Alternative approach to FEM-based modeling and simulation of power transformers in transient behavior

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The optimal design of power transformers requires analyzing the whole electromagnetic system, including the power supply and the load, in rated operation mode and malfunction modes. This aim requires adequate computer aided design tools capable to provide results with satisfactory accuracy. Even though cosimulation approaches involving a FEM-based simulator for the electromagnetic and thermal field analysis coupled with a time-domain circuit simulator could offer the most accurate results, they are the most costly regarding hardware/software requirements and simulation time. Moreover, the FEM-based simulators deal difficulty with the ferromagnetic phenomena, and they commonly fail in the management of the inertial behavior of ferromagnetic materials related to the static hysteresis. In this context, we propose an extremely effective modeling and simulation procedure of single-phase and multi-phase transformers in the time-domain, exploiting the known principle of equivalent diagrams with lumped circuits.

The modeling procedure leads to a mathematical model reduced to a nonlinear differential-algebraic equation system, so that it is SPICE-compatible. Our systematic study brings a significant improvement comparing to similar approaches of other authors, through the degree of generality and the ease of use due to a carefully exploited concept of modularity.

The main module of the model (conceived as a SPICE subcircuit) combines a ferromagnetic piece as magnetic field path carrying the main magnetic flux φ (assumed as uniform within the cross section), a winding of N turns and DC resistance R spooled on it and the corresponding flux leakage φ_l path (fig. 1a). The winding of the model can play either the role of primary or secondary coil. The corresponding model diagram (fig. 1b) is in accordance to the Kirchhoff's voltage law related to the winding loop and the Ampere's law for the magnetic circuit. It uses controlled voltage sources to accomplish the coupling between the electric and the magnetic circuit. The ferromagnetic piece is a nonlinear and inertial resistance treated according to the Jiles-Atherton model of the ferromagnetic hysteresis [1] with the Langevin approximation of the anhysteretic characteristic, combined with our previously developed model of eddy currents [2]). Convenient combinations of leg-winding models allow simulating power transformers of almost any structure.

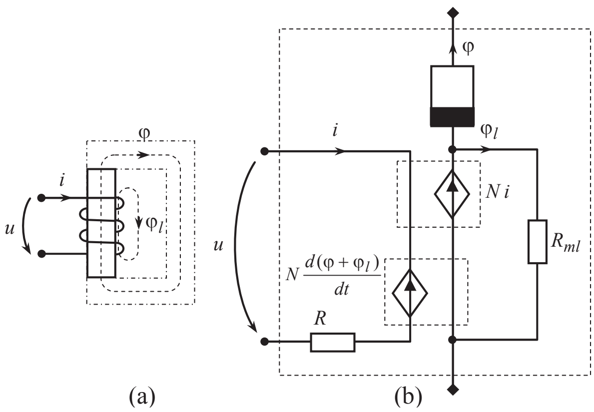

Figure 1: Transformer wired leg (a) and its time-domain model (b).

The method is remarkable through the extremely short computation time and satisfactory results, comparing to the FEM-based modeling and simulation approaches, as it will be proven in the extended form of the paper by means of the commercial simulators SPICE and FLUX 3D. It was conceived as an effective design and optimization tool.

[1] D.C. Jiles, D.L. Atherton, *Ferromagnetic Hysteresis*, IEEE Transactions on Magnetics, vol. MAG-19, No. 5, September 1983, pp. 2183-2185.

[2] L. Mandache, D. Topan, *Managing eddy current losses and ferromagnetic material nonlinearities in distorting regimes*, IEEE International Electric Machines and Drives Conference, IEMDC '09, Miami, 3-6 May 2009, pp.1449-1454.

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