IMPACT OF RESONANCE OVERVOLTAGES IN TRANSFORMERS ON INTERNAL INSULATION SYSTEMS

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Abstract: Usually courses of transient voltages generated in power systems include of transient damped oscillate components with different frequencies. Overvoltages manifesting such character and having lower amplitude than the protection level of the surge arresters are not attenuated at the transformer terminal. If the oscillating frequency component of the external overvoltage is equal to the natural frequency of the windings, then the magnitude of internal resonance overvoltages is having the maximum value. The resonance overvoltages generated inside the windings contributed to many transformer failures. Therefore it is very important to analyse internal overvoltages for determination of impact such overvoltages on winding insulation systems. The base of the analysis may be computer simulations and experimental investigations.

The paper presents the analysis of resonance overvoltages inside the high voltage winding of the power transformer of 25 MVA, 110/15 kV. The base of the analysis were used computer simulation results of internal resonance overvoltage done by use the mathematical model with lumped parameters of windings. The simulations were related to the investigation results.

1 INTRODUCTION

The transformers are subjected to different overvoltages generated in power systems. The crest value of overvoltages appearing at the transformer terminals are limited by such protective devices as surge arresters to the level determined by the insulation coordination. Those values are usually much higher than maximum nominal voltage. Thus, often the internal overvoltages formed inside the insulation system of high voltage equipment are caused by internal resonance in windings. Particularly some switching transients of oscillating character may cause high amplitude internal overvoltages. Overvoltages manifesting such character and having lower amplitude than the protection level of the surge arresters are not attenuated at the transformer terminal. They arrive to the transformer input practically without any changes both in amplitude and waveform. The overvoltages containing the oscillating components may be generated, for example, during switching operations in SF_6 based gas insulated substations (GIS), during power making or breaking in lines supplying the transformers [1, 2]. Ground faults can be also associated with oscillating overvoltages and amplitudes below protection level of applied surge arresters.

Transformer response on overvoltages generated in electrical networks is related to transient phenomena occurring inside the windings and waveforms of overvoltages, which appear at winding terminals, especially their duration and maximal values. Transformer windings can be represented as a complex *RLC* (resistive-inductive-capacitive) network. If the oscillating frequency component of the external overvoltage is equal to the natural frequency of the windings, then the magnitude of internal resonance overvoltages will have the maximum value.

The amplitude of the overvoltage depends on attenuation conditions and duration of the oscillating components. The probability of simultaneous occurrence of all dangerous conditions to form dangerous resonance overvoltage inside transformer is relatively small, but real. Thus, overvoltages generated in some transient and switching stages in electric power equipment may create hazard for the insulating system despite the applied overvoltage protection [3-5]. The resonance overvoltages generated inside the windings caused by switching phenomena in SF_6 switchgears and power networks, as well the overvoltages triggered out during ground faults due to lightning, contributed to many transformer failures protected by surge arresters, as reported, e.g. in [2,6,7]. Therefore it is very important to analyse such internal overvoltages for determination of impact overvoltages on winding insulation systems. The base of the analysis may be computer simulations of overvoltages.

The paper presents the analysis of internal resonance overvoltages of high voltage winding of power transformer of 25 MVA, 110/15 kV. As a base of the analysis were used the simulations of overvoltages in the winding done by use of model with lumped parameters of winding. The calculation results were compared to the measurements.

2 SIMULATION METHOD OF RESONANCE OVERVOLTAGES IN TRANSFORMERS

A numerical model with lumped parameters of the transformer windings is used in order to obtain the resonance overvoltages in transformer winding. It was constructed by replacing a part of the winding with corresponding self-inductance and mutual inductance, capacitance to earth, longitudinal capacitance, insulation conductance and the resistance [8,9]. The winding substitute scheme is shown in Figure 1. It represents the *w* winding of one transformer phase, whereas each is split into the *n* number of sections (Fig. 1a). It my be used both for a layer type windings as well as for disc ones.

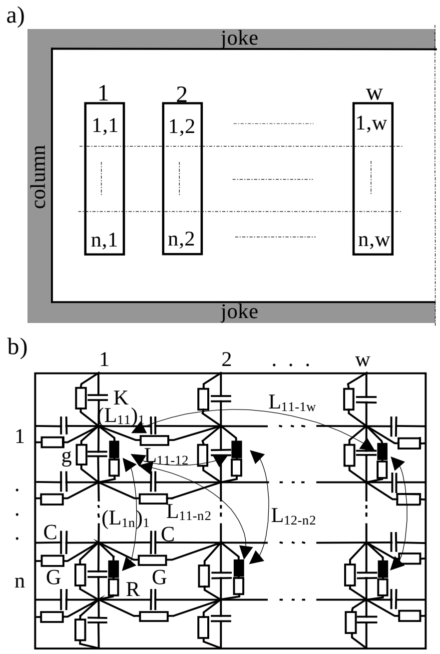

Figure 1: The model with lumped parameters of transformer windings: a - segmentation of winding (1, 2 ... *w*) on the sections (1, 2 ... *n*), b - equivalent diagram of windings [8,9]

Following dependencies are true for any node of the scheme presented in Figure 1b:

$$I'_C(t)+I'_G(t)+I'_L=0 \qquad (1)$$

where: $I'_C(t)$, $I'_G(t)$, $I'_L(t)$ - matrixes of currents flowing along the capacitance conductance and inductance-resistance branches connected to the node.

Voltage-current dependencies for branches of the diagram presented in the Figure 1b are given in the following form:

$$I'_C(t)=C_g\frac{dU'_C(t)}{dt} \qquad (2)$$

$$I'_G(t)=G_g\,U'_G(t) \qquad (3)$$

$$U'_L(t)=L\frac{dI'_L(t)}{dt}+RI'_L(t) \qquad (4)$$

where: $U_C(t)$, $U_G(t)$, $U_L(t)$ - matrixes of voltages on capacitance, conductance, and inductance-resistance branches,

C_g, G_g, R, L - matrixes of branch capacitances, conductances, resistances and the matrix of self inductance and mutual inductance between sections.

The purpose of subsequent transformations is to find dependencies between nodal voltages *U* and currents *I* and the vectors of both branch voltages and currents. They are dependent on the configuration of equivalent circuit. They may be taken into account by the introduction of:

- T_C connection matrix, which has a structure dependent on connections of capacitance in the equivalent circuit,
- T_G matrix - reflecting connections of conductances,
- T_L matrix - reflecting connections of inductances in the model.

The number of rows of the T_C matrix is equal to the number of capacitance and the number of columns equals to the number of nodes in the circuit. The matrix consists of values 1 or -1 placed at intersections of rows (whose numbers correspond to the number of capacitance in the circuit) and columns (with their numbers consistent with numbers of nodes that capacitance are connected with). Connection matrixes T_G and T_L are constructed in the similar method [9].

They are used to replace branch currents and voltages (except I_L currents) with nodal voltages and currents in equations (2 - 4). Equations (2 - 4) yield the following forms after transformation:

$$I_C(t)=C\frac{dU(t)}{dt} \qquad (5)$$

$$I'_G(t)=G_G\,U(t) \qquad (6)$$

$$T_L\,U(t)=L\frac{dI_L(t)}{dt}+R\,I_L(t) \qquad (7)$$

where: $C=T_C^t\,C_g\,T_C$ (8)

$$G=T_G^t\,G_g\,T_G \qquad (9)$$

$$I_L=T_L^t\,I_L \qquad (10)$$

After substituting dependencies (5), (6) and (10) into equation (1) and taking into consideration dependence (7) was obtained a system of equations that represents the dependencies between nodal voltages and currents in inductance-resistance branches:

$$C\frac{dU(t)}{dt}+GU(t)+T_L^tI(t)=0 \qquad (11)$$

$$L\frac{dI(t)}{dt}-T_L^tU(t)+RI(t)=0 \qquad (12)$$

where: $I(t)$ vector of currents $I_L(t)$ [10].

The boundary conditions – which are determined by several factors, like: earthing, the method of windings connection and the connection of an external voltage source $u_e(t)$ – are taken into account through appropriate transformations of the system of equations (11), (12). They were constructed:

- removing a row in equation (11) in T_L^t and $U_e(t)$ matrixes, removing columns in the T_L matrix and removing rows and columns in matrixes C and G with their numbers corresponding to the number of the grounded node - in the case of node grounding,
- adding up respectively rows and columns in matrix C and also columns in matrix T_L (matrix T_L^t has its rows added up) whose numbers correspond to numbers of connected nodes - in the case where nodes are connected.

Connecting an external source of voltage $u_e(t)$ to node k, the unknown voltage $u_k(t)$ in the equation system (11 - 12) is replaced by the known function $u_e(t)$. Then removed columns of matrixes C, G and T_L, denoted as C_u , G_u and T_{Lu} - in a similar way as in the case of node grounding - are transferred into the right side of the equation [10]. Column C_u with the factor $du_e(t)/dt$ as well as columns G_u and T_{Lu} - with factor $u_e(t)$ now become data.
After transformation the system of equations (11) and (12) has the following form:

$$C\frac{dU(t)}{dt}+GU(t)+T_L^t I(t)=-C_u\frac{du_e(t)}{dt}-G_u u_e(t) \quad (13)$$

$$L\frac{dI(t)}{dt}-T_L^t U(t)+RI(t)=T_{Lu}u_e(t) \quad (14)$$

where: C_u,G_{uz} - vectors created from matrixes C and G, consisting of appropriate capacitances and conductances between the node with is connected to the external voltage source $u_e(t)$ and surrounding nodes,
T_{Lu} - the matrix which consists of the column of matrix T_L, whose number corresponds to the number of the node which was connected to the external voltage source $u_e(t)$ [10].

In the equation system (13 - 14) matrixes U, C, G, T_L , T^t_L along with C_u, G_u and T_{Lu} do not contain rows and columns, that were previously removed in order to meet boundary conditions. Assuming the sinusoidal source voltage $u_e(t)$, the equation system (13 - 14) after application of the symbolic method and differentiation can be written as follows [10]:

$$(j\omega C + G)\ U + T_L^t\, I = - (j\omega C_u + G_u)\ U_e \quad (15)$$

$$(j\omega L + R)\ I - T_L U = T_{Lu}\, U_e \quad (16)$$

It, in a simplified form, takes the following form:

$$Y\ U + T_L^t\, I = - Y_u\, U_e \quad (17)$$

$$Z\ I - T_L\, U = T_{Lu}\, U_e \quad (18)$$

After transformation of equations (17 - 18) we obtain the following dependence between the vector of voltages U and currents I

$$U = (Y + T_L^t\, Z^{-1}\, T_L)^{-1}\ (T_L^t\, Z^{-1} T_{Lu}\, U_e + Y_u\, U_e) \quad (19)$$

$$I = Z^{-1}\,(T_L\, U + T_{Lu}\ U_e) \quad (20)$$

where: Y, Y_u, Z - matrixes representing respectively the admittance and impedance of the system that are expressed using the following equations:

$Y = j\omega C + G$

$Y_{uz} = j\omega C_u + G_{uz}$

$Z = j\omega L + R$

ω – angular frequency.

Values of elements $Y^{'}$ of the admittance matrix Y are equal to the sum of all admittance connected to the respective nodes. The values of elements Y^{*} are equal to admittance connected between the neighbouring nodes in the circuit of the same winding, whilst the values of elements Y^{**} are equal to admittance between neighbouring nodes of different windings (with a minus sign).
Four winding parameters are represented in the impedance matrix Z:

- the self inductance $L_{ii(k)}$ of section i of the winding k and its resistance $R_{ii(k)}$,
- the mutual inductance $L_{ij(k)}$ between sections i and j of the winding,
- the mutual inductance $L_{ik\text{-}jl}$ of section i of the winding k and of section j of the winding l.

The main diagonal of matrix Z is made up of section impedances in the respective windings. Other elements denote mutual impedances between the windings. The connection matrix T_L is composed of elements with values -1 or 1.
Capacitors C represent the capacitance to earth of the sections and the capacitance between the sections of the surrounding windings. They can be obtained from measurement or by computations carried out using dependencies presented in publication [11]. Conductances G and g represent power losses in the insulation system between the winding and the core as well as between windings. Calculations can be made with the use of equations published in article [12], assuming known value of the dissipation factor *tan delta* of the insulation material. Resistances R of winding sections are frequency dependent. The detailed calculations are presented in the paper [13 - 15].

3 THE EXPERIMENTAL OBJECT AND SCOPE OF INVESTIGATIONS

As a experimental object have been used the high voltage winding of power transformer 25 MVA, 110/15 kV. The test winding consists of 25 double interleaved coils. Each disc contains of 20 turns [16]. The simplified cross section of the winding is

presented in Figure 2 and the main winding dimensions are shown in Table 1.
Internal winding overvoltage can be produced by oscillatory component with variable frequency of overvoltages generated in power systems. Therefore the simulations of resonance overvoltages in the transformer windings have been done for sinusoidal function within the range 20 Hz - 250 kHz applied to the terminals of the experimental winding. This function simulate

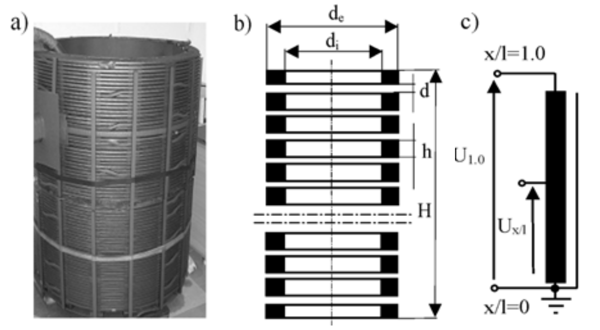

Figure 2: View of the power transformer winding 25 MVA and its simplified cross section: a - view of the winding, b - cross section of the winding, c - symbols of winding taps

Table 1: Basic mechanical parameters of the high voltage winding for transformer of 25 MVA

rated voltage, kV	110
winding type	coil
number of wires in coil, -	20
number of coils, -	50
height of winding H, mm	700
internal diameter d_o, mm	765
external diameter d_i, mm	893
width of coil h, mm	10.3
width of gap between coils d, mm	3.3

approximately the transient components of overvoltages generated in power systems in operate conditions. Overvoltages have been simulated at the selected winding taps. The basic aim of simulations is to confirm the influence of the courses of overvoltages at the winding terminals on overvoltages generated inside the windings and analysis of their maximal value and the shape.

4 SIMULATIONS OF THE OVERVOLTAGES

Calculations of resonance overvoltages in the winding of 110 kV (Fig. 2, Tab. 1) were carried out according to the model (Fig. 1), that consisted of fifty sections (n = 50).
Single section of the model consists of only one winding coil. The simulations cover the calculations of frequency characteristics of overvoltages inside the winding generated by the sinusoidal voltage signal $U_{1.0}$ applied at the winding terminal x/l = 1.0 and x/l = 0 (Fig. 2c).
The dangerous condition for insulation system of the winding may occur if the excitation frequency coincides with the natural frequency of transformer winding. At the first stage, the frequency dependences of winding-to-ground voltage inside the winding at pre-selected taps have been simulated. The spectrum has been determinated for discrete frequency values applying the sinusoidal stimulus at the winding terminals.
The simulation results of the overvoltages in the frequency domain at the selected coordinates x/l = 0.3; 0.5 and 0.7 (Fig. 2c) of the winding are presented in Figure 3.

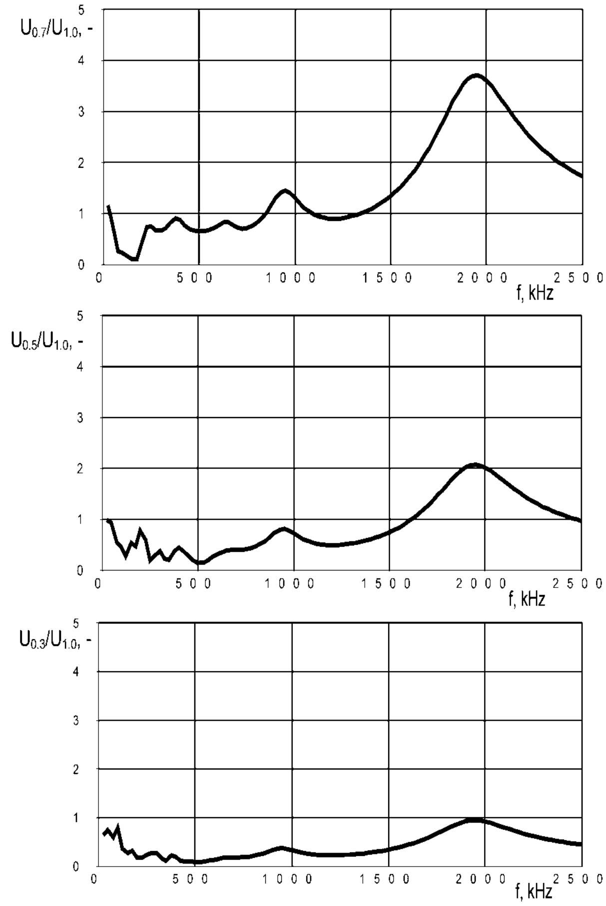

Figure 3: Theoretical frequency dependences of ground overvoltages $u = g(f)$ at selected taps of winding with rated voltage of 110 kV in the frequency range 20 Hz - 250 kHz: a - x/l = 0.7; b - x/l = 0.5; c - x/l = 0.3

At certain frequency bands of the stimulus, the internal overvoltage evidently reaches high values. The escalation of overvoltages is visible in the initial frequency range up to 1.96 MHz, where the culmination point occurs. The analysis of the plots in Figure 2 reveals that, e.g. the overvoltage at the winding coordination x/l = 0.7 is roughly 4 times higher than at the winding input terminal.

5 INVESTIGATION RESULTS OF OVERVOLTAGES

Investigations of the overvoltages generated in transformer windings of 25 MVA at sinusoidal stimulus with wide range of frequency have been carried out by system, which consist of programmable function generator, digital

oscilloscope 100 MHz, 1 Gs/s connected to the host computer by GPIB-PCMCIA interface [16]. The software based control, processing and analysis has been implemented in LabView™ from National Instruments. The sinusoidal supply voltage with stepwise variable frequency is put to terminals of the transformer windings. Maximal voltage at selected windings taps *x/l* (Fig. 2c) for selected frequencies have been recorded.
The measurement has been carried out using a low voltage stimulus, with amplitude up to 20 V, and tuneable frequency in the range 20 Hz up to 250 kHz, for 300 measuring points.
The investigation results of the overvoltages in the frequency domain at the selected coordinates x/l (Fig. 2c) of the experimental winding are presented in Figure 4.

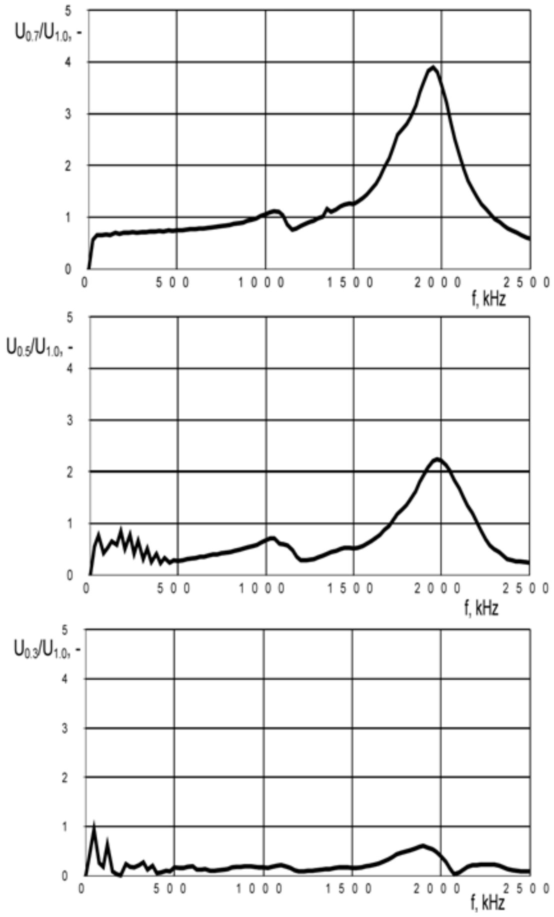

Figure 4: Investigation results of frequency dependences of earth overvoltages $u = g(f)$ at selected taps of winding with rated voltage of 110 kV: a - x/l = 0.7; b - x/l = 0.5; c - x/l = 0.3

The investigation results are similar to the simulations presented in Figure 3. They confirme that the escalation of overvoltages in the winding is visible in the initial frequency range up to 200 kHz. However, the dominant part is around frequency band 1.8 - 2.2 MHz. The analysis of the plots in Figure 4 [17] reveals that, e.g. the overvoltages at the winding coordination x/l = 0.7 is rougly four but at the x/l = 0.5 is about two times higher than at the winding input terminal.

6 ANALYSIS OF IMPACT OF RESONANCE OVERVOLTAGES ON INSULATION SYSTEM OF TRANSFORMERS

From the insulation withstand point of view, e. g. the to earth overvoltage is very important. voltage is critical. Interdisks insulation stress is designed to withstand the lightning impulse U_{BIL}. Assuming the linear voltage distribution the average voltage drop on selected part of the winding U_x will be determined by following dependence:

$$U_x = U_{BIL} \frac{n_x}{n_d} \tag{21}$$

where: n_x - number of disks in the part of the winding,
n_d - number of all disks in the winding.

On the other hand, assuming that resonance transient matches the amplification prone part of the winding spectrum, the resulting resonance overvoltage U_{rez} might be approximated as follows:

$$U_{rez} = k \frac{U_n \sqrt{2}}{\sqrt{3}} A_{TF} \tag{22}$$

where: k - the relative amplitude (per unit) of the incoming transient with respect to the nominal voltage level,
A_{TF} - transfer function based magnification factor obtained in frequency domain.

For example, for nominal voltage U_n = 110 kV the corresponding value U_{BIL} = 550 kV, thus for n_d = 50 and $\Delta x/l$ = 0.5 the value of $n_x = 25$ and from equation (21) we can calculated U_x = 275 kV.
Assuming k = 2 pu and A_{TF} = 2 (Figure 5a at 1.96 MHz), from equation (22) results that U_{rez} = 358.6 kV, which is approximately 1.3 times greater than the value resulting from basic impulse level.

7 CONCLUSIONS

This paper presents application of the mathematical model of windings for numerical simulations of the resonance overvoltages in winding of power transformer. It was used for the calculations of the such overvoltages in the high voltage coil type winding for power transformer of 25 MVA. Presented model allowed to achieve good conformity between results of theoretical simulation of overvoltages and measurements. The numerical simulations show that the presented winding model can be used to investigations for analysis of resonance overvoltages in transformers. Presented analysis of resonance overvoltages confirm that overvoltage risk of longitudinal insulation system of coil type transformer windings in resonance conditions may exceed overvoltages generated during the voltage standard test. This might be reason of some failures of transformers in power system.

8 ACKNOWLEDGEMENT

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