Influence of Frames, Flitch Plates and Shielding Under the Total Losses of a Single-Phase Shunt Reactor

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Abstract — The use of numerical technologies, e. g., 3D and 2D simulations, are essential to verify some critical aspects of design and performance on shunt reactors. This paper presents the study of influence of frames, flitch plates and shielding under the total losses of a single-phase shunt reactor. The simulated core losses are compared with measurements. The losses in frames, flitch plates and shielding are more difficult to measure. So, these simulation results are compared with analytical expressions especially developed for it. The contribution of this paper consists of using the finite element method as a tool to correct the total losses analytical equations.

I. INTRODUCTION

Shunt reactors and series reactors are widely used in the system to limit the overvoltage or to limit the short-circuit current. With more high-voltage overhead lines for long transmission distance and increasing network capacity, both types of reactors play an important role in the modern network system. Shunt reactors represent the large capital investment in the distribution section of a power system. Efficiency and cost reduction have become so important for the manufacturers [1]. An important factor in the design of shunt reactors is the total loss evaluation.

Fig. 1 shows the transverse cut plane of single-phase shunt reactor design (*left*) and the detailed view of an iron core divided by air gaps (*right*).

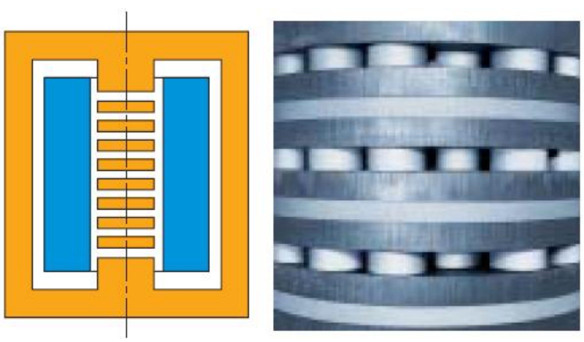

Fig. 1. Transverse cut plane of single-phase shunt reactor design with iron core and magnetic return circuit (*left*); and the detailed view of an iron core divided by air gaps (*right*).

Fig. 2 shows the core, the frames and the flitch plates of a shunt reactor. Frames (also called as yoke beams), serving to clamp yokes and support windings, are in vicinity of stray magnetic field of windings. The loss in frames made up of mild steel, aluminum and non-magnetic steel are compared. It has been shown that the losses in frame and tank have mutual effect on each other. Stray flux departing radially through the inner surface of windings hits fittings such as flitch plates mounted on the core (see Fig. 2). On the surface of the flitch plate the stray flux density may be much higher than that on the tank. Hence, although the losses occurring in a flitch plate may not form a significant part of the total loss of a reactor, the local temperature rise can be much higher due to high value of incident flux density and poorer cooling conditions. The loss density may attain levels that may lead to a hazardous local temperature rise if the material and type of flitch plate are not selected properly [2]. The higher temperature rise can cause deterioration of insulation in the vicinity of flitch plate, thereby seriously affecting the reactor life.

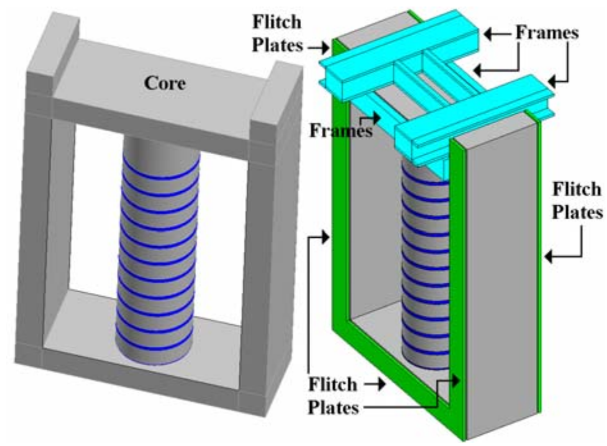

Fig. 2. The core, the frames and the flitch plates of the reactor analyzed.

The use the magnetic shunt or aluminum screen decreases the eddy current and overheating problems in the tank wall [1]. Moreover, in large transformers they are commonly fitted with magnetic bypass plates (MBP) near the coil ends to reduce the eddy current losses. In this paper, the influence of MBP on the total losses of a single-phase shunt reactor is studied and the losses on the tank wall are calculated for three cases: the tank wall with magnetic shunt, with aluminum screen or without any shielding. The optimal size, material and structure of tank shielding are suggested. The simulated core losses are compared with measurements. The losses in frames, flitch plates and shielding are more difficult to measure. So, these loss simulation results are compared with analytical expressions especially developed for it.

In the last decade, rapid developments have taken place in the design, analysis and manufacturing technologies of reactors. The increase in current and voltage ratings calls for special design and manufacturing considerations. With the increase in MVA ratings, the weight and size of reactors approach or exceed transport and manufacturing capability limits. Furthermore, due to the ever-increasing competition in the global market, there are continual efforts to optimize the material content in reactors. This optimization demands a revision of the analytical equations to determine the total losses of a single-phase shunt reactor.

The contribution of this paper consists of using the finite element method (FEM) as a tool to correct the total losses analytical equations. The single-phase shunt reactor modeling is realized using a magnetodynamic formulation. The iron loss complete model includes hysteresis losses, eddy current losses and the anomalous losses.

II. MAGNETODYNAMIC FORMULATION AND IRON LOSSES

A bounded domain Ω of the two or three-dimensional Euclidean space is considered. Its boundary is denoted Γ. The equations characterising the magnetodynamic problem in Ω are:

$$\operatorname{curl} \mathbf{h} = \mathbf{j}, \quad \operatorname{curl} \mathbf{e} = -\partial_t \mathbf{b}, \quad \operatorname{div} \mathbf{b} = 0, \tag{1a-b-c}$$

$$\mathbf{b} = \mu\, \mathbf{h}, \quad \mathbf{j} = \sigma\, \mathbf{e}, \tag{2a-b}$$

where $\mathbf{h}$ is the magnetic field, $\mathbf{b}$ is the magnetic flux density, $\mathbf{e}$ is the electric field, $\mathbf{j}$ is the electric current density, including source currents $\mathbf{j}_s$ in Ω_s and eddy currents in Ω_c (both Ω_s and Ω_c are included in Ω), μ is the magnetic permeability and σ is the electric conductivity.

The boundary conditions are defined on complementary parts Γ_h and Γ_e, which can be non-connected, of Γ,

$$\mathbf{n} \times \mathbf{h}\big|_{\Gamma_h} = 0, \quad \mathbf{n} . \mathbf{b}\big|_{\Gamma_e} = 0, \quad \mathbf{n} \times \mathbf{e}\big|_{\Gamma_e} = 0, \tag{3a-b-c}$$

where $\mathbf{n}$ is the unit normal vector exterior to Ω. Furthermore, global conditions on voltages or currents in inductors can be considered [3].

A. *Magnetic vector potential **a**-formulation*

The $\mathbf{a}$-formulation, with a magnetic vector potential $\mathbf{a}$ and an electric scalar potential v, is obtained from the weak form of the Ampère equation (1a) and (2a-b) [3], i.e.

$$\begin{aligned}(\nu \operatorname{curl} \mathbf{a}, \operatorname{curl} \mathbf{a}')_\Omega + < \mathbf{n} \times \mathbf{h}_s, \mathbf{a}' >_{\Gamma_h} + (\sigma\, \partial_t\, \mathbf{a}, \mathbf{a}')_{\Omega_C} + \\ + (\sigma \operatorname{grad} \mathrm{v}, \mathbf{a}')_{\Omega_C} - (\mathbf{j}_s, \mathbf{a}')_{\Omega_s} = 0, \quad \forall \mathbf{a}' \in F_a(\Omega),\end{aligned} \tag{4}$$

where $\mathbf{n} \times \mathbf{h}_s$ is a constraint on the magnetic field associated with boundary Γ_h of the domain Ω and $\nu = 1/\mu$ is the magnetic reluctivity. $(. \,, .)_\Omega$ and $<. \,, .>_\Gamma$ denote a volume integral in Ω and a surface integral on Γ of products of scalar or vector fields. $F_a(\Omega)$ denotes the function space defined on Ω which contains the basis and test functions for both vector potentials $\mathbf{a}$ and $\mathbf{a}'$. Using edge finite elements for $\mathbf{a}$, a gauge condition associated with a tree of edges is generally applied.

In evaluating iron losses with FEM, samples of the material under analysis are normally tested on the Epstein's frame. To obtain only the hysteresis losses as a function of the induction the measurements must be made at very low frequencies. Experimental results obtained for iron sheets at a fixed frequency and for several induction values are plotted in a curve which allows to obtain the hysteresis model parameters. The eddy current losses are calculated, at the rated feeding frequency, using a theoretical equation [4]. Finally, the anomalous or excess losses curve are obtained by subtracting from the total iron losses experimental curve the sum of eddy current and anomalous curves. With this method also called losses segregation it is possible to analyze the behavior of each component and their influence on the total losses.

III. RESULTS

The experimental example considered for validation of the proposed approach is a single-phase shunt reactor showed in Fig. 2. The tangential and radial magnetic flux density along the height of tank wall is shown in Fig. 3 and Fig. 4, respectively. In these figures it is possible to note that the amplitude of magnetic flux density decreases when the shunt is used.

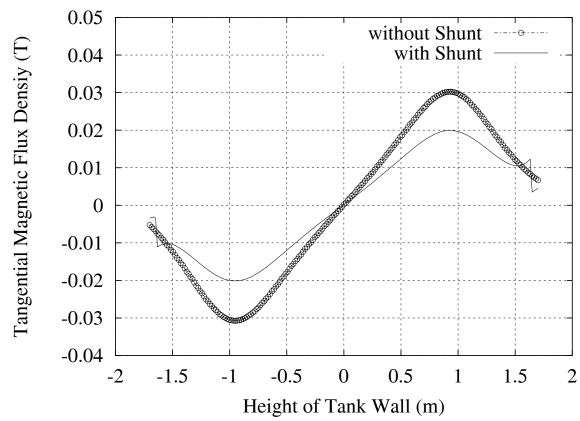

Fig. 3. Tangential magnetic flux density along the height of tank wall.

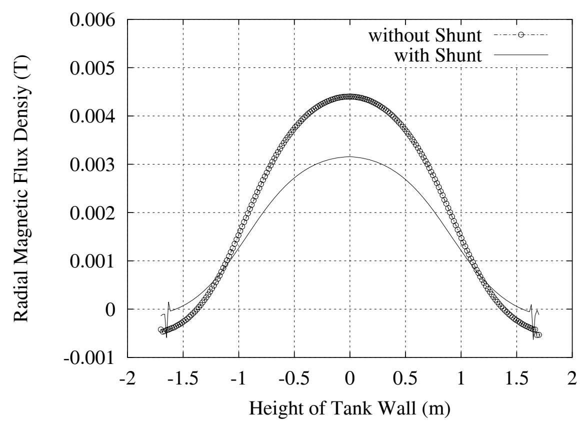

Fig. 4. Radial magnetic flux density along the height of tank wall.

The comparison between simulated losses and analytical or measured losses in the single-phase shunt reactor, and the methodology to correct the analytical equations using FEM will be detailed and will be presented in the extended paper.

IV. REFERENCES

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