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Alberto Delgado, Maria Iñiguez, Jesús A. Oliver

Accepted version of the paper presented at the 13th European Space Power Conference (ESPC 2023), Elche, Spain.

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Open-Source GUI for Fast Prototyping of Magnetic Components Based on Planar Conductors

Alberto Delgado
Universidad Politécnica de Madrid
Centro de Electrónica Industrial
Madrid, Spain
0000-0002-7099-6961

Maria Iñiguez
Universidad Politécnica de Madrid
Centro de Electrónica Industrial
Madrid, Spain

Jesús A. Oliver
European Space Agency
Noordwijk, Netherlands
0000-0002-5286-5378

Abstract Optimisation of magnetic components is a key factor in the development of robust and efficient power electronics converters for space applications. Analytical calculations could help with preliminary designs; however, more powerful tools are needed, such as FE tools. In this work, an open-source graphical user interface, esaFEMM, is presented for conducting finite element analysis of magnetic components based on planar conductors and to obtain preliminary PCB prototypes. The proposed tool allows one to analyze the electromagnetic parameters of a planar transformer or inductor based on finite element results using open-source software (FEMM®) without requiring knowledge on FE. The commercial magnetic cores RM, PT and PH are modeled, in order to perform 2D axisymmetric simulations to accelerate the analyses. In addition, the tool generates a preliminary PCB design for the simulated magnetic components.

Keywords— *Electromagnetic simulation, FEM, GUI, magnetic components, Open-source tool, PCB generation, Planar conductors.*

I. INTRODUCTION

Designing magnetic components in any power conversion application is a crucial task. In the design process of the magnetic components' details such as the magnetic flux density inside the magnetic core, the H field incident on the conductors, the inductance and winding resistance, and the power losses are very important to obtain. Analytical equations from the literature can help in a first stage to estimate inductances, flux densities, or core losses. However, applications such as space, further refinement steps of the magnetic component design need to be performed and that is why finite element tools are very necessary.

Ansys Maxwell® [1] or Comsol Multiphysics [2] provide you with all the necessary parameters for the design of magnetics. However, the cost of their licensing or ease of use, however, is not affordable for everyone.

Therefore, there are several examples of open-source programs [3-6], such as FEMM® which is a suite of programs to solve low frequency electromagnetic problems in two-dimensional planar and axisymmetric domains. However, their interface is not easy to use, the model preparation is very time-consuming, all parts of the magnetic components have to be drawn manually, etc.

For this purpose, in this work, it is presented esaFEMM (Fig. 1) that is an open-source project that focuses on fast prototyping of magnetic components based on planar conductors for space applications. The main objective is to provide a graphical user-friendly interface to conduct finite element simulations and design of different magnetic cores based on PCB or planar conductors using free software: FEMM [6] and KiCad [7].



Fig. 1. esaFEMM logo

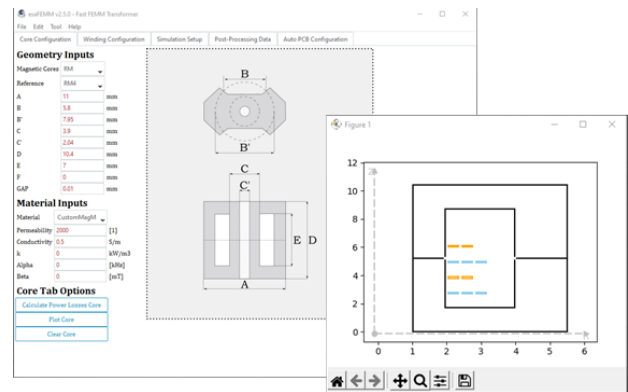


Fig. 2. GUI of esaFEMM based on Python

FEMM® is a very powerful tool to simulate different applications (electrical machine, magnetic components, etc.) but is limited to 2D. In this way, esaFEMM also includes analytical models to convert 3D magnetic cores, such as RM, into 2D axisymmetric cores. On the other hand, KiCad® is a free open-source electronics design suit that included printed circuit board layout with a high-quality component library.

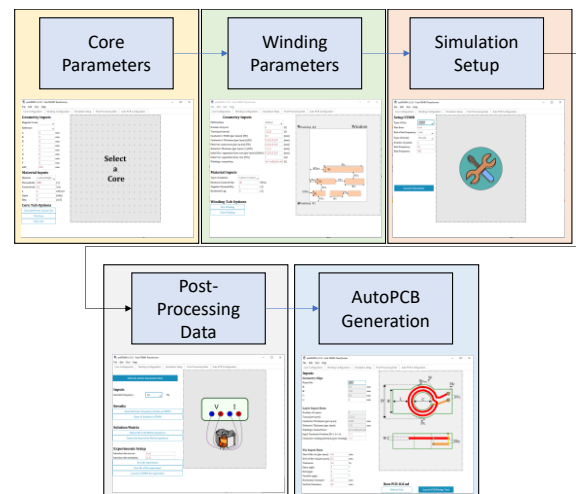


Fig. 3. Workflow of esaFEMM

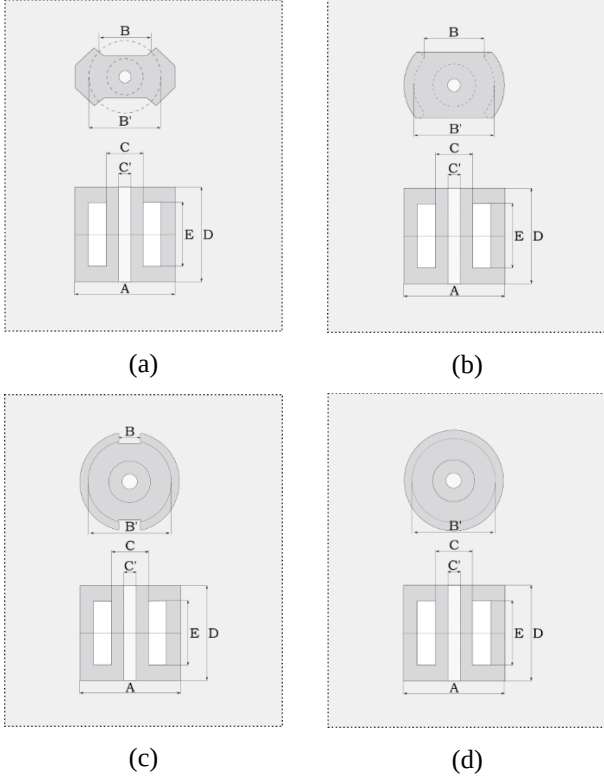


Fig. 4. Magnetic core included in esaFEMM: a) RM core,, b) PT core c) PH core d) 2D axisymmetric approximation of the geometry of the magnetic core that will be simulated.

The user-graphical interface of esaFEMM (see Fig. 2) is based on the open source programming interface Tkinter tool Tkinter from Python.

The workflow is shown in Fig. 3 which is divided into 5 sections. The first 2 sections allow one to introduce the geometrical parameters regarding the magnetic core and the winding specifications. The following 2 sections allow one to configure and to analyze the Finite Element simulation conducted in FEMM. In the last section, a tool is included for fast prototyping of the simulated magnetic components by obtaining a preliminary design of the PCB.

II. GEOMETRIC MODELER OF ESAFEMM

A. Magnetic Core Modeling and Configuration

The most commonly used commercial cores in this kind of applications are RM, PH and PT (see Fig. 4a, 4b and 4c). These three geometries are 3D, so if those cores want to be simulated, the 3D electromagnetic analysis tool needs to be employed. However, on the one hand, FEMM® only simulates in the 2D domain, and on the other hand, in order to speed up such simulations and reduce the complexity of the simulation, modeling should be done to translate the 3D geometry into a 2D geometry as in Fig. 4 d.

The advantage of the winding is that nothing needs to be adapted since the windings will be axisymmetric in all cases. However, the 3D core geometry has to be translated into the 2D axisymmetric domain.

For this purpose, the approach developed in [8] is applied, where the approach is based on the gap reluctance, R_{gap} , must be equal in the 2D geometry and in the real 3D geometry:

$$R_{gap} = \frac{l_{gap}}{\mu_{gap} A_{gap}} \quad (1)$$

Where l_{gap} , μ_{gap} and A_{gap} are the effective length, permeability, and area of the gap, respectively. Then, instead of changing all the parameters in a first iteration, it is more intuitive to change the area of the gap in order to have the same reluctance in the 2D as in the actual 3D geometry.

Thus, the A parameter of the 2D axisymmetric geometry shown in Fig. 4d, could be calculated by (2):

$$A_{2D} = \sqrt{C^2 - C'^2 + B'^2} \quad (2)$$

In order to introduce the configuration of the core, it is needed to select the magnetic core: RM, PT, PH or 2D Axisymmetric. esaFEMM includes several references from Ferroxcube [9], and in future releases other manufacturers will be included. The input fields for the geometry are the parameters A, B, C, D, E, and F, common in all manufacturers' datasheets, which allows any non-expert user to enter their reference, that will be set automatically when one reference is selected.

If the user would like to change the specifications, it is possible to set them, and there is even a tool to visualize the core to check that everything is correct, and internally it includes the necessary modeling to modify the parameters A, B, C, D, E and F into new ones that allow their simulation in 2D with axis of revolution (cylindrical about Z) as shown in Fig. 4d.

In addition to geometry, the material of the core must be defined. esaFEMM includes three different materials modeled for several frequencies. Provides the power losses for sinusoidal waveforms, since the FE simulations are conducted for sinusoidal excitations. As in the geometry input field, the material could be customized by the user by introducing the magnetic relative permeability, electrical conductivity, and the Steinmetz parameters.

B. Winding Configuration

The winding is based on PCB conductors and is fully customizable (see Fig. 5).

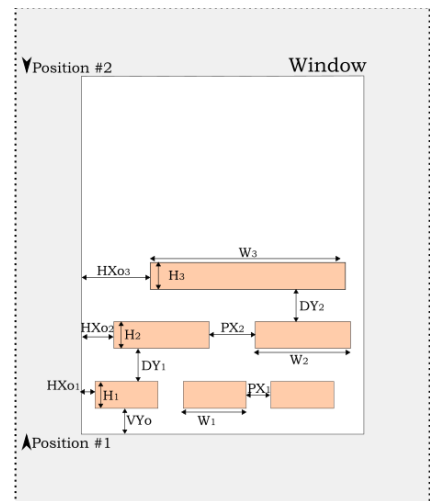


Fig. 5. Winding's geometry

Geometry Inputs

PCB Position	Bottom	
Number of layers	4	[1]
Turns [per layers]	2,4,2,4	[1]
Conductor's Width [per layers] (Wi)	0.8,0.3,0.8,0.3	[mm]
Conductor's Thickness [per layers] (Hi)	0.1	[mm]
Pitch btw conductors [per layers] (PXi)	0.1	[mm]
Dielectric Thickness [per layers-1] (DYi)	1	[mm]
Initial Hor. separation from core [per layers] (HXoi)	0.1	[mm]
Initial Ver. separation from core (VYo)	1	mm
Winding's connection:	w2*w4,w1,w3	[1]

Fig. 6. Input fields for winding geometry

At the beginning of the winding configuration, it is possible to define the position of the layers (bottom or top) on the window of the previously selected magnetic core. Then, the number of layers that will form the winding to be simulated/prototyped must be defined.

Do define the number of turns, two scenarios are then possible:

1. All the layers contain the same number of turns, then a number is introduced.
2. Each layer contains different turns, and then the number of turns is entered as a vector.

The same can be done for the width, thickness, pitch, and thickness of the dielectric between conductors and layers. In Fig. 6 is shown the Winding's Geometry Inputs field.

Due to the working of FEMM, each layer will be simulated as independent, so that its impedance matrix can be extracted, (more details in section III). Although esaFEMM includes a functionality that will serve in the post-processing tab to be able to obtain the equivalent impedance matrix of the simulated magnetic component. To this end, the connection between layers must be described in the winding's connection field. It is defined as w_i where i is the position of the defined layer, and using for series connection the symbol (+) or parallel connection by using (*), and to define separate windings, (,) is used.

Fig. 7 shows two different examples. Fig. 7a illustrates a winding consisting of 4 layers, with [3,2,3,2] turns. The winding's connection is defined by w1+w3, w2*w4, i.e., the primary is formed by the first and third layers and are

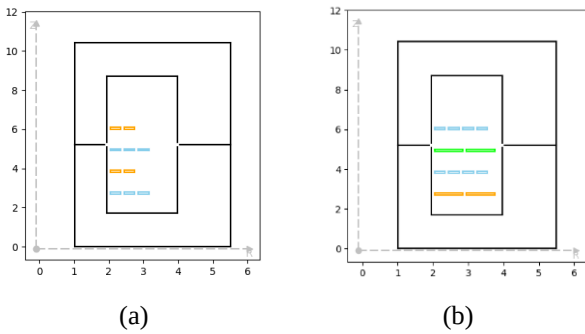


Fig. 7. A) A primary is defined as w1+w3, and a secondary as w2*w4. B) It is defined a primary winding formed by w1, a secondary with w2 in series with w4, and a tertiary formed by w3.

connected in series, and the secondary is formed by the second and fourth layers and are connected in parallel.

Fig. 7b shows three different windings where the first layer is the primary, the second and fourth formed the secondary, and the tertiary is formed by the third layer.

III. ELECTRO-MAGNETIC SIMULATION

A. FEMM configuration

Once all the geometrical aspects of the magnetic component to be simulated have been specified, the simulation parameters must be configured, such as the type of simulation: single or sweep frequency analysis, the maximum error allowed for the convergences, the frequency or frequency range.

Once configured, the algorithm of esaFEMM will build a Python file based on the femm library to perform a simulation for each defined frequency, and for each frequency it will perform a simulation for each defined layer. This is due to the fact that FEMM gives induced voltage and current of the defined excitations (windings), so, in order to obtain the full matrix of the magnetic components (3), esaFEMM conducts N-simulations where $I_i = 1$ and the others are configured to be 0, for $i = 1 \dots N$. In this way, the impedances Z_{i1} are going to be obtained in the first simulation, Z_{i2} in the second, and Z_{iN} in the Nth simulation.

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & \dots & Z_{1N} \\ Z_{21} & Z_{22} & \dots & Z_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ Z_{N1} & Z_{N2} & \dots & Z_{NN} \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_N \end{bmatrix} \quad (3)$$

For instance, if the component has three layers (see Fig. 8a), it is necessary to excite layer 1 first, while the other two layers are at 0. Thus, using (3), we obtain:

$$\begin{aligned} V_1 &= Z_{11}I_1 \\ V_2 &= Z_{21}I_1 \\ V_3 &= Z_{31}I_1 \end{aligned} \quad (4)$$

And by repeating this with the current I_2 and I_3 , the rest of the complete matrix can be obtained, with which, in the next tab of the application, short-circuit, open-circuit, excitation and load tests can be performed. In addition, it will also be

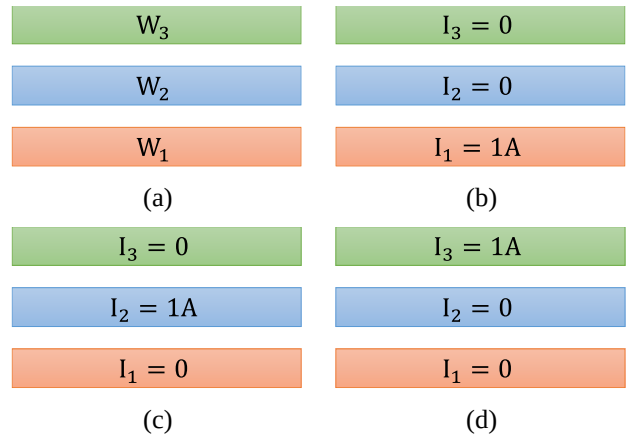


Fig. 8. A) 3-layer windings under study. B) First analysis where w1 is excited. C) Second analysis in which w2 is excited. D) Third analysis where w3 is excited.

possible to obtain the equivalent matrix following the connection configuration defined above.

The geometry is created based on rectangles; this will allow to include other geometries in future releases easily such as EE, EI, UI, etc. For instance, the bottom part of the core is:

- `lffBg.rectangle(Cp*0.5, 0, Ap*0.5-Cp*0.5, (D-E)*0.5, material)`
- `lffBg.rectangle(Cp*0.5, (D-E)*0.5, (C-Cp)*0.5, E*0.5, material)`
- `lffBg.rectangle(Bp*0.5, (D-E)*0.5, (Ap-Bp)*0.5, E*0.5, material)`

Once the geometry, materials, excitation and frequency configurations are defined for each of the different simulations to be performed, it is conducted the simulation in FEMM and all file models and results are saved for further post-processing.

B. Post-Processing Data

Once the finite element simulation is performed for each frequency and layer, the full impedance matrix is obtained. esaFEMM could analyze the full matrix to give different results: equivalent matrix regarding the winding connection, short- and open-circuit analysis, and under load tests.

For this, the full impedance matrix is analyzed by solving the equation generated by trees. For example, if the winding connection is $(W1 + W2) * (W3 + W4)$:

$$\begin{array}{lcl}
 \text{Step 3} & (W1 + W2) * (W3 + W4) & \\
 & v [1 \ 1 \ 0 \ 0] & \\
 & i [1 \ 0 \ 1 \ 0] & \\
 \\
 \text{Step 2} & (W1 + W2) & (W3 + W4) \\
 & v [1 \ 1 \ 0 \ 0] & v [0 \ 0 \ 1 \ 1] \\
 & i [1 \ 0 \ 0 \ 0] & i [0 \ 0 \ 1 \ 0] \\
 \\
 \text{Step 1} & w1 & w2 & w3 & w4 \\
 & v [1 \ 0 \ 0 \ 0] & v [0 \ 1 \ 0 \ 0] & v [0 \ 0 \ 1 \ 0] & v [0 \ 0 \ 0 \ 1] \\
 & i [1 \ 0 \ 0 \ 0] & i [0 \ 1 \ 0 \ 0] & i [0 \ 0 \ 1 \ 0] & i [0 \ 0 \ 0 \ 1]
 \end{array}$$

This allows us to solve the matrix and obtain an equivalent matrix that behaves like the given connection. Table 1 shows some results of esaFEMM compared to Ansys Maxwell® with different connections.

Table 1. Comparison Ansys Maxwell vs esaFEMM

Conection	w1,w2,w3,w4			
Matrix Ansys Maxwell®	$Z =$	$4.1m\Omega + j\omega 0.108\mu H$ $0.077m\Omega + j\omega 0.172\mu H$ $8.8m\Omega + j\omega 0.353\mu H$ $14.4m\Omega + j\omega 0.775\mu H$	$-0.0036m\Omega + j\omega 0.23\mu H$ $-0.0098m\Omega + j\omega 0.46\mu H$ $0.58m\Omega + j\omega 1.02H$ $22.41m\Omega + j\omega 1.63\mu H$	$-0.0094m\Omega + j\omega 0.306\mu H$ $-0.046m\Omega + j\omega 0.613\mu H$ $0.57m\Omega + j\omega 1.02H$ $22.38m\Omega + j\omega 1.63\mu H$
Matrix esaFEMM	$Z =$	$4.1m\Omega + j\omega 0.108\mu H$ $0.076m\Omega + j\omega 0.172\mu H$ $8.8m\Omega + j\omega 0.353\mu H$ $14.4m\Omega + j\omega 0.773\mu H$	$-0.0032m\Omega + j\omega 0.23\mu H$ $-0.0096m\Omega + j\omega 0.46\mu H$ $0.57m\Omega + j\omega 1.02H$ $22.38m\Omega + j\omega 1.63\mu H$	$-0.0084m\Omega + j\omega 0.305\mu H$ $-0.045m\Omega + j\omega 0.611\mu H$ $0.57m\Omega + j\omega 1.02H$ $22.38m\Omega + j\omega 1.63\mu H$
Conection	(w1+w2)*(w3+w4)			
Matrix Ansys Maxwell®	$Z = [20.681m\Omega + j\omega 2.05\mu H]$			
Matrix esaFEMM	$Z = [20.69m\Omega + j\omega 2.05\mu H]$			

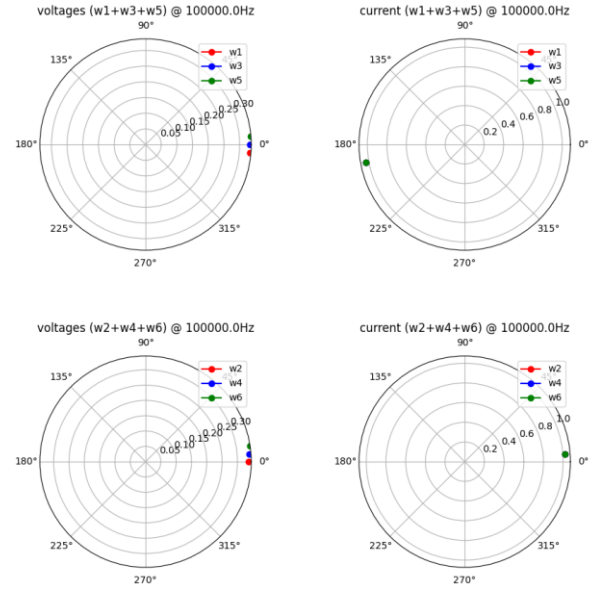


Fig. 9. Primary is excited with 1V and at secondary is placed a resistor of 1Ohm. Then, the calculated voltages and current are plotted.

In addition to the equivalent matrix, it is also possible to perform load analysis, where, for example, if we had a transformer consisting of a 3-turn primary and a 3-turn secondary, and we excite with 1 V at the input and a load of 1 Ohm, we could obtain the voltages and currents in each layer and also their phases (see Fig. 9).

IV. AUTOPCB GENERATION

Finally, this esaFEMM includes a tool that allows the generation of Gerber files for the PCB prototyping of the designed magnetic component.

This tool allows you to choose different geometric aspects of the tracks and vias as shown in Fig. 10. It is currently in a first development phase, which allows you to obtain basic preliminary designs as can be seen in Fig. 11. This is generated using the free tool kiCad [7].

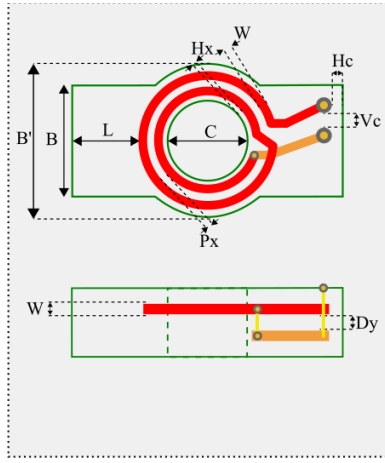


Fig. 10. Customizable PCB parameters

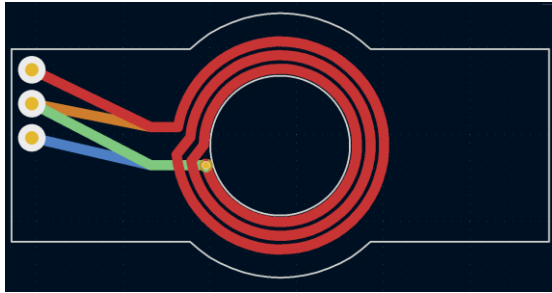


Fig. 11. Example of an inductors made of 4 layers.

V. CONCLUSIONS

The open source tool esaFEMM aims to facilitate the design and prototyping of magnetic components based on

planar conductors. For this purpose, esaFEMM consists of a GUI that allows the introduction of the geometrical parameters of the core and winding in a very simple way, as well as the selection of the materials for each geometry. In addition to the GUI, esaFEMM includes a tool for the generation of the PCB design of the designed coil or transformer. The results provided by esaFEMM and Ansys Maxwell show very good agreement between them, which means that it simulates correctly, in addition to giving the matrices correctly in the presence of different connections.

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