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Analytical calculation of detailed model parameters of cast resin dry-type transformers

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ABSTRACT

Non-flammable characteristic of cast resin dry-type transformers make them suitable for different kind of usages. This paper presents an analytical method of how to obtain parameters of detailed model of these transformers. The calculated parameters are compared and verified with the corresponding FEM results and if it was necessary, correction factors are introduced for modification of the analytical solutions. Transient voltages under full and chopped test impulses are calculated using the obtained detailed model. In order to validate the model, a setup was constructed for testing on high-voltage winding of cast resin dry-type transformer. The simulation results were compared with the experimental data measured from FRA and impulse tests.

1. Introduction

Transformers in operation are subject to various kinds of overvoltages caused by lightning strikes, switching operations or system disturbances. For designing the insulation of a transformer suitable for all kinds of overvoltages, the voltage stresses within the windings need to be determined. For this purpose, voltage distributions within the transformer windings for the specific test voltages are calculated. Generally, under normal conditions in a steady state, the voltage is distributed linearly inside the winding. For impulse voltage, the voltage distribution in the winding is not linear and for the calculation of impulse voltage distribution in the windings, they are required to be simulated in terms of an equivalent circuit consisting of lumped R, L, C elements. In this paper, the transient model of cast resin dry-type transformers is presented.

Cast resin dry-type transformers are the most suitable transformers for distribution of electricity in high degree of safety. Dry-type transformers compared with oil-immersed are lighter and non-flammable. They also do not have contaminating substances such as oil. Non-flammable characteristic of these transformers make them suitable for residential and hospital usages. Fig. 1 shows the structure of one phase of a cast resin dry-type transformer consisting of low and high-voltage windings. Low-voltage winding of this transformer is made of a full-height aluminum sheet wounded simultaneously with insulation layer. High-voltage winding is constructed from several series disks that every disk is made of aluminum foils interleaved with insulating layers. After the high-voltage winding is wounded, it is placed in a mold and cast in a resin under vacuum pressure. Lower sound levels are realized as the winding is encased in solid insulation. Filling the winding with resin under vacuum pressure eliminates voids that can cause corona. With a solid insulation system, the winding has superior mechanical and short-circuit strength and is impervious to moisture and contaminants.

Transformer transient modeling has been a subject of investigation and research for a century. In the 1954, Lewis [1] proposed that the transient behavior of a transformer winding can be studied with an equivalent ladder-type network composed of a finite number of uniform sections. Lewis's model was applicable only to a uniform winding. Furthermore, the representation of inductive coupling effect was included by modifying the self-inductance value. Subsequently with the advent of digital computers, McWhirter et al. [2], studied the same problem based on an equivalent circuit approach. Their model still suffers the restrictions arising from the size and symmetry of the equivalent circuit used to represent the winding. Dent et al. [3] used an equivalent circuit of the same general form as the proposed by Lewis, but with certain differences. Dent's model can represent a non-uniform winding and the effect of inductive coupling between sections is taken into account. After Dent's paper was published, most of the researchers in this area, concentrated their attention on the calculation of parameters of

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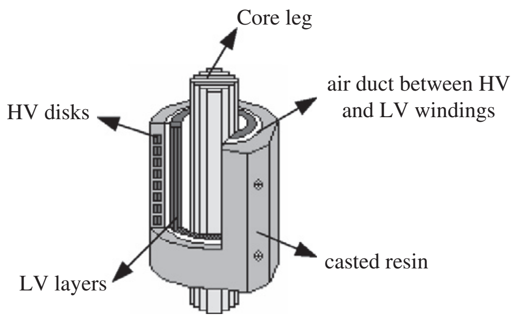

Fig. 1. Schematic view of cast resin transformer.

the equivalent circuits. Okuyama [4] calculated the self and mutual inductances of transformer winding through introduction of some correction factors obtained from experiment. Stein [5] and Kawaguchi [6] proposed a method to calculate equivalent series capacitance by computing the electrostatic energy stored in the coils. An equivalent network for a multi-winding transformer has been reported in [7] in which the conventional ladder network used for a single winding consisting of lumped elements is extended for multiple windings. De Leon and Semlyen [8] used the image method to calculate turn to turn leakage inductance and the charge simulation method to calculate the capacitance between turns and from turn to ground. They also proposed a detailed model of losses for accurate calculations [9]. Such a model, although very accurate, may be prohibitive from the point of time and memory of computers.

Until the introduction of the computer, there was a lack a practical analytical formulas to compute the mutual and self-inductances of coils with an iron core. Rabins [10] developed an expression to calculate mutual and self-inductances for a coil on an iron core based on the assumption of a round core leg and infinite core yokes, both of infinite permeability. Fergestad and Heriksen [11] improved Rabins's inductance model in 1974 by assuming an infinite permeable core except for the core leg. They also introduced a method of calculating voltage oscillations in multi-winding transformers during impulse test [12]. White [13] derived an expression to calculate the mutual and self-inductances in the presence of an iron core with finite permeability under the assumption of an infinitely long iron core. Wilcox et al. [14,15] derived a frequency-dependent impedance formula to calculate self and mutual impedances of coil sections on the assumption of a solid homogeneous core. Application of this formula accounts for the effects of transient flux penetration into the transformer core, including the effects of frequency-dependent inductances and transient eddy currents in the core laminations.

Nowadays, numerical methods especially finite element method (FEM) has become more popular between engineers. The most important advantage of FEM is that any complicated geometry is solvable by this method because the formulation of FEM is independent of the geometry. Until now many works about important phenomena of transformers such as inductance calculation and electric field analysis have been done successfully by this method [16,17]. 3D FEM computation of the high frequency parameters using a 3D complex permeability is presented in [18,19]. Frequency-dependent losses due to eddy currents are represented in [20] by means of a frequency-dependent complex permeability for iron core. Although FEM is an accurate method but it does not manifest basic concepts of the problem. Instead, using analytical methods makes it possible to directly involve with solving of equations which will provide a deep perception of the problem. On the other hand the accuracy of the FEM solution is usually a function of the mesh resolution while it requires substantial amounts of computer and user time. So analytical methods are still used and privileged by many designers especially where a quick theoretical solution of the problem is needed. However it will be so beneficial if the analytical results could be verified by the FEM and then modified if it is required. This is the main procedure that is used in this paper for calculation of detailed model parameters of cast resin dry-type transformers.

Up to now, all works done on transformer transients are for oil filled transformers and this was not done for dry-type transformers yet. As it is clear from its name, dry-type transformer do not have any oil and instead a solid dielectric material such as resin is used in its structure. The shape of conductor, types of dielectric materials and the structure of windings of dry-type transformers are different from oil filled transformers. Also the shape of electrical field is rather different. On the other hand, the surrounding air as an insulator and cooler is running in the space between windings and tips of bars. Because of large difference of air dielectric coefficient with other solid insulators of dry-type transformers (about four times), the large amount of voltage in this kind of transformers is dropped on air spaces and with respect to low resistance of air in compare with other solid materials, it's important to have information about the size and the way of electrical field distribution in transients to make sure about tolerance of air spaces. Therefore, study and research on dry-type transformers seems to be important and useful. In this paper we tried to study and simulate the transient behavior of dry-type transformers as a new generation of distribution transformers by using analytical formulas. Also all calculated parameters are compared with the FEM results and if it was necessary, correction factors are introduced for modification of the analytical solutions.

2. The equivalent circuit of dry-type transformer

Equivalent circuit used for modeling of dry-type transformers is shown in Fig. 2. In this case, each section of LV winding which is placed between two air canals and every disk of HV winding is considered as a branch in the equivalent circuit. Every branch is composed of parallel connection of self-inductance of L_i and series capacitance of K_i. There is a mutual inductance between every pair of branches ($L_{ij}, L_{ik}, \ldots$). Regarding that the last layer of LV is creating an equipotential surface in front of other layers of LV, only the capacitances of the last layer of LV to HV disks are considered which are shown with C_p. The C_e is the capacitance of the first layer of LV to the core which is grounded. R_i is ohmic losses of each branch and G_i, G_p and G_e are conductance which is representing the dielectric losses.

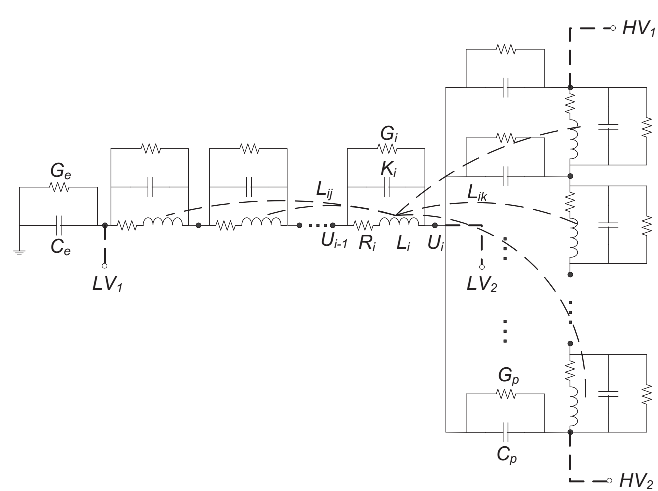

Fig. 2. Equivalent lumped parameter circuit.