Teaching and Researching Power Electronics with the Help of Finite Element Analysis

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Abstract - Ferrite inductors are widely used in the field of power electronics, a subject included in various curricula in the universities both at the undergraduate and postgraduate level. These inductors are difficult to model due to the wide variety of shapes, number of turns, and the nonlinear behavior of the core that exhibit saturation, hysteresis and power losses. For this reason, it is necessary to resort to numerical methods such as Finite Element Analysis. In this paper we give some guidelines and recommendations for students to correctly use Finite Element programs for modeling inductors with different shapes. We give a vision of the modeling procedure of inductors including the simplifications that students should make in the 3D inductor model to achieve convergence and the assigning of materials as well as boundary and meshing conditions. Finally, we show representative results of the procedure.

Index Terms - Power electronics, Research in education, Ferrite cores, Finite Element Analysis.

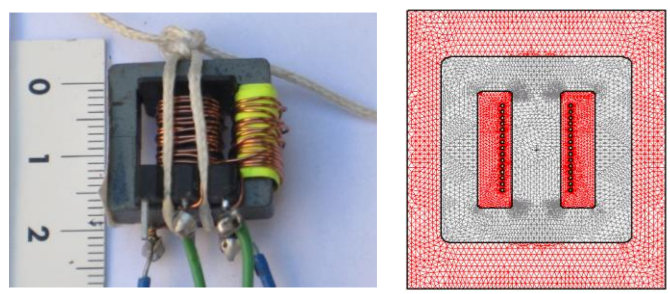
I . Introduction

Power electronics is taught in the majority of universities at both the undergraduate and postgraduate level. It is a multidisciplinary subject which involves knowledge about electromagnetic fields, modeling and simulation[1,2]. The conception, design and analysis of power electronic systems are important tasks often requiring the help of computers to perform fast and accurate computations or simulations[3]. Specifically, these systems use inductors with ferrite cores due to their magnetic properties[3-7]. They come in different materials, sizes and with different number of turns; as for their shape, they can be ungapped such as toroidal or gapped such as E (Figure 1), RM (Figure 2) or POT (Figure 3) among others[4,7]. Gapped inductors consist of two identical halves where the gap-thickness can be varied depending on the applications[4,7]. Ferrites exhibit saturation, hysteresis and power losses[3-9], which can be difficult to understand for the students. Thus, visual programs such as circuit simulators and Finite Element programs are widely used[10,11]. When we need to obtain solutions of complex domains that cannot be solved by means of analytical solutions or which have complex boundary conditions we resort to numerical methods such as finite volume, finite differences and finite element methods[12-15].

In particular, Finite Element Analysis is of great help in power electronics because most of the system components, especially these ferrite inductors[16], are described by nonlinear equations which most often do not have analytical solutions.

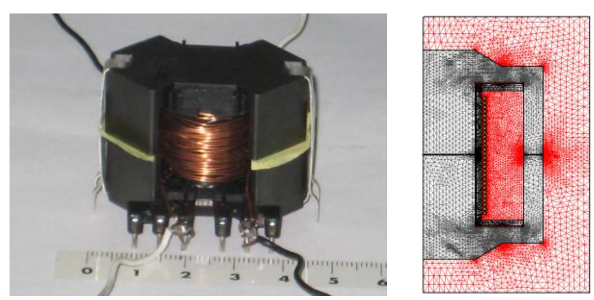
In this paper we focus on the modeling of soft ferrite inductors by means of Finite Element Analysis to be used by students of power electronics. In particular, we give some recommendations for the correct use of these programs. We focus on the choice of the adaptative meshing and the approximations and simplifications that students should make in the 3D inductor models to achieve convergence.

The structure of the paper is as follows. In section 2 we give information about the domain design in 2D and 3D. In section 3 we describe the physical input parameters and the assigned boundary conditions and excitation sources. Some recommendations and simplifications that help to achieve convergence and the meshing conditions are discussed in section 4. Some illustrative results are presented in section 5. Finally, in section 6 we summarize our results and offer some conclusions.



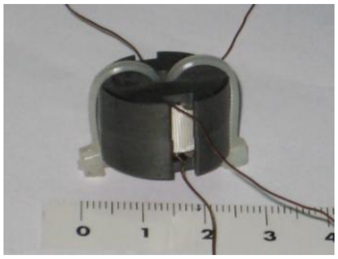
(a) (b)

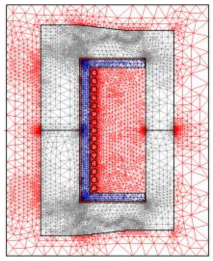
Fig.1 (a) Real magnetic component with an E core.(b) Triangular mesh generated by the 2D simulations.



(a) (b)

Fig.2 (a) Real magnetic component with RM core including an air-gap thickness of 100 μm and two windings of 28 turns. (b) Triangular mesh generated by the 2D simulations.





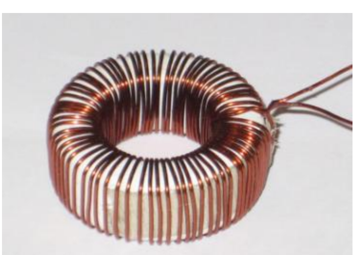
(a) (b)

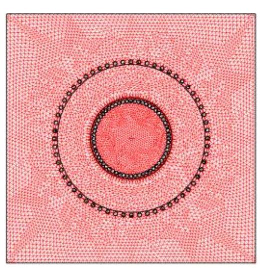
Fig.3(a) Real magnetic component with POT core and two windings of 15 turns. (b) Triangular mesh generated by the 2D simulations.

II. Modeling of ferrite inductors in 2d and 3d

Simulations by means of Finite Element Analysis can be performed in 2D or 3D. Thus, the modeling procedure begins with the domain design with AutoCAD, defining domain as the spatial region that includes the geometry of the inductor (core, winding and sometimes a coil former). This spatial region can be cylindrical in the case of 3D or rectangular or square in the case of 2D. The advantage of the 3D simulations is the precision of the geometry and that the solution is rigurous. Nevertheless, the disadvantages are that convergence is difficult to achieve in specific situations (large sizes, some air-gap thickness and excitation current values) and the high computational cost. The 2D simulations have as advantages and characteristics the simplicity, reduced computational cost and that the fact that they converge in nearly all situations. However, as disadvantages they have the difficult choice of the computational domain.

In the case of the inductors with toroidal (Figure 4) and E cores (Figure 1), for the 2D simulations it is possible to reproduce the behavior of the real inductor by choosing a cross-section of the real inductor. In Figures 1(b) and 4(b) we show the cross-sections of the real inductors. However, as the RM and POT geometries do not display a complete rotational symmetry we design 2D equivalent computational domains with the same volume and distribution of the magnetic fields[17,18]. In Figures 2(b) and 3(b) we show the 2D equivalent domains of the real RM and POT magnetic components, respectively.





(a) (b)

Fig.4 (a) Real inductor with toroidal core with 60 turns. (b) Triangular mesh generated by the 2D simulations.

III. Physical input parameters and boundary conditions

Once students have designed the 2D or 3D domains with AutoCAD, they need to assign the physical input parameters of the materials of the inductor (core, windings and coil former) and background. They assign the relative permeability of the ferrite, which is a constant if the behavior of the ferrite is considered to be linear. If the ferrite is considered as nonlinear as happens with the real ferrite, students assign the *B-H* curve that characterizes the core material and reproduces the behavior of the material from the linear to the saturation regions. This curve can be measured by students in the laboratory. They also assign the relative permeability and conductivity of the copper wire, relative permeability of the background and relative permeability and conductivity of the coil former if present. Students also define and assign the boundary conditions and values of the excitation sources. In the case of the magnetostatic solver they need to assign values of the DC excitation current, and in the case of a transient solver, data of the voltage or current waveform (amplitude and frequency) and details of the windings such as initial current, resistance R_{Ω}, leakage inductance, capacitance and number of turns.

Regarding the boundary conditions, these provide the description of the behavior of the electric and magnetic field at object interfaces or edges of the problem region (on inside surfaces or edges of the problem space). In the case of the magnetostatic solver, the boundary conditions that students choose in 3D are natural on the material surfaces and Neumann boundary conditions at the interface of the domain. The boundary conditions that they choose in the simulation of the 2D model are “Balloon” at the limits of the rectangular domain of the drawing, and the Neumann condition on the material surfaces. With the “Balloon” boundary condition the vector potential **A** tends to zero at infinity. The field lines are neither tangential nor normal to the border. Balloon boundaries model the region outside the drawing space as being nearly “infinitely” large, effectively isolating the model from other sources of current or magnetic fields.

IV. Recommendations about meshing and convergence

The choice of the correct 2D or 3D computational domain and meshing are crucial in the modeling procedure in order to achieve convergence and find a solution to the problem. Our experience shows that meshing and convergence are related and this is the idea we want to transmit to the students. In the 3D simulations we can simulate simplified models while still obtaining equivalent results from the magnetic point of view. For example, when we simulated a toroidal inductor with rounded borders (Figure 5(a)) as the real case (Figure 4(a)), we were unable to achieve convergence. This was solved by simulating the inductor with right-angled borders (Figure 5(b)).

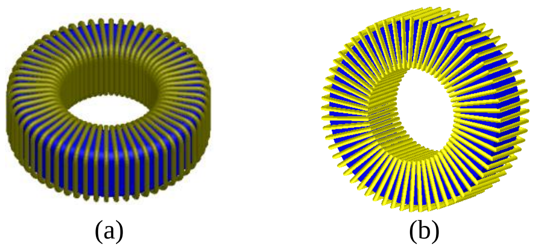


Fig.5 (a) Realistic 60-turn toroidal ferrite inductor with rounded borders. (b) Simplified 60-turn toroidal ferrite inductor with right-angled corners.

Another interesting case is the RM core. This inductor consists of two identical core halves with inner and outer slots, a pair of clips to fasten the core halves, a coil former with several pins for PCB mounting and a winding of copper wire. In some occasions the core halves are separated by an air-gap with a variable thickness. While attempting to simulate the realistic 3D model of an ungapped RM14/I with 28 turns (Figure 6(b)) we ran into convergence problems when the core was saturated. The solution found was to eliminate the slots and clips, as can be seen in Figure 7, achieving convergence in all regions (linear, intermediate and saturation). In the case of the gapped core we had to apply the same simplifications in order to achieve convergence in all regions.

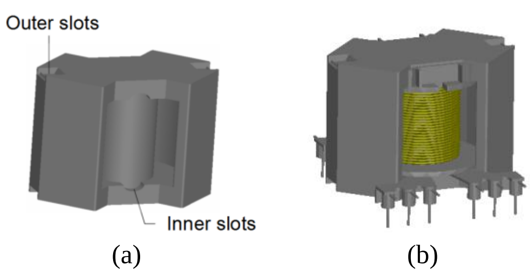


Fig.6 (a) Realistic 3D RM ferrite core with outer and inner slots. (b) Realistic 3D RM ferrite inductor including a coil former and winding.

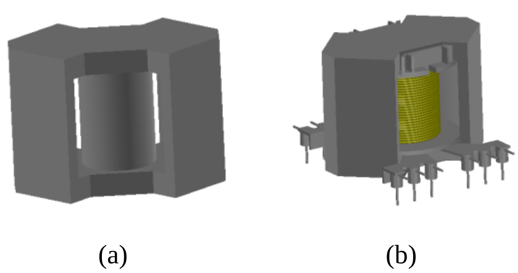


Fig.7 (a) Simplified 3D RM ferrite core. (b) Simplified 3D RM ferrite inductor including a coil former and winding.

Another inductor that is widely used in power electronics is the POT core. This core, as happens with the RM core, consists of two identical halves, a coil former with pins for PCB mounting, and a winding of copper wire. The real core also includes slots and bevels.

While attempting to perform 3D simulations with a realistic ungapped P22/13 POT core with 15 turns (Figure 3(a)) we encountered problems in achieving convergence for a DC excitation current in the saturation region, being unable to generate the mesh. Afterwards, we performed 3D simulations for the saturation value without including slots, bevels and coil former, achieving convergence in this case. Our recommendation in order to achieve a complete convergence in all regions (linear, intermediate and saturation) is to eliminate slots, bevels (using right angles instead) and coil former.

Sometimes it happens that even with simplifications of the inductors we are not able to achieve convergence in 3D and we have to resort to 2D simulations. Such is the case of the inductors with an E geometry (Figure 1(a)). These inductors consist of two E type core halves with rounded edges, a coil former and a winding. We carried out 3D simulations with four diferent sized cores (E65/32/27, E47/20/16, E34/14/9 and E20/10/5) with coil formers and rounded edges and we only achieved convergence in the case of the smallest core. We ran the 3D simulations again under different excitation current values (linear, intermediate and saturation regions) for the other cores without coil former and rounded edges, but were still not able to achieve convergence. Then we carried out another set of 2D simulations using a cross-section of the inductor for all studied inductor sizes, excitation current values and values of air-gap thickness between 0 and 200 μm, achieving convergence in all cases. In this case, our recommendation is that students perform 2D simulations directly.

Regarding the meshing conditions, we chose the adaptative mesh refinement technique to reduce the number of elements. The algorithm uses high resolution grids only at the physical locations and times where they are required, which reduces the computation time. In each iteration the program computes the magnetic fields, makes an error estimation and refines the mesh. Then students specify the parameters related to the adaptative analysis to generate the mesh: percent refinement per pass, the number of requested passes to stop the algorithm and the percent error (τ).

V. Illustrative examples and results

At the *postprocessing step* we obtain the physical variables as an output of the program. Based on this, students can investigate and analyze the results and values, and show the magnetic fields in the inductor graphically. Apart from this, by comparing results computed by 2D and 3D students can observe that both simulations obtain very similar results while the 2D procedures show a considerable reduction of the computational cost, defined by CPU time and number of finite elements, and solve the convergence problems. As an example, we show some representative results of students' simulations carried out with the Ansoft Maxwell software. We show results of two different solvers: magnetostatic (2D and 3D) and transient (2D). For the magnetostatic solver we show results obtained with the TN36/23/15 toroidal ferrite core with 60 turns (Figure 4(a)). In Table 1 we show the computational cost of the 2D and 3D procedures for three values of the DC excitation current I = 0.01 A (linear region), I = 0.34 A (intermediate region) and I = 10 A (saturation region), showing a reduction while obtaining equivalent results.

Table 1 Comparison of the computational cost between 2D and 3D simulations.

	CPU time		Elements	
I (A)	2D	3D	2D	3D
0.01	15 s	28 min. 20 s	10642	373406
0.34	9 s	1 h. 45 min.	10642	373406
10	8 s	2 h. 8 min.	10642	373406

In Figure 8 we show the distribution of the **B** field on the surface of an ungapped RM14/I ferrite core with 28 turns (Figure 7(b)) under a DC excitation current of I = 10 A (saturated core), for both the 3D and 2D models. It can be observed that the higher values of the magnetic field are located at the column of the core.

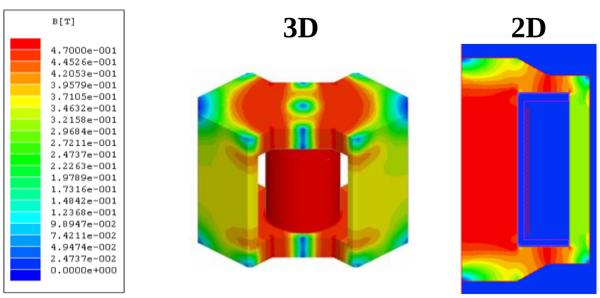


Fig.8 Values of the **B**-field module in 2D and 3D on the surface of the core.

By using a gapped (g = 100 μm) RM14/I ferrite core with 28 turns (Figure 2(a)) we show the results of the magnetic flux for each DC excitation current from the linear to the saturation regions (Φ-I curve) and the inductance curve (L-I curve) derived from this, as well as the experimental curve measured in the laboratory (Figure 9). This way students can obtain and observe how the inductance and flux vary with the current. This could not be obtained by means of analytical equations. In Figure 2(b) we show the effect of the adaptative meshing showing a higher number of triangles at some regions, especially close to the angles of the ferrite material.

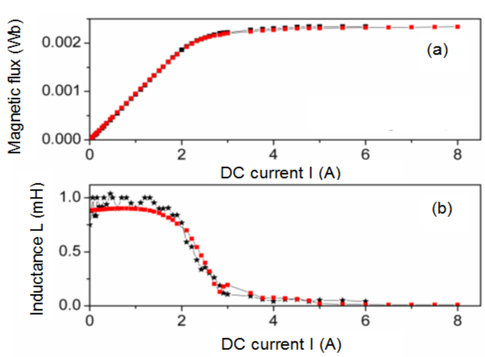


Fig.9 (a) Experimental (*) and simulated by 2D Finite Element Analysis (–■–) Φ-I curves. (b) Experimental (*) and simulated by 2D Finite Element Analysis (–■–) L-I curves.

As a final point, in Figure 10 we show the current and voltage waveforms obtained by 2D simulations with the Maxwell software for the case of a toroidal core with 60 turns under an excitation voltage of 20 kHz where the core is saturated. We also show the experimental waveforms measured in the laboratory. Then students can observe the agreement between the results and the effect that the current waveform shows in a saturated core (Figure 10(b)).

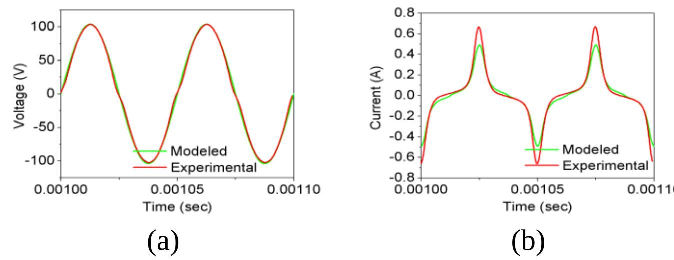


Fig.10 Example of experimental (red line) and 2D simulated (green line) voltage and current waveforms for the saturation region.

VI. Conclusions

In the teaching of power electronics the use of design programs such as circuit simulators and Finite Element Analysis softwares is very useful as they help students to understand the behavior of the electronic components of the circuits, in particular the inductors with soft ferrite cores. By means of Finite Element simulations students can determine physical variables which would not be practically obtainable by analytic methods. In this paper we have given some recommendations and guidelines for the correct use of Finite Element Analysis for modeling inductors of different geometries. In particular, we have briefly discussed the steps that students should carry out for modeling an inductor with a soft ferrite core. These steps are design of the inductor in 2D or in 3D, assignment of the materials of the inductor and assignment of boundary conditions and adaptative meshing that reduce the computation time and facilitate the convergence. In order to achieve convergence in 3D in general, it is necessary to simplify the geometrical shape, eliminating for example rounded borders in the toroidal core, bevels and outer and inner slots in the RM core, and slots and coil former in the case of a POT core. In addition, we have shown the students that it is possible to perform 2D simulations using 2D computational domains of the real cores obtaining results equivalent to the 3D ones. This way the computational cost is reduced and convergence problems found in 3D simulations are resolved. Finally, we have shown some illustrative results of students' simulations carried out with the Ansoft Maxwell software. Students can investigate and analyze the results and values, and show the magnetic fields in the inductor graphically. We think that this procedure is useful for both undergraduate and postgraduate students since it helps them understand and apply difficult concepts of the magnetic fields. In addition, we think that it can be applied to a great variety of geometries and number of turns of the inductor.

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