Analytical Calculation of Copper Losses in Litz-Wire Windings of Gapped Inductors

A. Stadler, R. Huber, T. Stolzke and C. Gulden
STS Spezial-Transformatoren Stockach GmbH & Co. KG
Am Krottenbühl 1, 78333 Stockach, Germany
stadler@sts-trafo.de

***Abstract*—In this paper, an analytical procedure is presented, how to predict the AC resistance of litz-wire windings considering air gap fringing fields. For this purpose, an equivalent complex permeability model is derived for hexagonally packed wires. It is shown, how the real- as well as the imaginary part of the complex permeability can be determined with the copper filling factor as a parameter. An analytical 2D model is deduced to describe the air gap fringing fields of gapped inductors. Accordingly, the proximity losses of the litz-wire winding are determined correctly and the AC resistance of practical inductors can be predicted over a wide frequency range with high accuracy. This offers the opportunity to optimize such components. Finally, the influence of various parameters on the copper losses is investigated and verified by means of experimental data drawn from impedance measurements.**

***Index Terms*—Inductors, air gaps, eddy currents, electromagnetic analysis, analytical models.**

I. Introduction

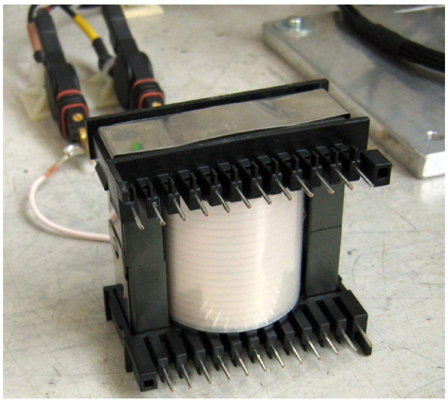

Fig. 1. Inductor under test: ETD59/31/22-N87, air gap length l_g=5mm, number of turns N=72 (litz-wire 7x35x0.1mm)

High frequency (HF) litz-wire is generally used to avoid strong eddy current losses due to the fringing fields of adjacent air gaps. If the radius a of the insulated strands is smaller than the skin depth

$$\delta = \sqrt{\pi f \sigma \mu_0}^{-1}, \qquad (1)$$

the well known skin effect can be neglected and a homogeneous distribution of the conducted current is expected. Nevertheless, considerably high losses can still be generated due to the fact that all of the strands are influenced by external magnetic fields generated by adjacent strands, windings and air gaps as well (proximity effect).

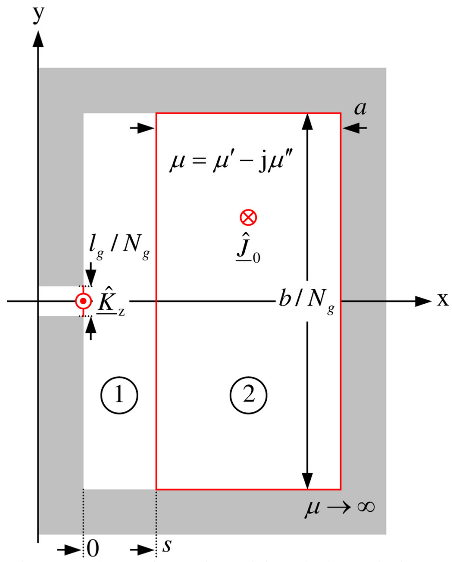

Fig. 2. Basic configuration of the winding window (distributed air gap with N_g parts of length l_g/N_g)

When designing high frequency inductors and integrated magnetic components, these effects have to be predicted with high accuracy. Especially air gap fringing fields can lead to much higher losses than expected. As a disadvantage, these losses develop in a small region around the air gap. Due to the poor thermal conductivity of insulated litz-wire, heat cannot be dissipated outside and insulation failures are the consequence.

In recent work (e.g. [1], [2]), eddy current losses of round and rectangular wires have been investigated. These results were extended to bundles of wires [3] and litz-wire windings [4]-[5]. Nevertheless, numerical simulations as well as analytical solutions (e.g. by the modal decomposition of the boundary value problem) come to their limits when the great number of litz-wire strands has to be taken into account. To provide a solution, equivalent complex permeability models [6]-[8] were derived for the winding area and linked either with FEM simulation or rough (usually 1D) estimations of the penetrating magnetic field.

The novelty of the approach presented in this paper is given by the fact that an exact 2D analytical solution is conducted to describe the air gap fringing field. Furthermore, the distance s between air gap(s) and winding can be considered as a degree of freedom as well as the number of single gaps N_g to realize a distributed air gap.

II. Calculation

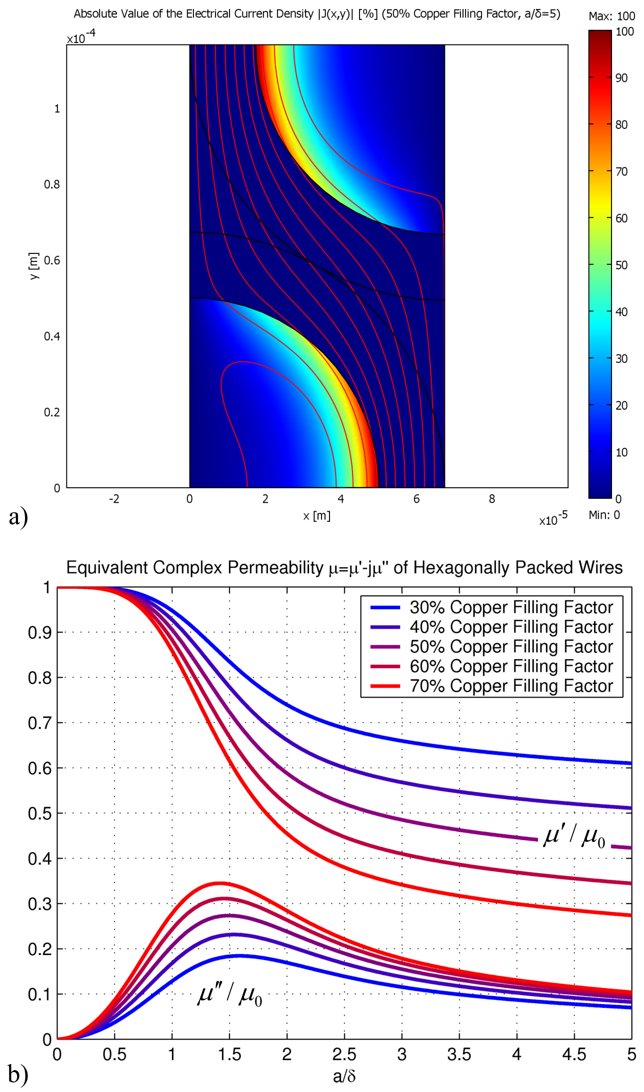

Fig. 3. Simulation (a) of the elementary cell of hexagonally packed wires to obtain the equivalent complex permeability $\mu = \mu' - j\mu''$ (b)

To begin with, a complex equivalent permeability model is derived for hexagonally packed wires [8]. Fig. 3a shows the FEM-simulation of the elementary cell. The picture depicts the absolute value of the electrical current density in a per-cent scale for 50% copper filling factor and a relation between strand-radius a and skin depth (1) of $a/\delta = 5$. In Fig. 3b the results are presented with different values of the copper filling factor as a parameter.

These curves now are used for the calculation of the air gap fringing fields. Fig. 2 shows the basic configuration. The problem (complex amplitudes) can be solved by means of the 2D magnetic vector potential $\underline{\hat{\mathbf{A}}} = \mathbf{e}_z \underline{\hat{A}}_z(\mathrm{x},\mathrm{y})$. For region 1 and 2 in Fig. 2, the two solutions

$$\underline{\hat{A}}_{z1}(\mathrm{x},\mathrm{y}) = \underline{A}_0 + \underline{B}_0 \mathrm{x} + \sum_{n=1}^{+\infty}\left[\underline{A}_n \frac{\cosh(\lambda_n \mathrm{x})}{\cosh(\lambda_n s)} + \underline{B}_n \frac{\sinh(\lambda_n \mathrm{x})}{\sinh(\lambda_n s)}\right]\cos(\lambda_n \mathrm{y}) \quad \text{and} \tag{2a}$$

$$\underline{\hat{A}}_{z2}(\mathrm{x},\mathrm{y}) = \frac{1}{2}\mu \underline{\hat{J}}_0\left[\mathrm{x} - (s+a)\right]^2 + \sum_{n=1}^{+\infty} \underline{E}_n \frac{\cosh\{\lambda_n[\mathrm{x}-(s+a)]\}}{\cosh\{\lambda_n[s-(s+a)]\}}\cos(\lambda_n \mathrm{y}) \tag{2b}$$

are found. After determination of the Eigenvalues λ_n and the parameters $\underline{A}_0$, $\underline{B}_0$, $\underline{A}_n$, $\underline{B}_n$ and $\underline{E}_n$ (a detailed derivation will be given in the final paper), the proximity losses of the winding area 2 in Fig. 2 can be calculated using Poynting's theorem.

In Fig. 4 the results are compared with measured data. Four different types of litz-wire are used for measurements – each with different twist pitch length. To describe the parasitic effects of the inductor, a constant parallel capacitance $C \approx 62\mathrm{pF}$ is assumed. Fig. 4 illustrates the high accuracy of the model.

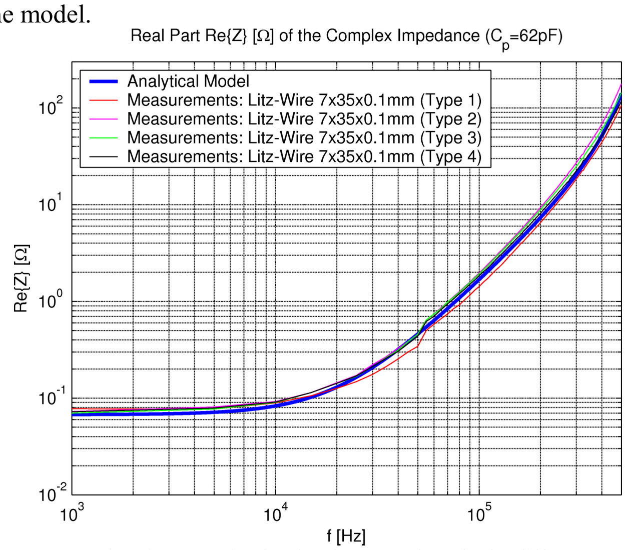

Fig. 4. Comparison between simulated and measured results for different types of 7x35x0.1mm litz-wire (parameter: twist pitch length)

References

[1] X. Nan and C. R. Sullivan, "An improved calculation of proximity-effect loss in high-frequency windings of round conductors," *IEEE Power Electronics Specialists Conference PESC*, pp. 853-860, June 2003.

[2] C. Larouci, J.-P. Keradec, J.-P. Ferrieux, L. Gerbaud and J. Roudet, "Copper losses of flyback transformer: Search for analytical expressions," *IEEE Transactions on Magnetics*, vol. 39, no. 3, pp. 1745-1748, 2003.

[3] J. Gyselinck and P. Dular, "Frequency-domain homogenization of bundles of wires in 2-d magnetodynamic FE calculations," *IEEE Transactions on Magnetics*, vol. 41, no. 5, pp. 1416-1419, 2005.

[4] F. Tourkhani and P. Viarouge, "Accurate analytical model of winding losses in round Litz wire windings," *IEEE Transactions on Magnetics*, vol. 37, no. 2, pp. 538-543, 2001.

[5] J. A. Ferreira, "Analytical computation of AC resistance of round and rectangular litz wire windings," *IEE Proceedings-B – Electric Power Applications*, vol. 139, no. 1, pp. 21-25, Jan. 1992.

[6] O. Moreau, L. Popiel and J. Pages, "Proximity losses computation with a 2D complex permeability modelling," *IEEE Transactions on Magnetics*, vol. 34, no. 5, pp. 3616-3619, 1998.

[7] X. Nan and C. R. Sullivan, "An equivalent complex permeability model for litz-wire windings," *IEEE IAS*, vol. 40, no. 3, pp. 2229-2235, 2005.

[8] H. Roßmanith, M. Döbrönti, M. Albach and D. Exner, "Measurement and characterization of high frequency losses in nonideal litz wires," *IEEE Transactions on Power Electronics*, vol. 26, no. 11, pp. 3386-3394, Nov. 2011.