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Effect of DC biasing in 3-legged 3-phase transformers taking detailed model of off-core path into account

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ABSTRACT

Modeling of 3-legged, 3-phase transformers under DC biasing is a challenging topic due to the need to an adequate representation of flux paths beyond the active part including the tank. The main contribution of this paper is to present a new dual circuit model which takes the off-core flux path into consideration. Tank elements including the walls, bottom and cover are considered with a detailed as well as a steady state equivalent circuit. Having a new model, the behavior of a test transformer is studied under DC excitation in terms of magnitude and harmonic content of exciting current as well as reactive and active power flowing through the transformer.

1. Introduction

Modeling of transformers subjected to DC excitation is the topic of several papers published recently [1–5]. DC biasing of transformer is mainly due to the event of geomegnetically induced currents (GIC) [6,7]. This is also observed in HVDC converter transformers [8]. A DC current flowing through the windings generates a DC flux in the core with a magnitude depending on the magnitude of the DC current, number of turns in the windings carrying the current and reluctance of the DC flux path. This impressed DC flux shifts the operating point of the magnetizing characteristic and causes half cycle saturation in the core leading to an increase in harmonic currents and reactive power consumption [9]. The important aspects to consider for analyzing a DC biased power transformer are the topology of the core, the nonlinearity of ferromagnetic materials, the coupling and connection of coils, and the system series resistances. The models used for analyzing DC biasing situation are categorized in two FEM-based models [9–11], and magnetic circuit models [12–19]. The FEM models can be very accurate particularly for the cases where power losses and temperature rises in the tank and other metallic components are of interest. However, the requirement of detailed design information and the computational burden makes the application of FEM modeling not viable for power system studies.

The models based on magnetic circuit theory have been widely used for the analysis of GIC effects on transformers. Some models consider only very basic magnetic circuits lacking a topological representation of the core structure and DC flux paths, and using only simple calculation of model parameters. More advanced models proposed for GIC studies are based on a topologically correct core representation modeling, independent core sections and air-flux paths [1,17–19].

DC flux impressed in the windings is in the same direction for all legs, therefore the flux will flow through the zero sequence flux (ZSF) path. In the case of three-phase three-leg constructions, the ZSF goes outside the core, flows through the air gap and tank, and returns to the core. For five-leg constructions, the lateral legs act as return paths for ZSF. As long as they do not saturate, the air-paths and the tank will have no considerable effect. For high level of DC excitation the lateral legs saturate and part of the flux flows outside the core through the oil and the tank leading to increased losses and the temperature rise in the tank [19]. This paper contributes with a modeling approach for analyzing the effect of DC excitation in power transformers with focus on off-core flux path modeling. A detailed equivalent circuit is presented for the mentioned off-core path including the non-magnetic space beyond the windings and the tank. Applying the model to a 3-legged 3-phase transformer, the impact of DC flux offset is studied in terms of

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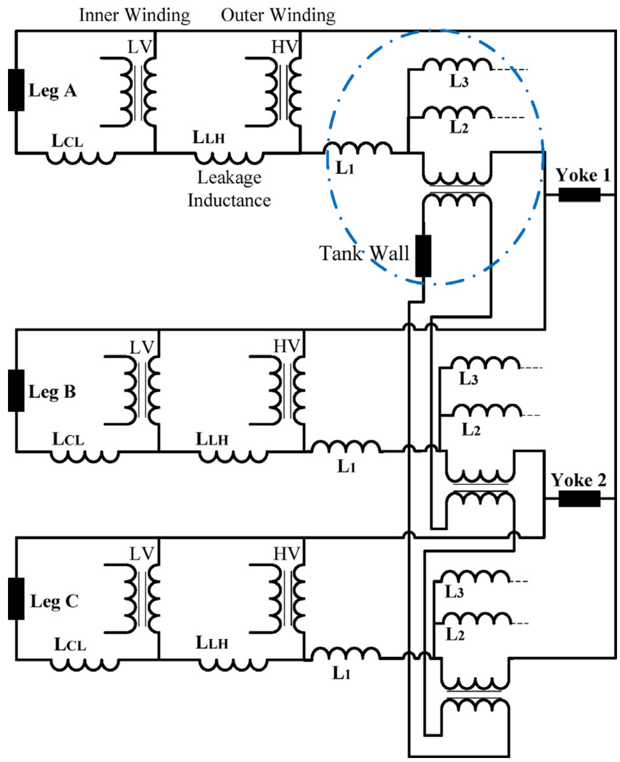

Fig. 1. Transformer equivalent circuit.

Table 1
Summary of the simulation cases.

	Boundary condition			
	Wall	Cover	Bottom	
Case 1	N	T	N	$L_{eq1} = L_1 + (L_3 + L_5)\|\|(L_2 + L_4)$
Case 2	T	T	T	$L_{eq2} = L_1$
Case 3	N	T	T	$L_{eq3} = L_1 + L_2\|\|L_3$
Case 4	N	T	N	$L_{eq4} = L_1 + (L_3 + L_5)\|\|L_2$
Case 5	N	N	T	$L_{eq5} = L_1 + (L_2 + L_4)\|\|L_3$

harmonic content of the magnetizing current, increase of the reactive and active power as well as copper losses in the windings. Section 2 describes the transformer model used in the simulations and the equivalent circuits proposed for the off-core flux path. Section 3 describes the system topology and simulation results for a transformer under study. Finally, Section 4 discusses on differences of the results obtained from three different alternatives for the off-core path and how the tank influences these studies.

2. The proposed model of transformer

Fig. 1 shows overall dual circuit model of 3-legged 3-phase transformer considered for analyzing DC biasing condition. The difference between this dual equivalent circuit and conventional ones is the use of detailed circuit for off-core flux path as shown within blue dashed circle for phase A. There is a same circuit for other two phases. Since the tank elements encompasses all three phases, there should be a magnetic coupling between the phases through these elements. This fact is considered by means of ideal transformers with unit turns ratio connecting the tank elements to each phase as shown in Fig. 1. In this figure the circuit corresponding to the cover and bottom is not shown in order to make it more readable. Fig. 2 illustrates how the mentioned off-core equivalent circuit is obtained from the magnetic structure. As can be seen, the linear inductances (L_1, ..., L_5) represent non-magnetic space beyond the windings (oil gaps) and non-linear branches represent the tank elements.

In order to calculate the linear inductances (L_1, L_2, ..., L_5) 3D-FEM is employed using the commercial software ANSYS-Maxwell v.15. In the FEM simulations, the tank elements (The wall, cover, and bottom) are excluded and a set of boundary conditions are set to the tank surfaces. In fact, the equivalent impedance of tank elements in the circuit of Fig. 2c is set to extreme values of zero or infinite. These zero and infinite values are achieved by set of flux tangential (T) and flux normal (N) boundary conditions to the each element, respectively. Based on different combination of the boundary conditions, 5 simulation cases are defined as shown in Table 1 where, $L_{eq,i}$ is the equivalent off-core inductance seen from the terminal in Fig. 2c for the ith simulation case. As an example, flux tangential boundary condition is set to all tank surfaces in simulation case 2. This is corresponding to zero tank impedances in the circuit of Fig. 2c. Thus, the equivalent off-core inductance seen from the terminal becomes L_1. Accordingly, the i^{th} simulation case leads to an equation with respect to the circuit parameters (L_1, ..., L_5) and the $L_{eq,i}$. Solving this set of equations (Table 1) gives the circuit parameters. It should be noted that the off-core inductance ($L_{eq,i}$) is directly obtained from 3D-FEM in each simulation case. In these simulations, once the inductance matrix is calculated by means of the energy method, the open circuit-zero sequence (OC-ZS) inductance is calculated by the approach stated in Appendix 1. Neglecting the reluctance of the main legs and the yokes effect, the OC-ZS inductance becomes equal to the equivalent off-core inductance ($L_{eq,i}$).

In order to represent the tank elements two equivalent circuit are used. The first one is a simplified parallel equivalent circuit (PEC) as shown in Fig. 3. Non-linear inductance represents DC magnetization characteristic of the tank elements and non-linear resistance

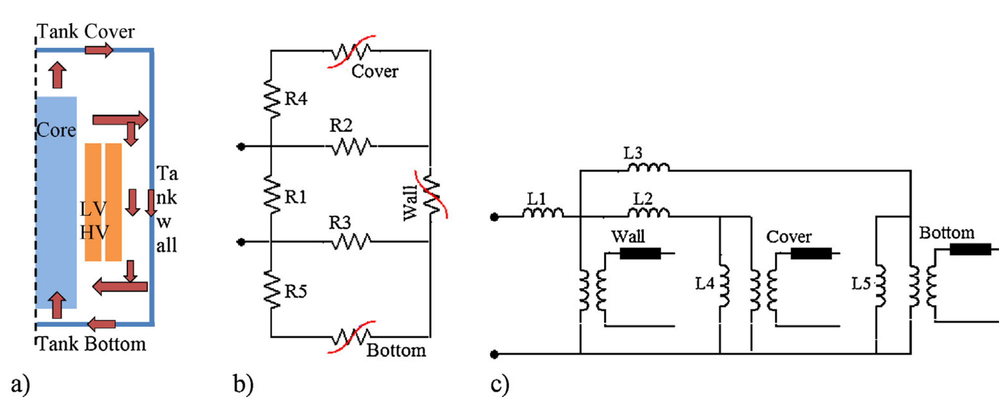

Fig. 2. (a) Off-core flux path, (b) magnetic circuit and (c) electric equivalent circuit obtained from duality principle.