 \cdot U/64)^2$ - represents the energy stored in the capacitances between conductors that have the difference of potential equal to "2U/64". For example, the capacitance between turns :3b-5a on a control step.

$1/2 \cdot C \cdot (7 \cdot U/64)^2$ - represents the energy stored in the capacitances between the conductors which are placed at the end of one turn and respectively the beginning of the next turn. For example: 2b-1a on a control step.

$$E_R = 8 \cdot \left[6 \cdot \frac{1}{2} \cdot C \cdot \left(\frac{16U}{64}\right)^2 + \frac{1}{2} \cdot C \cdot \left(\frac{8 \cdot U}{64}\right)^2\right] + \frac{7}{2} \cdot C \cdot \left(\frac{7 \cdot U}{64}\right)^2 = \tag{6}$$
$$= 1.6 \cdot C \cdot U^2$$

If we note with Cs the total series capacitance of a step in the tap winding, it results from the equality between the stored energy that:

$$3.2 \cdot C \cdot U^2 / 2 = C_s \cdot U^2 / 2 \tag{7}$$

so $C_s = 3.2 \cdot C$

The capacitance between two turns is calculated by the relation:

$$C = [\varepsilon_0 \cdot \varepsilon_h \cdot \pi \cdot D_m (h_c + t_h)] / t_h \tag{8}$$

where:

ε_0 - is the permittivity of vacuum,

ε_h- relative permittivity of the oil-impregnated paper,

D_m-average diameter of the tap winding,

h_c- height of conductor in radial direction,

t_h - thickness of paper insulation.

The total capacitance between turns is:

$$C_{total} = 4 \cdot C \tag{9}$$

The total series capacitance of a control step of the winding has the value

$$C_s = 3.2 \cdot C_{total} \tag{10}$$

F. Calculation of tap winding resistance

With R_{cc} we note the measured DC resistance of a tap step. For the equivalent circuit of the tap winding, the resistance will be calculated taking into account the penetration of the electric field with the electrical frequency of 15 kHz to the conductor winding.

The frequency of 15 kHz is specific to the lightning impulse wave front [10]. Corresponding to this frequency, the penetration depth is 0.6 mm, according to the relation [7]:

$$\delta = 1/\sqrt{\pi \cdot f \cdot \mu \cdot \sigma} \tag{11}$$

It results that the equivalent resistance for a tap step is:

$$R = R_{cc} \cdot \left(S_{cu} / S^*\right) \tag{12}$$

where:

S_{Cu} - the conductor section,

$$S^* = 2 \cdot \pi \cdot r \cdot \delta \tag{13}$$

S^* -the equivalent section for high frequency

r - the copper conductor radius,

δ - the depth of penetration of the electric field in the copper section.

Input capacity value can not be increased enough to provide insulation between inlet and coil layers. For this reason, it is necessary to determine by numerical modeling the voltage level that occurs at the endless potential end of the control winding. This optimizes the level of insulation required in the tap winding area.

III. Simulation Results

This choice was made taking into consideration the statistical results of the defects occurred after the laboratory testing with high voltage lightning impulse (for voltage rating 400 [kV] the impulse voltage level is of 1425 [kV], and for voltage rating of 231 [kV] the impulse voltage level is of 1050 [kV], according to standards [45], [46].

The surge that occurs at the potential-free end of the tap winding is due to its free oscillation.

The model of tap winding energized directly by the lightning impulse (see Fig.1) is a R-L-C network with lumped parameters invariable in time (Fig.3).

For the validation of the proposed model was performed this test with low voltage lightning impulse.

The circuit proposed to be implemented in the ATP/EMTP program, is for a three-phase oil immersed transformer ATUS-OFAF 400/400/80MVA; 400/231±8x1.25%/22kV (see Fig.3).

The program has a library of comprehensive electrical symbols and an interactive interface that allows the achievement of the wiring diagram and the analysis of the operating conditions without delay.

The results obtained with the ATP/EMTP program for three-phase transformer ATUS-OFAF 400/400/80MVA; 400/231±8x1.25%/22kV are presented in figures 4, 5, 6.

According to the literature [1], [2], [6] and [7] in order to obtain a uniform distribution of the lightning impulse voltage, the size of the input capacity must be as large as possible, and the ratio between the magnitude of the series capacity of the adjustment infiltration and the size of its capacity towards the ground is approaching the unit.

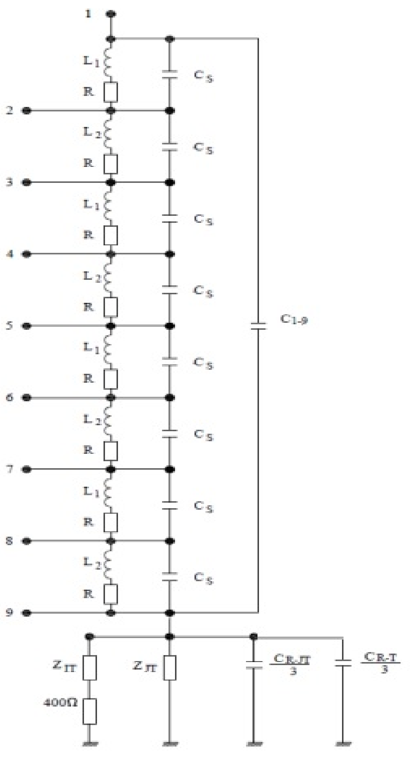

Fig. 3. The circuit proposed to be implemented in the ATP/EMTP program

The input capacitance value cannot be increased enough for reasons of insulation insurance between the input turns and between the layers. For this reason a compromise is made between the level of insulation of the end free of potential of the tap winding. These insulation levels are influenced by the level of insulation between the turns of the winding. To optimize these levels it is necessary to use the specialized ATP/EMTP program.

In Fig.3 it is presented the circuit proposed to be implemented in the ATP/EMTP program where $C_{R-JT}/3$ and $C_{R-T}/3$ - represent the dynamic capacitances between the tap winding and the secondary winding with earthed neutral, respectively between the tertiary winding and ground.

In the first analyzed case the capacity C_{1-9} has the value, and the waveform obtained is shown in figure 4.

In order to highlight the importance of choosing the type of interweaving and the reciprocal lay-out of the two winding steps, two other cases were simulated where the capacitance C_{1-9} had the values:0.34 nF and 9.78 nF.

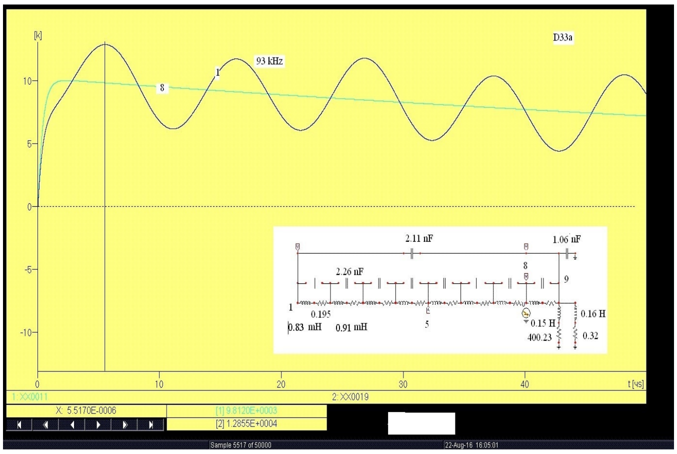

Fig. 4. The waveform of the surge transmitted at the free end of the tap winding of an transformer (ATP/EMTP)

$U_{max\ trans}$=1.28*Umax imp, t_{Umax}=5.5 μs, f=93 kHz

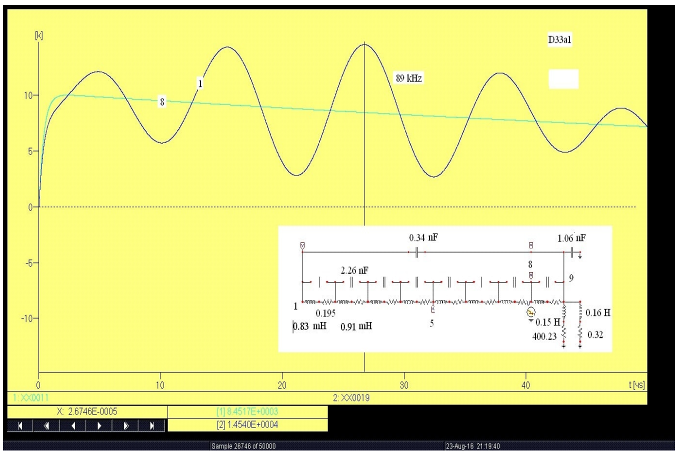

Fig. 5. The waveform of the surge transmitted at the free end of the tap winding of an transformer when the capacitance is 0.34nF (ATP/EMTP)

$U_{max\ trans}$=1.45·Umax imp, t_{Umax}=23 μs, f=111 kHz

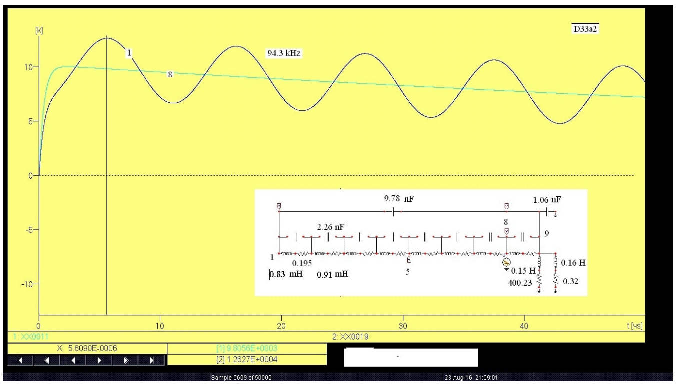

Fig. 6. The waveform of the surge transmitted at the free end of the tap winding of an transformer the capacitance is 9.78 nF (ATP/EMTP)

$U_{max\ trans}$=1.26·Umax imp, t_{Umax}=5.5 µs, f=94.3 kHz.

IV. Experimental Results

The structure of the circuit for experimental determination of surges that propagate at the free end of the tap winding of a transformer subjected to low voltage lightning impulse is presented in Fig.7.

Measuring equipment and apparatus contained in the measuring circuit for voltages transmitted are: Repeated impulse generator (GIR), type 48, series 693306 100W/220V, 50Hz HAEFELY-Switzerland; Oscilloscope type AGILENT 54624A, series 40003458, USA; Pentium 4 computer.

With the untanked transformer, single low-voltage impulses were applied to position 8 of the tap winding a lightning impulse type voltage with the maximum amplitude of 120 V and the time parameters 1.2/100 µs and was recorded the surge transmitted at position 1, which represents the free end of the tap winding.

The oscilloscope was programmed to display the maximum values of the two phenomena recorded as well as the time bases (common for both phenomena) and amplitude (two scales 20V/div and 50V/div respectively).

The results obtained in the test laboratory for a three-phase transformer 400 MVA/400kV are presented in figure 8.

Compared to the results obtained from the simulation, (see Fig.4, 5, 6) the differences are very small.

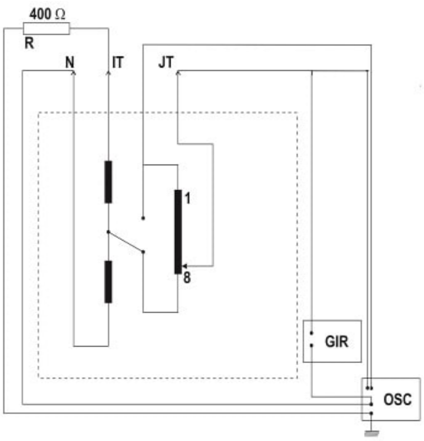

Fig. 7. The circuit for experimental determination of surges that propagate at the free end of the tap winding of a transformer subjected to low voltage lightning impulse

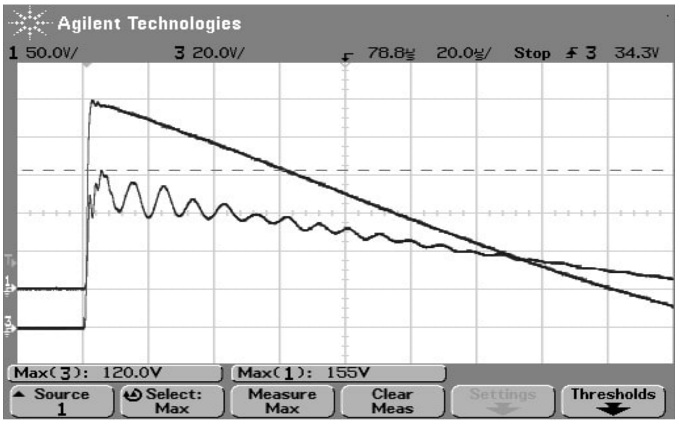

Fig. 8. The recorded waveform of the voltage transmitted at the free end of the tap winding of a 400MVA/400kV transformer when it was subjected to lightning impulse

$U_{max\ trans}$=1.28·Umax imp, t_{Umax}=5.5 µs, f=100 kHz.

V. CONCLUSIONS

At the first analysis it can be concluded that the use of this type of winding is perfect, but taking into consideration the difficulty of the execution of this type of winding and the duration necessary to achieve it arises the problem of reduced productivity. By numerical modeling of the transient phenomena manifested in the windings, new solutions can be implemented, such as the winding interleaved in steps at which the element subjected to optimization is the length of the winding section interleaved and the rest achieved with continuous winding and also how the connection is made with the partially interleaved tap winding.

In the case study presented it was analyzed the importance of sizing the axial insulation at the ends of the tap winding and the importance of the connections between the wires in the structure of the transposed conductor (CTC).

The modification of the longitudinal and radial insulation between the layers of the coil led to obtaining different values of the surges transmitted at the free end of the tap winding. To obtain a value of the voltage distribution constant $\alpha = \sqrt{C_m / C_s}$, as close as possible to the value "1", it was imagined an original system for potential realization of the conductive elements in the structure of the CTC conductor.

The design of the transformer was done taking into account the results obtained with ATP / EMTP. This fact allowed the design of the winding structure as well as their location in space to obtain uniformly distributed overvoltages along the axial and radial direction of the coil assembly. The results of the laboratory tests performed on the transformer, validated the results obtained with ATP / EMTP.

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