Development of a Simplified Transformer Model for Transient Studies

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The transformer is one of the main components within an electrical power system, because a failure in the transformer can interrupt the continuous supply of electrical energy. One of the faults to which the transformers are exposed is due to electromagnetic transients,that may be generated from switching operations or electrical faults. This work presents the analysis of the electromagnetic transients in a power transformer of 2.5 MVA. The paper contribution is related to the development of a simplified power transformer model for transient analysis with the aim to reduce the computational simulation time, and also to be able to have a reduced order model for the transient analysis of an electric power system. The analysis is carried out by determining the capacitances related to the transformer, the analysis of the initial voltage distribution in the transformer windings obtained from a simplified model. The results will be shown and discussed in the full paper, where the entire model of the transformer windings will be presented.

***Index Terms*— Winding transformer, initial voltage distribution, transient.**

I. Introduction

Transformers are defined as static electric devices, and used in electrical power systems to transfer energy between two circuits through the use of electromagnetic induction. The complexity of the system leads to a variety of transmission and distribution voltages. Transient voltages are the main cause of failure reported in the power system, with the transformer being one of the most affected elements. The calculation of the internal stress and the modeling of the transformer are required to analyze whether transients by switching operations, lighting and failures to earth actually provoke these surges. When voltage surges reach the transformer terminals, the voltage between turns and between layers can severely damage the inner insulation of the transformer [1].

In a transient phenomenon at the transformer terminals, an overvoltage may be present in the transformer windings if the protection devices do not operate quickly. In order to analyze the response of a transient phenomenon in the winding, it can be represented by a uniformly distributed circuit of inductances and capacitances in series. When a voltage impulse is applied to this circuit, the initial voltage distribution is completely determined by a capacitive network [2]. The winding inductance does not affect the initial voltage distribution, since the magnetic field requires a finite amount of time to induce a current through an inductor; the initial voltage distribution is predominantly determined by the capacitances in the network. The distribution constant (α) is defined by the relation (1), where C_g and C_s are the ground and series capacitances, respectively.

$$\alpha = \sqrt{\frac{C_g}{C_s}} \tag{1}$$

Figure 1 illustrates the effect of α on the initial voltage distribution along the winding, as shown by curve a, since there is a difference between initial and final voltage distributions, a transient phenomenon takes place.

This paper presents a simplified network of capacitances for representing the transients in the windings of a power transformer. The model can be used in commercial electromagnetic transient software where the lack of parameters is normally a problem for engineers.

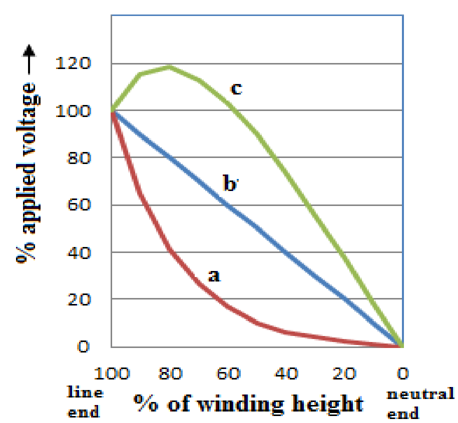

Fig. 1. Impulse voltage distribution within the transformer winding. a) Initial distribution (b) Final distribution (c) Maximum voltage to ground

II. Calculation of capacitances

The capacitance in the transformer winding significantly affects the voltage distribution [3]. In order to estimate the voltage distribution within the transformer, in the transient winding, the knowledge of capacitances in series and ground is essential [4]. The capacitance between two concentric windings (or the inner winding and the core), is given by (2):

$$C_{gw} = \frac{\varepsilon_0 \pi D_m H}{(t_{oil}/\varepsilon_{oil}) + (t_{solid}/\varepsilon_{solid})} \tag{2}$$

where D_m is the mean diameter of the space between the concentric windings, t_{oil} and t_{solid} are the thicknesses of the oil and the solid insulation between the windings, and H is the height of the windings, ε_0 is the permittivity of the vacuum, ε_{oil} and ε_{solid} are the permittivity of the oil and the solid insulation, respectively.

The capacitance between the outer winding and the tank is defined by (3).

$$C_{gt} = \frac{2\pi\varepsilon_0 H}{Cosh^{-1}\left(\dfrac{s}{R}\right)}\left[\frac{t_{oil}+t_{solid}}{(t_{oil}/\varepsilon_{oil})+(t_{solid}/\varepsilon_{solid})}\right] \quad (3)$$

where R and H are in this case, radius and height of the winding, respectively, s is the distance from the axis of the winding to the tank.

The turn to turn capacitance is given by (4).

$$C_t = \frac{\varepsilon_0\varepsilon_p\pi D_m\left(w+t_p\right)}{t_p} \quad (4)$$

where D_m is the average winding diameter, w is the bare conductor width in the axial direction, t_p is the total thickness of the paper insulation, ε_p is the permittivity of the paper. It is possible to calculate the value of the capacitance layer to layer between two layers of turns, and it is given by (5).

$$C_{ll} = \frac{n_t(n_t+1)(2n_t+1)}{6^2} lC_t \quad (5)$$

where l is the average of the length of a turn and n_t is the number of turns.

III. Transient Transformer Simplified Model

Models of transformer windings for transient studies require the application of a capacitive network for their study [5], to calculate transient voltage surges in transformer windings and to improve their insulation design [6]. In this paper, we present the analysis of a simplified model of the capacitive network to reduce the computational time in comparison to a complete model. Transformer design data are presented in table 1.

The voltage distribution along the winding can be calculated from a capacitive network [7]. This model presents the minimum number of elements in the capacitive network. The simplified model of the transformer windings is shown in Fig. 2, it is composed of capacitances between layers, core to low voltage, capacitance between low voltage and high voltage, and capacitance between the external winding and tank.

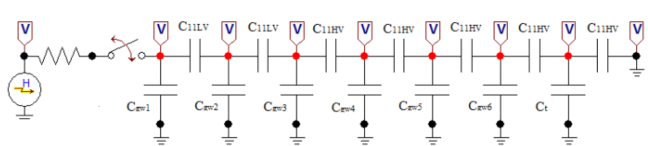

Fig. 2. Simplified transient transformer model.

IV. Results

The voltage distribution coefficient depends on the capacitances values and it defines the behavior of the voltage within the windings. The initial results of the response to the transients of the simplified model are shown in Fig. 3. Further results and comparisons against finite element models will be presented in the full paper.

TABLE I
Transformer Main Design Parameters

Transformer Data		
Power	2.5	MVA
High voltage	13200/7621	Volts
Connection	Star/Delta	
Low voltage	690	Volts
Diameter inside (HV)	39.9	cm
Diameter outside (HV)	48	cm
Height (HV.)	71.2	cm
Diameter inside (LV)	28.4	cm
Diameter outside (LV)	36.1	cm
Height (LV)	75.2	cm
Relative oil permittivity	2.25	
Relative permittivity of paper	4.2	
Permittivity of vacuum	8.854E-12	F/m

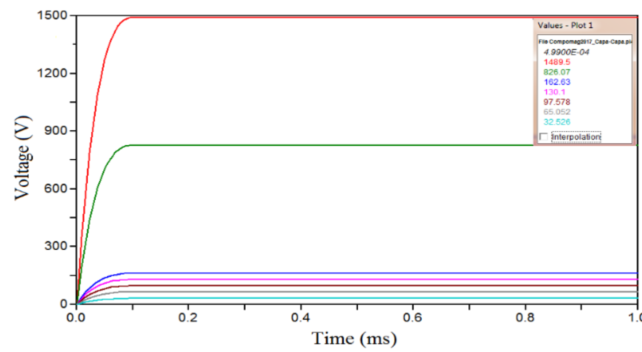

Fig. 3. Simplified model voltage distribution.

V. Conclusions

In this work, we have presented a methodology for determining a simplified transient model to reduce the computational time and to give the power analyst engineer a transformer model for his power system studies. An analysis of the transients in the transformer windings considering the geometry of the design is also given. A response of the voltage distribution is observed in the capacitances network of the symmetric model of the transformer, which must be compared with a finite element model, the above is to evaluate the model accuracy, the results of the comparison will be presented in the full paper.

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