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Lightning impulse voltage distribution over voltage transformer windings — Simulation and measurement

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ABSTRACT

This paper presents a fast and precise method for the calculation of internal voltage transients over the voltage instrument transformer windings. Lumped circuit parameters of the transformer winding are calculated using self-developed solvers based on the boundary element method and integral equations approach. A detailed equivalent circuit of the transformer winding is solved in time domain. Test model of the voltage instrument transformer is constructed with a number of measurement points along the windings. Results of the calculation are in a good agreement with the measured voltages.

1. Introduction

Voltage transformers in a power system are designed to transform voltages from high voltage on a transmission level to low voltage necessary for relays and measurement equipment. During their operation, the voltage transformer's windings are subjected to high frequency transient overvoltages due to switching operations and lightning strikes. Transient overvoltages can potentially lead to excessive electric stress in the transformer windings and insulation and consequently result in insulation failure and breakdown. In order to adequately dimension the transformer windings and interturn or interlayer insulation, the transient voltage distribution needs to be obtained on a design level. Considering the typical winding geometry of a voltage transformer, which normally entails a very large number of turns and discrete interlayer insulations, this is a complex task.

In order to model and simulate the transient voltage distribution, an equivalent electric circuit representation of distributed or lumped parameters is developed [1]. It is of great interest to calculate the equivalent parameters accurately since they have a major influence on transient voltages. They are commonly calculated using simple analytical formulas [1–3] or finite element method (FEM) based calculations [4–7]. Calculation of lumped circuit parameters can be performed using genetic algorithm [8]. Due to a complex geometry of system model, order reduction techniques can be employed [9]. In this paper, boundary element method and integral equations approach are employed to calculate the equivalent electric circuit parameters. The solvers for evaluating the parameters are self-developed and presented in Section 2.

The system of equations is often formulated using the methods based on Dommel's approach [10–14]. Transient analysis can be performed in frequency domain [15,16] and time domain [4]. In this paper, a transient solver specially developed for this purpose, and based on formulations made by Dommel, is presented. Measurement based analysis of transformers can be based on frequency response analysis (FRA) methods [17].

Analysis of very fast transient overvoltages is of great interest and it has been the topic of various papers which mostly revolve around power transformers [18–26]. Even though some of those methods can be used in voltage transformers, their specific design differences make the transient analysis approach slightly different. The position of voltage transformers in substations and the large number of turns in the high voltage winding can lead to highly nonlinear voltage distribution during fast transients. This can result in high interturn voltages which can be hazardous to the insulation.

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The purpose of this paper is to present the methodology for simulating the overvoltage distribution along the high voltage winding of the voltage transformer. As such, its goal is different from most of the EMTP (Electromagnetic Transients Program)-type programs used for simulation of the transferred overvoltages between the power transformers' windings that are beneficial to network operators. Presented method relies on the detailed geometry and material data of the transformer. Obtaining the interturn voltages can help transformer manufacturers during the design stage of the voltage transformer production.

The results of the presented calculation approach are benchmarked against the measurements. For testing purposes, a special model of an inductive, SF_6 insulated voltage transformer active part was acquired. The model consists of the magnetic core, secondary winding and a primary winding with a large number of custom-made measurement points.

2. Calculation methods

In order to calculate the voltage distribution over the transformer winding, a lumped parameter circuit model of the winding is applied. Methods used to obtain the capacitance and the inductance matrices are described in the following subsections. Resistance matrix consists of resistances at 50 Hz. Since the large number of high-voltage winding turns have to be grouped in order to model the winding, it is possible to simulate them as solid thick conductors that behave as a stranded coil in which the current density is uniform. Due to the nature of the winding configuration in instrument transformers, the simple DC calculation, omitting the influence of skin effect and proximity effect is sufficient.

2.1. Capacitance calculation

Capacitances are calculated by a method based on the boundary element method (BEM). As a result of a boundary-only discretization, usage of BEM enables the reduction of the problem by one dimension. Capacitances of the transformer winding can be assumed to be independent of frequency and are calculated using the electrostatic analysis.

Electric field potential $\varphi\left(\vec{r}\right)$ at any point $\vec{r}$ due to the distribution of the surface charge density $\sigma\left(\vec{r}'\right)$ is represented by Ref. [27]:

$$\varphi\left(\vec{r}\right)=\frac{\int_{S'}\sigma\left(\vec{r}'\right)\mathrm{d}S'}{4\pi\varepsilon|\vec{r}-\vec{r}'|}, \tag{1}$$

where $\vec{r}$ is the vector distance of a calculation point, $\vec{r}'$ is the vector distance of a referent point on a source, and S' is the surface of two-dimensional elements.

Constant surface charge density is assumed on each segment. The expression for the electric field potential on the surface segments can be written as:

$$\varphi\left(\vec{r}\right)=\sum_{k=1}^{N}\frac{\int_{\Delta S_k}\sigma_k\left(\vec{r}'\right)\mathrm{d}S'}{4\pi\varepsilon|\vec{r}-\vec{r}'|}, \tag{2}$$

where N is the number of segments, and ΔS_k is the surface of each segment.

Unknown coefficients σ_k are obtained from known potentials by using the collocation method which gives a densely populated system matrix.

Total charge on the j-th conductor influenced by the charge on the i-th conductor Q_{ij} is:

$$Q_{ij}=\int_{S_j}\sigma_j\mathrm{d}S_j=\sum_{k=1}^{N}\sigma_{kj}S_{kj}, \tag{3}$$

where σ_{kj} is the surface charge density on the k-th segment of the j-th conductor and S_{kj} is its surface, while N is the number of the finite segments of j-th conductor.

Capacitance matrix elements are calculated with equation:

$$C_{ij}=\frac{Q_{ij}}{\varphi_i-\varphi_j},\quad i\neq j. \tag{4}$$

Here, φ_i and φ_j are the potentials of i-th and j-th conductor.

2.2. Inductance calculation

Inductance calculation is based on the method for calculating inductances of coaxial circular coils in air with rectangular cross section and uniform current densities presented in Ref. [28]. The influence of the iron core on the inductance is essentially negligible since the secondary winding is short-circuited during the lightning impulse test. The problem is therefore considered linear.

Assuming that the current densities are uniform over windings' conductor cross sections, energy W stored in the magnetic field is:

$$W=\frac{\mu_0 I^2}{4(Z_2-Z_1)^2(R_2-R_1)^2}\int_{\varphi=0}^{\pi}\int_{z=Z_1}^{Z_2}\int_{Z=Z_1}^{Z_2}\int_{r=R_1}^{R_2}\int_{R=R_1}^{R_2}\frac{\cos\varphi rR\,\mathrm{d}r\,\mathrm{d}R\,\mathrm{d}z\,\mathrm{d}Z\,\mathrm{d}\varphi}{\sqrt{r^2+R^2-2rR\cos\varphi+(z-Z)^2}}. \tag{5}$$

Using quintuple integration, both height and thickness of the observed conductor is taken into account. Here, (Z_2-Z_1) represents the height of the coil, R_1 is the inner and R_2 the outer radius of the coil, and φ is the angular coordinate in a cylindrical coordinate system.

Eq. (5), when compared with $W=\frac{1}{2}LI^2$, gives the term for the self-inductance L of the coaxial circular coil with rectangular cross section:

$$L=\frac{\mu_0}{(Z_2-Z_1)^2(R_2-R_1)^2}\int_{\varphi=0}^{\pi}\int_{z=Z_1}^{Z_2}\int_{Z=Z_1}^{Z_2}\int_{r=R_1}^{R_2}\int_{R=R_1}^{R_2}\frac{\cos\varphi rR\,\mathrm{d}r\,\mathrm{d}R\,\mathrm{d}z\,\mathrm{d}Z\,\mathrm{d}\varphi}{\sqrt{r^2+R^2-2rR\cos\varphi+(z-Z)^2}}. \tag{6}$$

Similarly, the equation for the total energy stored in the magnetic field gives the expression for the mutual inductance M of a pair of coaxial circular turns [28]:

$$M=\frac{\mu_0}{(Z_2-Z_1)(Z_4-Z_3)(R_2-R_1)(R_4-R_3)}\int_{\varphi=0}^{\pi}\int_{r=R_1}^{R_2}\int_{R=R_3}^{R_4}\int_{z=Z_1}^{Z_2}\int_{Z=Z_3}^{Z_4}\frac{\cos\varphi rR\,\mathrm{d}r\,\mathrm{d}R\,\mathrm{d}z\,\mathrm{d}Z\,\mathrm{d}\varphi}{\sqrt{r^2+R^2-2rR\cos\varphi+(z-Z)^2}} \tag{7}$$

where R_1 and R_2 are the inner and the outer radii of the first coil, R_3 and R_4 are the inner and the outer radii of the second coil, (Z_2-Z_1) represents the height of the first coil, and (Z_4-Z_3) represents the height of the second coil. Therefore, r and z are radial and axial coordinates of source field point varied over the cross section of one coil, while R and Z are the coordinates of the field influencing point varied over the cross section of the other coil. When calculating the diagonal elements (self-inductance), the bounds of the two