Numerical Computation of Ohmic and Eddy-Current Winding Losses of Drive Transformers Including Higher Harmonics of Load Current

Jasmin Smajic[1], Jillian Hughes[1], Thorsten Steinmetz[1], David Pusch[1], Wolfgang Mönig[2], Martin Carlen[3]

[1]ABB Corporate Research Ltd., Segelhofstrasse 1K, CH-5405 Baden-Dättwil, Switzerland
[2]ABB AG, Keffelkerstrasse 66, D-59929 Brilon, Germany
[3]ABB Power Products, Dry-Type Transformers, Segelhofstrasse 1K, CH-5405 Baden-Dättwil, Switzerland

Abstract — Two different numerical algorithms for computing the Ohmic and eddy-current winding losses of variable speed drive (VSD) transformers are presented. The higher harmonic components of the electric current generated by the VSD power electronics are fully taken into account. The obtained numerical results are verified by comparison against the corresponding measurement results.

I. Introduction

A fully energized and loaded power transformer dissipates the following electromagnetic losses: (a) hysteresis and eddy-current core losses, (b) Ohmic and eddy-current winding losses, (c) eddy-current structural components losses, (d) Ohmic and eddy-current low-voltage (LV) busbars losses, and (e) Ohmic and eddy-current high-voltage (HV) lead-outs losses [1]. However, the winding losses are the most dominant component, accounting for 60-80% of the total transformer losses [1].

It is fairly simple to compute the Ohmic winding losses since these losses are caused by the Ohmic resistance of the winding material ($R\cdot I^2$). Having the winding geometry and electric conductivity of the chosen material (usually either aluminum or copper), it is possible to analytically obtain highly accurate results.

On the other hand the eddy-current winding losses are very difficult to compute. There are several different reasons for that: (a) winding geometry is very complicated, (b) winding geometry contains a large number of small details (thin wires and foils), and (c) magnetic stray field has a complex spatial distribution that can not be analytically computed.

The first published analytical method for computing the non-uniform current density distribution in the foil-wound transformer winding dates back to 1968 and the work of N. Mullineux at al. [2]. This analytic approach highly simplifies the problem by introducing several unrealistic assumptions such as: infinitely permeable core, infinite yoke-to-winding distance, and perfectly rectangular windings. Decades later, to overcome these limitations, field computations based on the 2D Finite Element Method (FEM) were applied as reported in 1998 in the work of R. S. Ram [3]. In this paper, the LV winding foils were realistically represented but the HV winding was approximated by stranded blocks. Only the effects of the first harmonic current component (50Hz) were considered.

The increase of the transformer winding losses due to the higher harmonic components of the non-harmonic load current was analyzed and reported for the first time as early as 1970 in the work of S. Crepaz [4]. It contains an analytical consideration of the increased winding losses due to the non-harmonic rectifier current for two-, six-, and twelve-pulse systems. The outcome of the analysis presented in the work [4] was simple analytical formulas for corrective factors representing the effect of the higher harmonic components.

After these initial numerical results, the significance of the problem of increased transformer losses due to the higher harmonic current components was recognized and, consequently, the practice for establishing transformer capability for supplying non-sinusoidal load current was recommended by a sequence of IEC and IEEE standards [5] and [6].

Compared to the above listed previously published methods and results, this paper contains the following original contributions: (a) two essentially different general algorithms for computing the winding losses of non-sinusoidal load current based on electromagnetic field simulation are presented, (b) both windings (LV and HV) are modeled in their full geometrical complexity and interconnected via direct coupling of the field solver and external electric circuit, and (c) the obtained results of the two methods are verified by comparison against each other and against the measurements.

II. Numerical Algorithms

The first algorithm for computing the winding losses we consider here is based on a 2D axisymmetric time-domain FEM electromagnetic field simulation. As shown in Fig. 1 the windings of one phase around a limb are modeled in their full geometrical complexity (every single foil and wire) but as a 2D axisymmetric model.

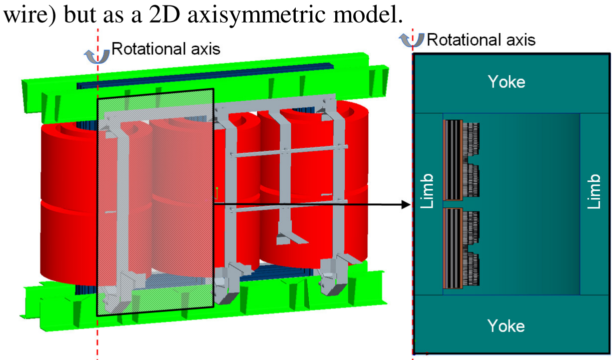

Fig. 1. Mapping between the 3D real-life model (left) and 2D axisymmetric model (right)

The dry-type 11kV / 12MVA drive transformer presented in Fig.1 (left) is connected to the rectifier module of the ABB 12-pulse Megadrive-LCI (Load Commuted Inverter) [8].

For the 2D axisymmetric quasistatic magnetic analysis in time-domain the commercial field solver MagNet of Infolytica was used [7]. In MagNet the classical 2D axisymmetric field formulation based on the vector magnetic potential was implemented.

Having the 2D axisymmetric model presented in Fig.1 (right) it is not possible to geometrically define the connections of the windings to each other. Therefore, an electric circuit is needed in order to define these connections. The electric circuit used for modeling of the transformer windings is shown in Fig. 2.

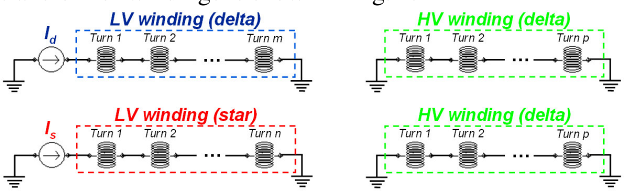

Fig. 2. The electric circuit describing the mutual connection of the windings and the connection of the windings and current sources.

The electric load currents flowing through the upper LV winding, connected in delta, and the lower LV winding, connected in star, when the transformer is connected to the rectifier module of the MEGADRIVE-LCI were measured and are presented in Fig. 3 (left). These time-functions are assigned to the current sources shown in Fig. 2.

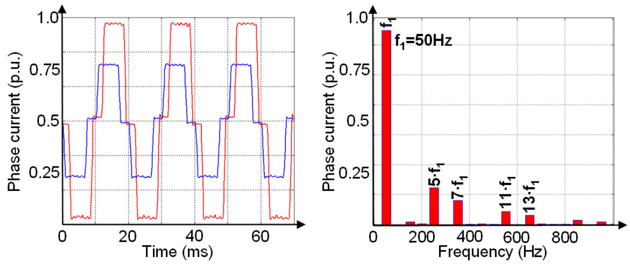

Fig. 3. Non-harmonic load current in time-domain (left) and its harmonic content (right). The current through the upper LV winding (delta) and through the lower LV winding (star) is depicted in blue and red, respectively.

So, our first algorithm is based on the 2D axisymmetric time-domain field computation coupled with the electric circuit presented in Fig. 2 where the current sources represent the measured non-harmonic currents shown in Fig. 3. Evidently, if performed for a certain number of the load current periods (usually 4 periods) with sufficiently small time-step, this algorithm will compute accurate losses in the windings. However, it will also require a long CPU time.

In order to accelerate the computation, the second algorithm based on the harmonic decomposition of the load current (Fig. 3, right) was developed. This algorithm consists of frequency-domain field computations for each harmonic component separately. Provided that the harmonic components are sufficiently separated from each other in frequency-domain the total losses could be obtained as a sum of the separately computed losses for each harmonic component. This second method is less accurate but much faster in terms of CPU time.

III. Numerical Results

The winding losses computed by using the described transient and harmonic superposition algorithm are compared in Table I.

TABLE I RESULTS COMPARISON
TRANSIENT COMPUTATION VS. HARMONIC SUPERPOSITION

	Total Losses (relative numbers)	
Component	Transient Algorithm	Harmonic Superposition
LV winding (Delta)	18.64%	19.38%
LV winding (Star)	20.81%	20.20%
HV winding	60.23%	60.41%
Total losses	99.68%	100.00%

The CPU time of one single field computation in frequency domain was around 30 minutes. Thus, the total CPU time for computing the losses of the first 5 dominant harmonic components (Fig. 3, right) was 2.5 hours. The corresponding transient simulation was run for four load current periods (80ms) with the time-step 0.5ms. Thus, the total CPU time of the transient simulation was around 3.33 days. Evidently, Table I shows that the accuracy of the harmonic superposition method is very good which justifies the application of this method and allows for radical reduction of the CPU time.

TABLE II RESULTS COMPARISON (50Hz)
FREQUENCY-DOMAIN COMPUTATION VS. MEASUREMENTS

	Total Losses (relative numbers)	
Component	Simulation	Measurement
LV winding (Delta)	16.83%	-
LV winding (Star)	17.72%	-
HV winding	71.56%	-
Total losses	106.11%	100.00%

Table II shows the comparison of the winding losses computed at 50Hz against the available measurements. Evidently, the accuracy is excellent.

The mathematical background of the field computations, the obtained stray magnetic fields and winding losses, and the physical interpretation of the influence of higher harmonic components will be given in the full paper.

IV. References

[1] S. V. Kulkarni, S. A. Khaparde, "Transformer Engineering: Design and Practice", Design and Practice, Marcel Dekker Inc., New York, NY, 2004.

[2] N. Mullineux, J. R. Reed, I. J. Whyte, "Current Distribution in Sheet- and Foil-Wound Transformers", *Proc. IEE*, Vol. 116, No. 1, pp. 127-129, 1969.

[3] B. S. Ram, "Loss and Current Distribution in Foil-Windings of Transformers", *IEEE Proc. Gener. Transm. Distrib.*, Vol 145, No. 6, pp. 709-716, 1998.

[4] S. Crepaz, "Eddy-Current Losses in Rectifier Transformers", IEEE Trans. Power Appar. Systems, Vol. 89, No. 7, pp. 1651-1656, 1970.

[5] International Standard, "Converter Transformers – Part 1: Transformers for Industrial Applications", IEC 61378-1, International Electrotechnical Commission, Geneve, Switzerland, 1997.

[6] Transformer Committee of the IEEE Power Engineering Society, "IEEE Recommended Practice for Establishing Liquid-Filled and Dry-Type Power and Distribution Transformer Capability When Supplying Nonsinusiodal Load Current", IEEE Std C57.110-2008, IEEE Power Engineering Society, 2008.

[7] Infolytica MagNet: Design and Analysis Software for Electromagnetics, www.infolytica.com, Infolytica Corporation.

[8] Medium Voltage AC Drive, MEGADRIVE-LCI for Control and Soft Starting of Large Synchronous Motors, ABB Switzerland, 2010.