Numerical Simulations for Power and Distribution Transformers

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Summary. Numerical simulations of different physical design aspects of ABB distribution and power transformers are presented. The design aspects include stray loss assessment, dielectric insulation and thermal management. The simulations contribute to a better understanding of the operation of transformers, which allows to improve the transformer product development.

1 Introduction

In the present days, energy-efficiency is a paramount requirement in the life-cycle of power products, as it is mandatory for an ecological and economical operation of transmission and distribution networks. Important components of these networks are distribution and power transformers. Hence, a high energy-efficiency has to be targeted in the development and design of modern transformers.

Evidently, low power losses during operation are of particular importance to achieve a high energy-efficiency. However, according to life-cycle-assessment, low material usage for the production of transformers contributes further to highly energy-efficient devices. As a consequence, competitive transformer designs have to be as compact as possible, thus approaching the physical limits.

Power losses and compactness are mainly determined by the electric and the magnetic design of a transformer. A part of this is the dielectric insulation which clearly limits the compactness, because certain insulation distances have to be maintained to prevent failures by electric discharges. Moreover, the dissipated power losses heat up the transformer components during operation. The temperature rise within the device, which affects the power losses and limits the expected lifetime of the insulation, needs thus to be controlled by a thermal management.

To achieve competitive transformer designs considering the aforementioned aspects, numerical simulations have become a very significant tool in product development and optimization.

2 Electromagnetic Simulations

For magneto-quasistatic simulations in transformers, the commercial field solver MagNet is applied [1]. Its Finite-Element-Method formulation is based on hierarchical elements which allow to use shape functions of various polynomial orders in the same mesh [4]. In the frequency-domain, the magnetic vector-field $\mathbf{H}$ in conductive domains,

$$\operatorname{curl}\left((\sigma + \mathrm{i}\omega\varepsilon)^{-1}\operatorname{curl}(\mathbf{H})\right) + \mathrm{i}\omega\mu\mathbf{H} = 0, \qquad (1)$$

and the scalar magnetic potential Ψ in non-conductive domains,

$$\operatorname{div}\left(\mu\left(\mathbf{H}_S - \operatorname{grad}(\Psi)\right)\right) = 0, \qquad (2)$$

are the solved for. The angular frequency is denoted by ω, while μ and ε denote the permeability and the permittivity. In non-conductive domains, the magnetic field is computed by $\mathbf{H} = \mathbf{H}_s - \operatorname{grad}\Psi$ with $\mathbf{H}_s$ being a known source field. The resulting (non)-linear systems of equations are solved by standard methods, e.g. a Newton-Raphson scheme for linearization and a preconditioned Conjugate Gradient solver for the linear systems.

2.1 Stray Loss Assessment

Three-dimensional magneto-quasistatic simulations are applied e.g. for stray loss assessment of ABB transformers. For example, Fig. 1 shows the distribution of the stray losses on a dry-type transformer.

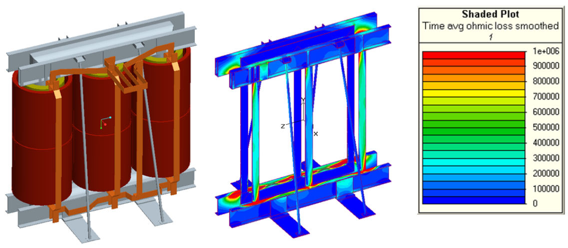

Fig. 1. CAD model of a dry-type transformer (left), and the stray loss distribution on its structural components(right).

The accuracy of the simulated stray losses reached here is about 7% [3]. Furthermore, the stray field emission of transformers are subject to legal regulations in some countries. An analysis of the magnetic stray field of this unit will be shown.

Beyond this assessment, electromagnetic simulations are used to evaluate objective functions in the frame of multi-objective optimization schemes. An application of these schemes based on an evolutionary algorithm will be presented.

2.2 Dielectric Insulation

Standardized tests have to be passed in order to verify the dielectric insulation of real transformers, for instance the applied voltage (AC) test or the lightning impulse (LI) test. The prediction of test results for dry-type transformers requires an evaluation of the dielectric design criteria that are based on stages of the electric discharge in air, i.e. streamer inception, streamer propagation and leader transition [2].

Under the AC and LI tests, for example, streamer inception can be tolerated in small regions at sharp edges of the core or terminals as long as the streamer propagation criterion (based on clearances) is fulfilled [2]. But streamer inception cannot be tolerated in the weakly inhomogeneous field of the main duct between low- and high-voltage windings, unless complex barrier systems are used. To avoid inception, the following criterion must be evaluated using electrostatic field computations:

$$\int_S \alpha_{\text{eff}}(E)\,\mathrm{d}x < \ln(N_c) \tag{3}$$

Here, α_{eff} denotes the effective ionization coefficient w.r.t. the electric field magnitude E. Inception does not occur if the integral along the discharge path S (typically computed as a field line) is smaller than the logarithm of the limit for electron generations N_c. Applications of the dielectric criteria to transformer design will be presented in the extended version of the paper.

3 Thermal Simulations

One significant duty of the thermal management is to control the temperature rise of the windings, which originates from dissipated power losses. The higher the average temperature of the windings, the higher is their electric resistance, and thus the poorer is the energy-efficiency in operation. Furthermore, the lifetime of the transformer depends on the highest temperature in the windings.

The heat generated in the windings is transferred by conduction through the solid winding insulation. The heat is then taken away from the surfaces of the solid insulation by the insulation fluid (e.g. oil or air) via convection. The latter can be either forced or natural depending on whether the flow is driven by an externally imposed pressure gradient or by buoyancy effects, respectively.

Numerical simulations are applied to solve the physical models that govern the heat transfer mechanisms described above. The numerical thermal problem involves the solution of the Navier-Stokes equations in the fluid, the heat conduction equation in the solid parts and the radiation model for describing the radiating energy exchanged between mutually facing surfaces. As a result of the simulations, the spatial temperature distribution inside the transformer is determined. This simulation procedure has become possible recently for full three-dimensional transformer configurations by using state-of-the-art computational tools along with modern high-performance computers.

The simulation procedure was validated by comparing numerical results against measurements for a dry-type transformer winding prototype, where the conductors of the winding turns are casted in epoxy. The maximum deviation between simulation and measurements at the 31 sensor locations was less than 5%. The simulated temperature distribution is shown in Fig. 2.

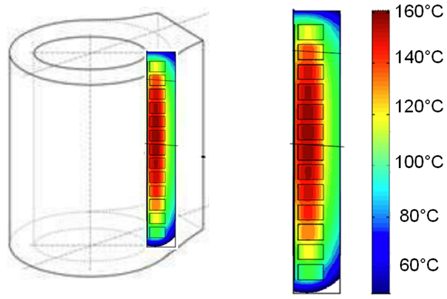

Fig. 2. Simulated temperature distribution of a dry-type transformer winding prototype cooled by natural convection.

This validated procedure was applied to compute the temperature distribution of many transformer designs. Details on the application to a particular dry-type transformer will be presented.

References

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