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Abstract

Usually the inductance of toroidal coils is calculated either analytically or on the base of the manufacturer given data. One common simplification in the first approach is calculating inductance of a long solenoid and "curving" the latter in a circular loop [1]. Core manufacturers usually specify inductance per turn L1, from which the coil inductance having W turns comes out as classical quadratic W2L1 dependence. Both methods fall short in the case of sparsely wound coils, especially when using low permeability cores.

Analytical inductance calculation of a straight helix is feasible [2]. In principle, this may provide better understanding of the inductance dependence on the axial current components that are tacitly neglected in common calculations [3], [4]. The inductance equations, however, are very complex, to the point of being unwieldable, to be of much use. Extrapolations to a real toroidal shape are risky.

Numerical field analysis, again in principle, can provide "exact" figures. Being essentially 3D, such calculations are not straightforward. In this paper, we used the Magnetic Field interface of the AC/DC Module of the COMSOL Multiphysics® software. We outline several simulation methods. Simplifications, assumptions, and analysis bifurcations are as follows.

1. We neglect the leads.
2. Winding is made by a round multistrand wire. It is perfectly symmetrical. We do not consider here windings with small number of turns wound densely on a small area.
3. For the simplicity sake, the core section is round, and the winding is a toroidal helix.
4. Core material is linear with constant permeability thru its volume.
5. In AC analyses, coil is excited by a sine wave.

In the model building, the first alternative is modeling full coil or using symmetry and thus modeling only 1/W of the space to minimize computing expense [5]. We make both.

Then, the winding can be represented as a set of W discrete toroidal turns or modeled as a toroidal helix. The next bifurcation is neglecting or not the wire thickness.

The main takeout from these simulations are physical aspects, which, if not revealed, were quantified, providing thus better insight into coils design and characterization. The main results are as follows:

1. For sparsely wound coils, the dependence of the inductance on number of turns is far from quadratic;
2. For low-permeability cores, wire inductance is a considerable factor, especially for very low number of turns and large-diameter cores. Thus, for inductance calculation, accounting for the wire thickness is important.
3. Fringe field, however, can be calculated modeling the winding as an edge current, as sketched in [5]. Fringe field of a coil sparsely wound on a low-permeability core is low but not negligible.
4. Using a discrete-turns approximation results in a large error when modeling a sparsely wound coil.

Reference

[1] A.V. Bossche and V.C. Valchev, “Inductors and Transformers for Power Electronics”, CRC Press, Boca Raton, 2005. P. 8.1.3
[2] C. Snow, “Formula for the Inductance of a Helix Made with Wire of Any Section”, Scientific Papers of the Bureau of Standards, Vol. 21, p. 431-519 (1926) Scientific Paper 537 (S537), 100pp.
[3] F.W. Grover, “Inductance Calculations”, Dover, NY, 1946.
[4] P. L. Kalantarov and L. A. Zeitlin, “Inductance Calculation”, 3rd Ed., Leningrad, EnergoAtomIzdat, 1986 (in Russian), 488pp.
[5] W. Frei, “Exploiting Symmetry to Simplify Magnetic Field Modeling”, Comsol blog, 2014.

Figures used in the abstract

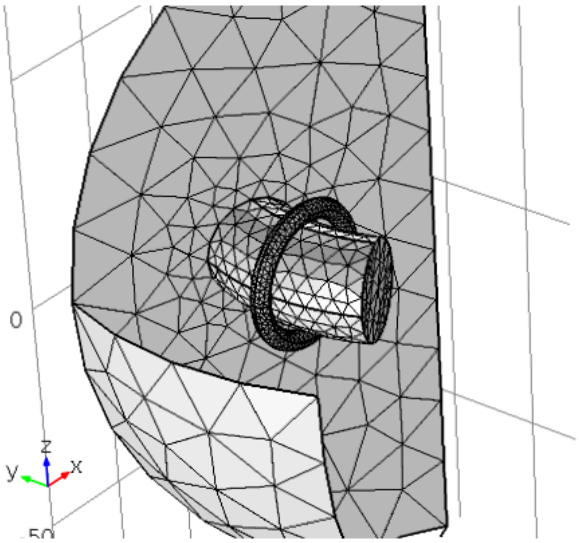

Figure 1: Model of a W-turn coil (W=8) discrete turns. Perfect Magnetic conductor BC.

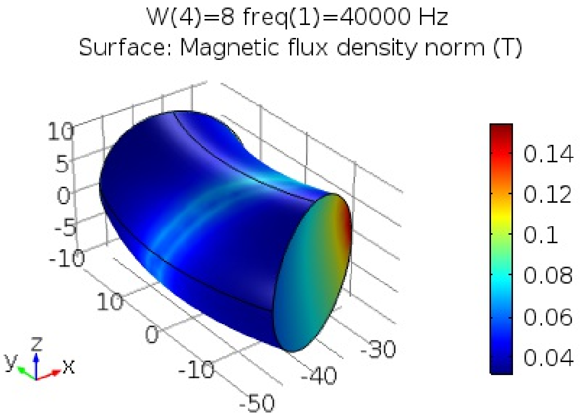

Figure 2: Model of a W-turn coil (W=8) filament current. Periodic BC.

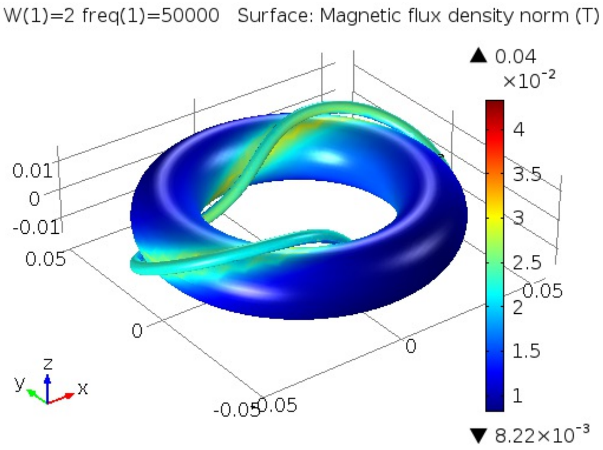

Figure 3: Model of a W-turn coil (W=2) full winding.

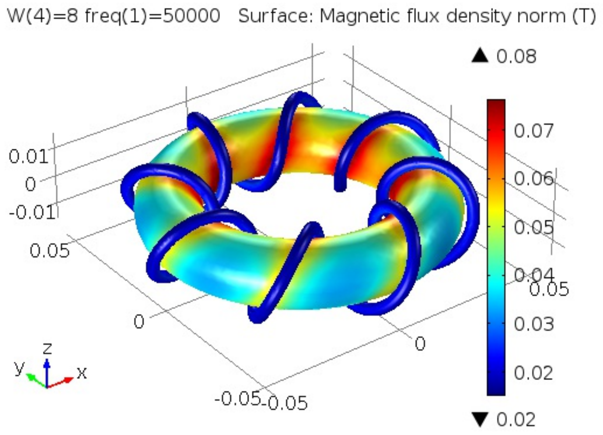

Figure 4: Model of a W-turn coil (W=8) full winding.