Combined Use of Measurements, Simulation and Numerical Computation of Magnetic Fields for Power Electronics Teaching

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***Abstract*—We present a procedure that combines modeling, simulation and experimental measurements on real inductors. We apply this procedure to the modeling and simulation of ferrite inductors, widely used in the field of power electronics. It can be applied to undergraduate and Master level students to help them understand the behavior of circuits and the nonlinear physical phenomena involved in power electronics.**

***Index Terms*—Power Electronics, education, nonlinear inductors, ferrite cores, Finite Element Analysis (FEA).**

I. Introduction

Power electronics is a multidisciplinary subject, taught in universities at both undergraduate and Master levels, which covers many areas such as electronics, electromagnetics, power systems, simulation and computing and so on [1]. Although this is an attractive area for students it can be sometimes difficult for them to grasp [2]. Many of the circuits used in power electronics include inductors that consist of a ferrite core, a winding of copper wire and sometimes a coil former [3]. The modeling of the ferrite inductors is a complicated task due to the nonlinearity of the magnetic fields and the great variety of shapes, sizes of the core and number of turns in the winding (Figure 2(a)). Therefore, it is necessary to resort to modeling and simulation techniques as well as experimental measurements to understand circuit operation and obtain enough information to achieve a robust design. Procedures for teaching power electronics considering a linear behavior of the ferrite are found in the literature [4]-[9]. Nevertheless, there is lack of nonlinear procedures suited for this purpose.

In this paper we present a procedure that combines modeling, simulation and experimental measurements on real inductors. We apply this procedure to the modeling and simulation of ferrite inductors, widely used in the field of power electronics. It can be applied to undergraduate and Master level students to help them understand the behavior of the circuits and the nonlinear physical phenomena involved in power electronics. The procedure uses different programming and modeling techniques coupled together: A Computer Aided Design software (AutoCAD), a Finite Element Analysis program (Maxwell), two scientific calculus programs for the numerical solving of derivatives and integrals (Origin and Matlab), numerical simulation program (Simulink) combined with Matlab, and finally, an electronic circuit simulation program (PSIM).

As the procedure is very laborious and complex, we have decided to divide it into four levels with growing complexity that can be applied to students at different educational stages. We will show the division of the procedure and how we will apply the procedure in teaching.

II. Procedure to Simulate Ferrite Inductors

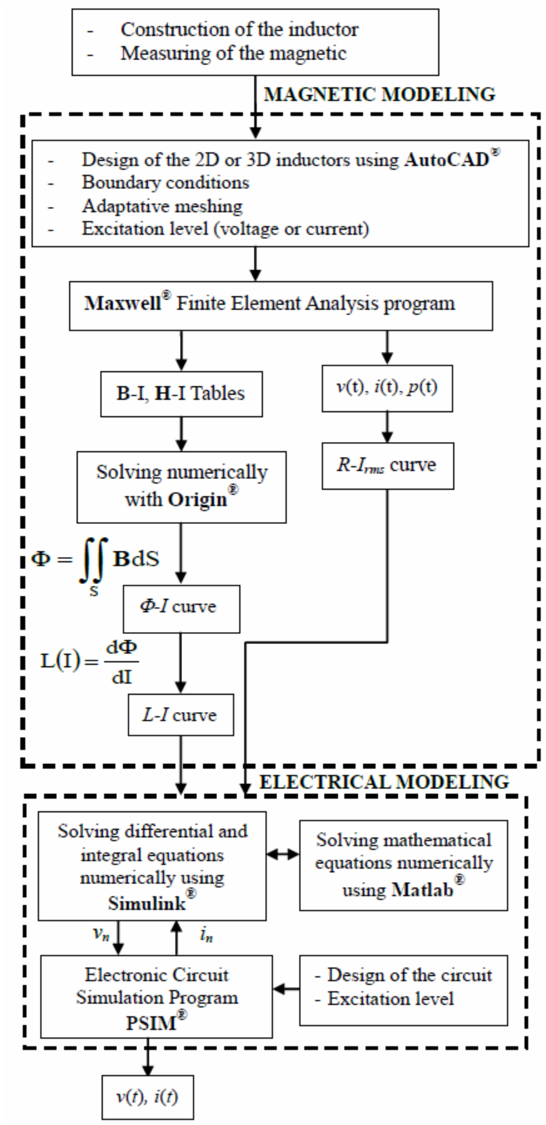
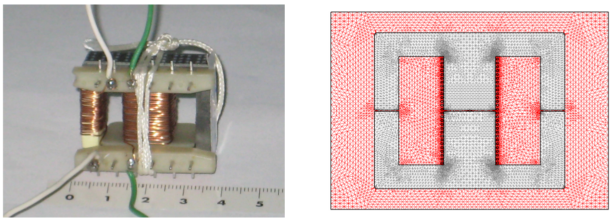


Fig.1. Calculation process diagram.



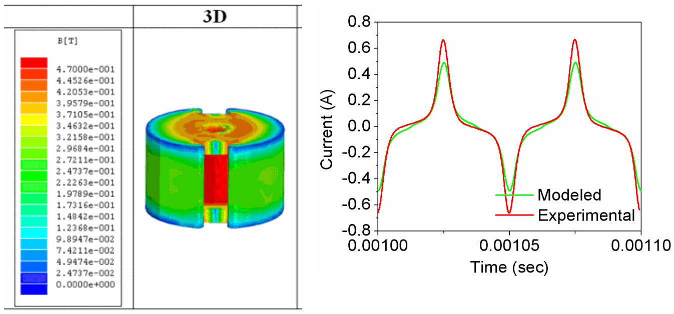
(a) (b)

Fig.2. (a) Real magnetic component with an E core and two windings of 28 turns. (b) Triangular mesh generated by the 2D simulations.

The objective is to obtain the voltage and current waveforms of an inductor of ferrite core corresponding to its serial electric circuit. It consists of two nonlinear parameters: inductance L as a function of the current (L-I curve) and core resistance R as a function of the rms current I_{rms} and frequency (R-I_{rms} curve). Students get these parameters by 2D or 3D Finite Element simulations following the diagram of Figure 1. The process begins with the construction of the inductor and the measurement of the magnetic properties of the core (B-H curve). Next, students use AutoCAD to design the inductor in 2D or 3D. These designs are introduced in the Maxwell software together with the adaptative meshing conditions and the excitation levels values (voltage and current). Students then run the Maxwell FEA software and obtain the distribution of the **B** and **H** fields as a function of the current I and the power and current waveforms. Students use Origin at the postmodeling step to obtain the values of L and R by derivation and integration. After this, students develop a computer software based on Matlab, Simulink and PSIM where the L and R values are included. Finally, they get the waveforms from PSIM.

The level division is as follows. The first level consists of four activities: design and construction of the inductors and transformers (Figure 2(a)), preliminary experimental measurements at low current intensity, DC current experiments and AC current experiments. These activities are useful for undergraduate students and can be suggested as optional additional work for the subject. The optimal organization would be individual or groupwork.

The second level, also useful for students at the Bachelor level, focuses on the design, analysis and simulation of the inductors with ferrite cores using Finite Element Analysis. In general, the software based on this analysis has a visual interface and provides a physical and extremely useful perspective which helps students understand concepts that are difficult for them (Figures 2(b) and 3(a)). As the simulations can be carried out in 2D or in 3D, the instructor can propose different geometries and compare the 2D to 3D results.



(a) (b)

Fig.3. (a) Values of the **B**-field module in 2D and 3D on the surface of a POT core. (b) Experimental and PSIM current waveforms when the core is saturated.

Finally, the third and fourth levels can be applied to students at the Master level. The complete procedure is applied to a specific geometry and the results are validated with experimental measurements for the case of a sinusoidal waveform. An example can be seen in Figure 3(b). Another more interesting example would be its application and validation with experimental measurements for the case of a square waveform widely used in power converters.

As an alternative to the software that we have proposed other software can be used, such as OpenCascade, FreeFEM, Scilab, Octave, and so on. The methodology would be the same.

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