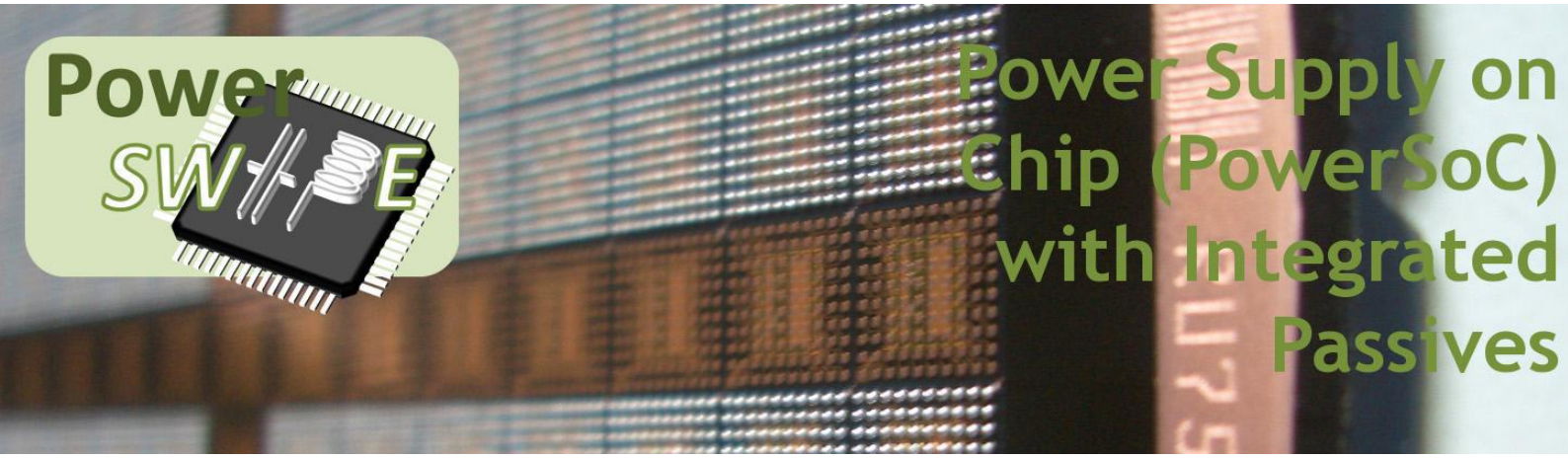

PowerSWIPE (Project no. 318529)

"POWER SoC With Integrated PassivEs"

D2.2: Status Report

"Analysis and optimisation of the integrated passives"

Dissemination level:

Responsible Beneficiary

Centro de Electrónica Industrial, Universidad Politécnica de Madrid

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Summary					
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1. Objectives

As part of the PowerSwipe project, this work focuses on the virtual optimization of integrated passives once they have been optimized by the high level optimization tool (D1.1 Architecture Analysis and Optimization)

The optimization is done by the combination of analytical and finite element analysis tools. For the design, simplified analytical equations are used to have a physical understanding of the critical parameters and then finite element analysis simulations are performed to obtain high accuracy on the calculations.

The document is divided in the following sections:

1) Review of the state of the art in integrated magnetic modeling.
2) Development and implementation of integrated magnetic component models by means of analytical methods.
3) Developmenent and implementation of integrated magnetic components models by means of Finite Element Analysis.
4) Optimization of the integrated passives for the convertes

At the end there are four annex that describes the tool developed in MATLAB and how to use it, the main functions with their parameters and returned outputs to serve as documentation for future improvements and a guide on how to setup the finite element analysis tool for the analysis of magnetic components.

2. State of the art of integrated magnetic

The magnetic components are one of the main parts of the power converters so their integration and miniaturization are needed to achieve high performance in low-volume converters. In addition, inductors and transformers are the largest and most expensive components in power electronic circuits.

In order to achieve the use of smaller passive components the increase of switching frequencies has played a key role. In recent research, converters have been developed to operate at switching frequencies above 10 MHz [1], and up to hundreds of megahertz [2].

However, the scaling of passive component size with frequency is a far more complex issue. For example, in magnetic components depends on winding loss effects, magnetic material core loss characteristics, and heat transfer limits among other considerations. So a compromise between these factors is needed.

Several approaches to microfabricating high-efficiency power magnetic are been explored. As the switching frequencies of the power electronics rise and the size of the magnetics falls, new fabrication strategies for the magnetics become possible as discussed below.

2.1. Power inductors in package vs power inductors on silicon

Now, with advanced technologies, small inductors can be integrated with power ICs and it is possible to realize fully integrated DC-DC converters, which are more compact and have lower cost and better transient performance.

Many techniques have been developed to integrate inductors with power ICs and there are still numerous under-going research and development projects. Currently, Power System in Packaging (PSiP) [3] and Power System on Chip (PSoC) [4] are the two most widely adapted approaches for power inductor integration.

It is an ongoing debate on which approach is better. But people do agree that it depends on the applications and the developed technologies. The table below tries to make simple comparisons between inductors in packages and inductors on silicon.

	Inductors in package	Inductors on silicon
Inductance	High	Low
DC resistance	Low	High
Saturation current	High	Low
Magnetic material	More options	Limited
Output power	High	Low
Size	Large	Small
Cost	High	Low

Table 1: comparisons between inductors in packages and inductors on silicon [5]

2.2. Power inductors on silicon

More interestingly and promisingly, the microelectromechanical systems (MEMS) technology provides the capability of producing high-power-density inductors at the micron scale and monolithically integrating these tiny inductors on power ICs, and realizing Power System on Chip (PSoC), which can lead to further size reduction of power converters. Moreover, the fabrication advantages of MEMS technologies will further reduce inductor cost and ease the packaging.

A number of research teams have developed microinductors. There is a table below that shows previous works in magnetic microinductors, tested in dc/dc converter applications [6][7], [8]

Author	Freq (MHz)	L (μH)	Conv. Eff.	Inductor Area
Kowase '05	1.0	0.14	80.0%	225 mm^2
Kim '01	1.2	1.6	80.0%	78 mm^2
Kim '02	1.8	1	81.0%	25 mm^2
Park '03	2.2	2.3	75.0%	65.55mm^2
Nakazawa '00	3.0	0.96	81.9%	16 mm^2
Sato '00	5.0	0.36	82.0%	36 mm^2
Prabhakaran '05	5.0	0.01	78.0%	9.02 mm^2
O'Donnell '08	20.0	0.1	67.0%	6.4 mm^2

Table 2: microinductor technology implemented in a dc/dc converter [9]

However, these inductors were still relatively large. Significant size reduction can be achieved by increasing the switching frequency further, and others works have demonstrated high efficiency inductors-on-silicon for power conversion applications, e.g., [4], [10]–[15]

Also, below are some examples of current research and recently works:

In [10] a range of low value micro-fabricated inductors (100 – 400 nH) have demonstrated high efficiency in a 20 MHz switching converter. The area of these devices ranged from 2.4 – 11.7 mm.

In [16][30] a 2.9 mm^2 embedded inductor with an inductance of 43.6 nH and a peak Q-factor of 16.2 is fabricated. It achieves a saturation current of 10 A, making it promising for on-chip light-emitting diode driver applications.

In [17] V-groove inductors were fabricated and the inductors exhibit an inductance of 3.4 nH from 10 to 100 MHz, a dc resistance of 3.83 mΩ, and a quality factor up to 66. The prototype inductors are a promising candidate for high-power-density high-efficiency dc–dc converters.

2.3. Topologies

Microfabricated inductors are implemented either with or without magnetic core material. Air core inductors benefit from having no core losses, but the resulting required switching frequency is very high (e.g., several hundreds of megahertz) due to the relatively low inductance value obtainable.

To increase the specific inductance, and thereby lower the switching frequency, it is necessary to form a closed-loop for the magnetic flux [10]. That is an important consideration for the integration of inductors in the power converter. High magnetic fields may have adverse effects on the active circuitry in an enclosed packaging.

2.3.1. Inductor designs with thin-film magnetic cores

In order to take full advantage of the core (increase the inductance and confining the flux) the core path has to be closed or nearly closed. The winding and the core must then constitute two interlinked loops [18]. Interlinking the two requires at least three deposition steps: either the core orthe winding can occupy just one layer, but the other needs to be deposited in two steps.

We can see an example of two depositions of magnetic material in figure (a) and (c) because they have magnetic material surrounding a coil (pot-core). An example of two depositions of conductor is shown in figure (b), (d) and (e) where they have a coil surrounding a core (toroidal).

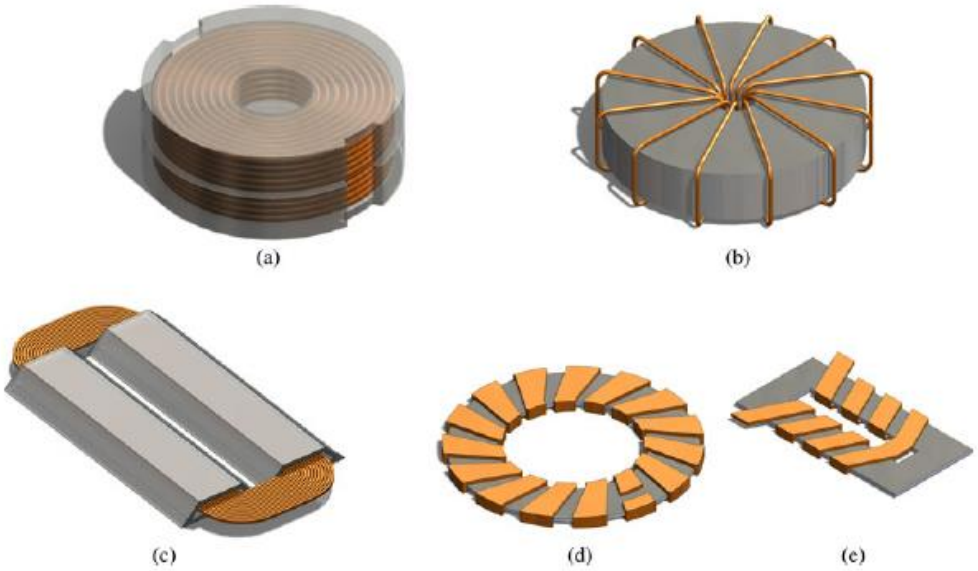


Figure 1: Classes of magnetic-core inductor and transformer geometries [18]

It was shown that using two magnetic layers (the “potcore” category) results in higher power density for typical constraints.

Another factor favoring the use of two magnetic layers is that many of the materials are anisotropic, and it is necessary to keep the direction of magnetic flux parallel to one axis.

The most common type thin-film “pot-core” geometry is the **racetrack design** in Fig. (c), which uses magnetic material only on two sides to allow the use of anisotropic material with aconsistent orientation [18].

Our tool focuses on the design of this type inductor.

Other varieties of microfabricated inductors in the “pot-core”class include single-turn strip-line inductors such as V-groove inductors [17], and inductors with the windings embedded in

the substrate with magnetic material deposited on both sides of the substrate to surround the coil [19].

3. Racetrack inductor design

As is shown in [1], the micro-fabricated racetrack inductor is an effective geometry for PSiP and PwrSoC systems due to the simpler manufacturability of magnetic material around straight conductors rather than rounded conductors. Also, the magnetic flux travels in the device in a single direction, perpendicular to the long axis of the core, and it allows for the exploitation of anisotropy in the material, to reduce core losses.

In the following sections, we show an overview of the construction process in racetrack inductors to understand the design limitations. Then the analytical model is described for performing a fast approximate design. After that, it is explained how to design by means of a finite element tool that allows us to obtain a more accurate design.

3.1. Overview of fabrication process

This section details the Tyndall 'Magnetics on Silicon' process [2]. The 'Magnetics on silicon' process was developed for the fabrication of micro-inductor and micro-transformer structures. The process is currently employed to fabricate 'elongated spiral' or 'racetrack' device structures. The top view and the cross-section of the racetrack magnetic structure are shown in Figure 2.

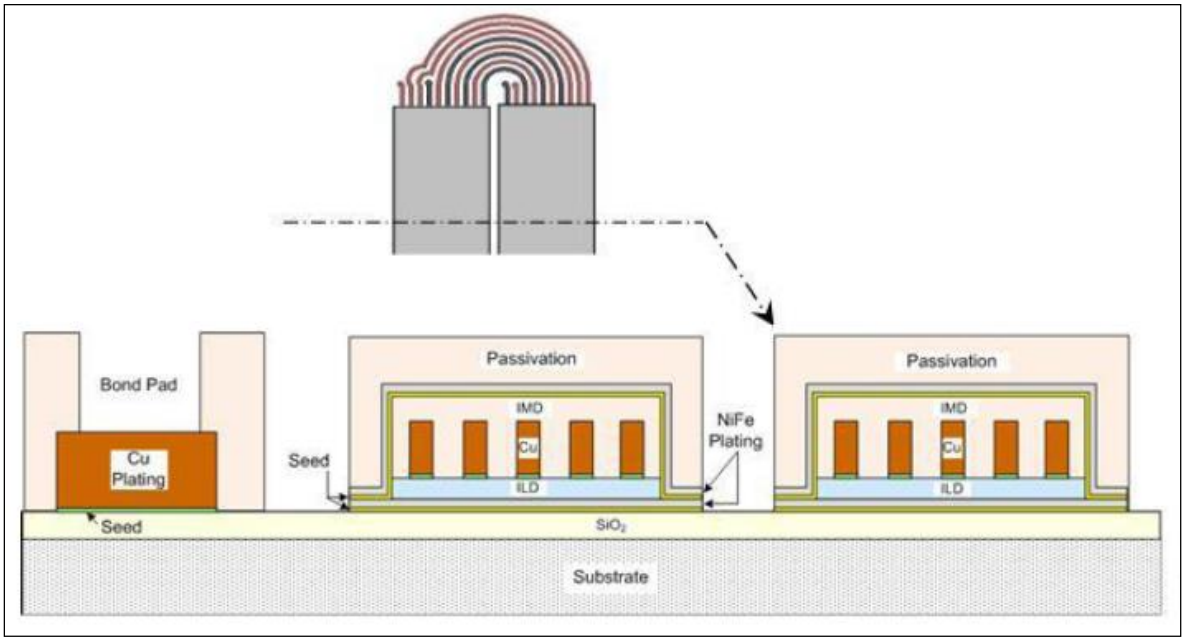
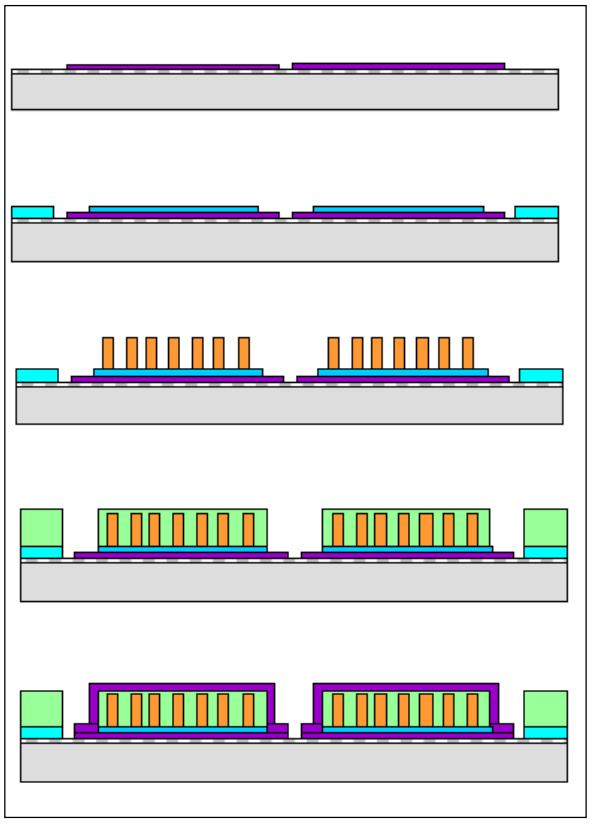


Figure 2: top view and cross-section of the racetrack structure [2]

The Tyndall Magnetics on silicon process is a 5 mask with 20 process steps. A flow chart of all the steps involved in shown in the next figure.



Layer 1: electroplated bottom core layer

Layer 2: insulator layer between bottom core and winding

Layer 3: electroplated copper winging layer

Layer 4: insulator layer between top core and winding

Layer 5: electroplating top core layer

Figure 3: fabrication process of the racetrack inductor [2]

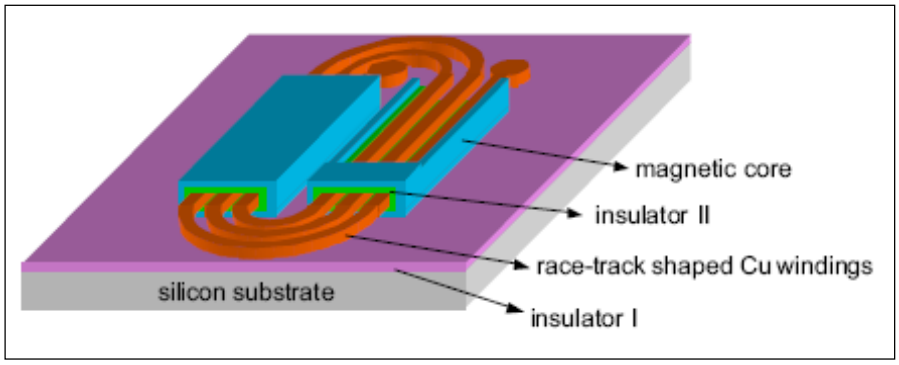


Figure 4: different materials of the inductor [2]

The Tyndall racetrack micro-inductor structure employs $Ni_{45}Fe_{55}$ as a core material. The magnetic and physical properties of $Ni_{45}Fe_{55}$ thin films are shown in the next table.

Property	Value
Flux Density	1.44 T
Coercivity	80 A/m
Resistivity	45 μΩ·cm

Table 3: magnetic and physical properties of $Ni_{45}Fe_{55}$ thin films

These properties suggest $Ni_{45}Fe_{55}$ with relatively higher resistivity and high flux density is an ideal core material for high frequency inductor structures.

The Tyndall magnetics on silicon process employs BCB 46 as Inter Layer Dielectric (ILD). It provides insulation between bottom magnetic core and copper conductor tracks. Su-8 50 is employed as an Inter Metal Dielectric (IMD), to insulate copper conductor tracks and top magnetic core. As BCB, Su-8 is also a photo sensitive negative resist which is patterned using lithography.

Finally, copper is used as conductor in the micro-inductor structure. Copper is deposited using direct current electroplating technique.

3.2. Influence of technological parameters

The numbers of turns, conductor width and thickness, core thickness and all the geometrical parameters affect the electrical properties and losses of the inductor. Several parameters must be fixed or constrained, due to technology limitations of the process.The key parameters are:

The **core thickness** is usually limited by the eddy current losses and hence, the core thickness can not be much greater than the skin depth at the operation frequency of interest.

$$\delta = \sqrt{\frac{\rho}{\pi f \mu}}$$

If thicker cores are needed, then the solution can be the use of laminated cores.

The **conductor width,** the higher the width the lower its DC resistance (and consequently the higher the quality factor). Nevertheless, the width is limited by the area of the inductor and the number of turns. As the frequency of operation increases, the improvement in resistance achieved by increasing the width begins to diminish due to the skin effect. If the width is kept below two skin depths at the frequency of operation, this diminishing return effect is minimal. The **conductor height**, behaves somewhat similarly to the width.

Another consideration is that the minimum **conductor spacing and aspect ratio** are dependent on the limitations of the photoresist and lithography process used for the windings.

N (number of turns) has the largest influence on the inductance in the area consumption. For smaller footprint areas the conductor width are smaller in order to fit the turns into the area and hence the ratio of dc resistance to inductance increases. In order to decrease the dc-resistance to inductance ratio further, the minimum conductor spacing would need to be reduced, the aspect ratio of the conductors increased (i.e., thicker but not wider conductors), or the allowable thickness of the magnetic core should be increased [11].

Another solution could be a multilayer inductor, which provides benefits such as higher inductance values using the same on-chip space or inductor area.

3.3. Analytical design

Brute force optimization of the magnetic components using finite element analysis is prohibited due to the high number of degrees of freedom: material properties, core dimensions,

conductor thickness, number of turns, etc.. To guide the design process, analytical equations will be used to provide physical insight into the optimization process and once the design is optimized a more accurate model of the magnetic component will be obtained by means of FEA tools.

In high frequency AC inductors, the quality factor Q is an important figure of merit of the inductor. However, for DC power inductors, especially when the AC ripple current is relatively small compared to the DC component of the current, the DC value of the resistance has a significant impact on the conduction losses and, if the dimensions of the conductor are chosen to be smaller than two times the skin depth, the increase of the resistance at the switching frequency will not be significant.

So in the first stage of design, we used an approximated method to achieve the lowest DC resistance satisfying the inductance requirements and all the technological restrictions. The analytical model allows optimizing the design due to its speed and gives us a physical sense on the optimization procedure.

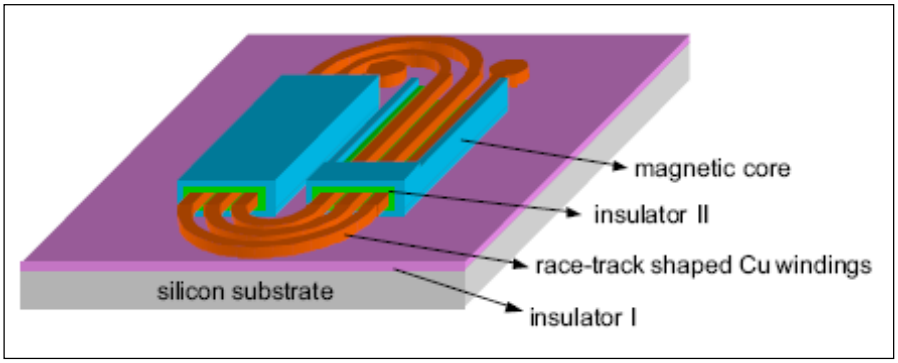


Figure 5 Racetrack inductor schematic

The following assumptions are made for the racetrack inductor of Figure 5:

1) The current through the conductors is equally distributed (skin and proximity effects are negligible). These effect will be taken into account with the FEA tool in the last stage of the design.
2) The racetrack inductor can be divided in two parts, one with a magnetic core and other without the magnetic core
3) For each of these parts we can assume infinite long magnetic component and calculate the inductance and resistance per unit length.
4) All the magnetic energy is stored in the cores.

In the next figures, we specify the names of the different parameters:

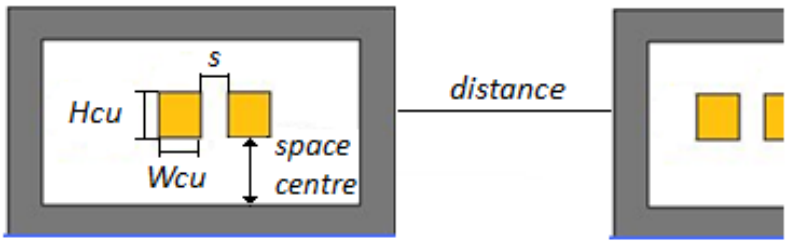


Figure 6: parameters of the inductor I

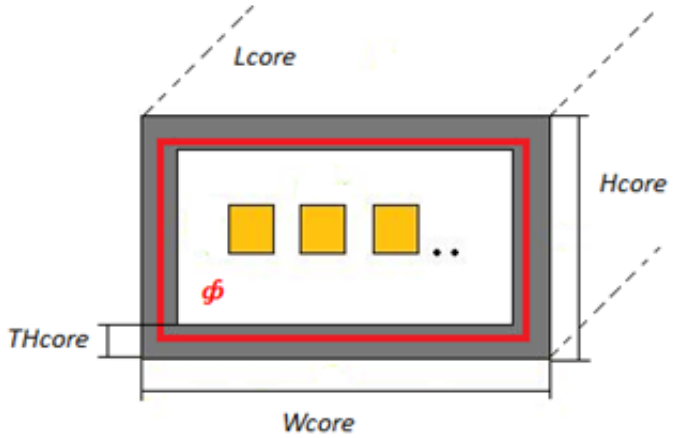


Figure 7: parameters of the inductor II

Our analytical model begins by calculating the **length of the core,** function of the number of turns and the desired inductance value. The more inductance needed, the greater length of the core will be required. On the contrary, as we increase the number of turns, decrease the length. We assume that the flux is concentrated in the core and is constant. [20] (can be related to the volume and the maximum flux density of the material

Combining (4) and (5)

(3)(6)

Where:

conductor

(

(

(see 9)

$$X = 2 \cdot Wcore + distance$$

$$Y = Lcore + X$$

$$Area = X \cdot Y$$

Where:

- **X** is the width of the racetrack inductor
- **Y** is the height of the racetrack inductor
- **Distance** is the core separation

Now that we know the maximum number of turns, we calculate the resistance Rdc for all designs to Nmax. The final design will be the one with the **least resistance**.

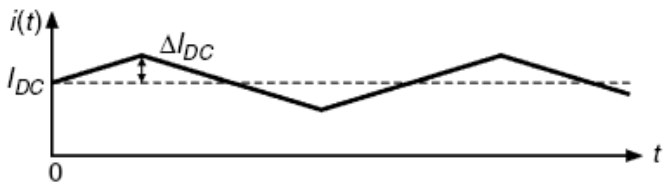
Sometimes the occupied inductor area is larger than desired, so the tool that we developed shows a message via Matlab and it selects the number of turns for which you get the smaller area (see an example in section 5.2).

Most of the energy losses of an inductor come from its DC resistance (R_{DC}) as long as the ripple can be reflected. We assume that $R \simeq R_{dc}$. **The power loss due to DC resistance** is given by:

$$\boxed{P_{dc} = R_{dc} \cdot I_{L\_rms}{}^2} \qquad ($$

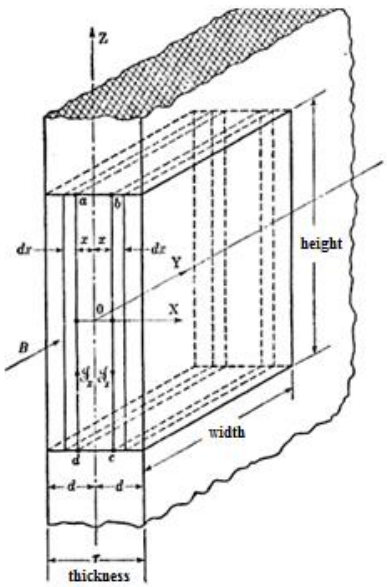
where I_{L_rms} is the rms current of the inductor (10) and it is calculated as:

$$I_{L\_rms} = \sqrt{I_{dc}{}^2 + \frac{\Delta I_{dc}{}^2}{3}} \qquad ($$



Triangular Waveform with DC Component

We have also developed a model based on simple equations for estimating **losses in the core**. To illustrate the conditions that exist in a core, consider a thin flat block of conductive material as shown in 11. Assumed uniformly distributed magnetic field.



core losses calculation [53]

If the conductive material has a conductivity of σ, the current density along "bc" or "da" can be calculated as:

$$J_x = x \frac{dB}{dt} \sigma \qquad ($$

The instantaneous power loss in the block with a width of 1, a height of 1 and a thickness of τ is calculated as:

$$2\int_0^d \frac{J_x{}^2}{\sigma}\,dx = 2\left(\frac{dB}{dt}\right)^2 \sigma \int_0^d x^2\,dx = \frac{2}{3}\left(\frac{dB}{dt}\right)^2 \sigma\, d^3 \qquad ($$

In our case, the width and height are not unitary, but correspond to Lcore and (2Hcore +2Wcore) respectively. Furthermore, our thickness d corresponds to THcore/2. Therefore, we have:

$$\boxed{Pcore = \frac{2}{3}(2Hcore + 2Wcore)Lcore\left(\frac{dB}{dt}\right)^2 \sigma \left(\frac{THcore}{2}\right)^3} \qquad ($$

3.4. Design based on finite element analysis

In order to obtain more accurate results, a two dimensional finite element analysis tool has been used. The tool selected is Maxwell 2D. Maxwell is an interactive software package that uses finite element analysis (FEA) to solve two-dimensional electromagnetic problems.

To analyze a problem, you specify the appropriate geometry, material properties, and excitations for a device orsystem of devices. The Maxwell software then does the following:

• Automatically creates the required finite element mesh.

• Calculates the desired electric or magnetic field solution and special quantities of interest, such as force, torque, inductance, capacitance, or power loss. The specific types of field solutions and quantities that can be computed depend on which Maxwell 2D solution type you specified (electric fields, DC magnetics, AC magnetics, transientfields and data).

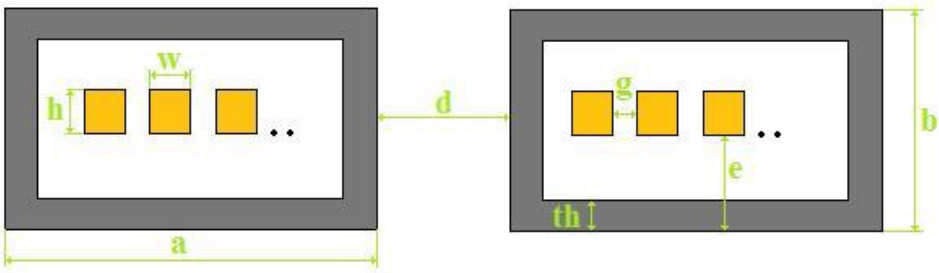
• Allows you to analyze, manipulate, and display field solutions.

Below we detail the process for designing racetrack inductors.

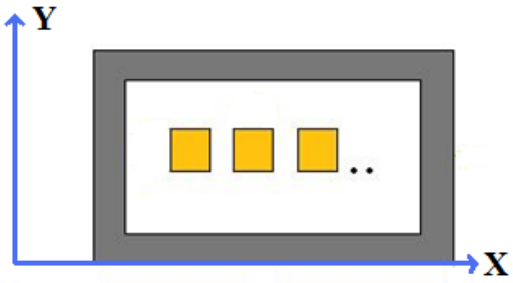
3.4.1. Racetrack inductors

The problem we want to address is in 3D, but we simplified to 2D because it requires less computation time, which is an advantage in iterative processes of optimization.

The strategy for designing racetrack inductors in Maxwell involves drawing half of the cross section of the inductor and then applies symmetry on the Y axis (12 and 13).

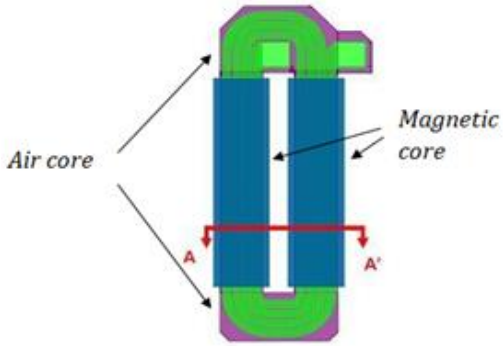


typical cross section of inductor



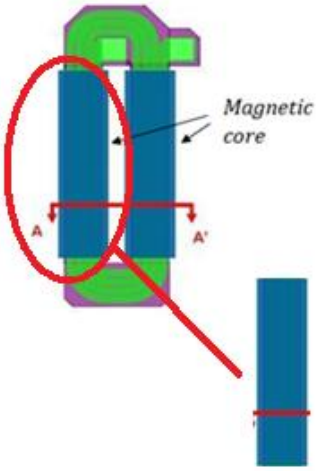
half of the cross section of inductor

We performed two calculations, one with **magnetic core** and one with **air core**.



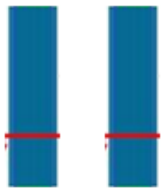
top view of the inductor

The **magnetic core calculation** corresponds to 15:



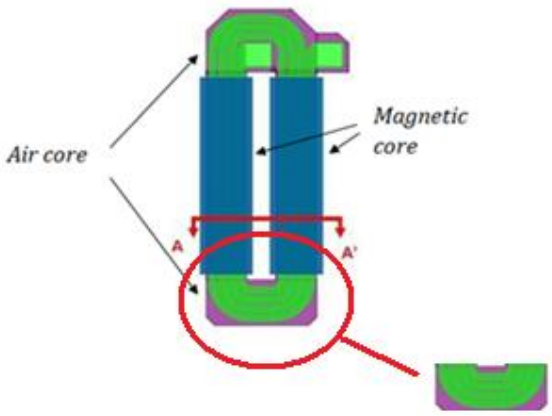
magnetic core calculation I

The results (inductance and resistance) are multiplied by two to get the final result, as it is shown in 16:



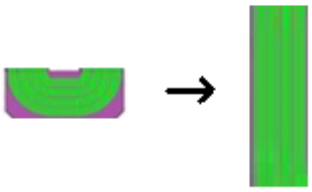
magnetic core calculation II

The **air core calculation** corresponds to 17



air core calculation

We make the approximation that it is shown in 18:



XY approximation for the air core

We obtain this approximation by calculating the length of the circle formed by the windings, employing an average radius.

$$L_{air} = \pi \cdot r_{average} \qquad ($$

Where L_{air} is the length of the circle and $r_{average}$ is the average radius. The results (inductance and resistance) are multiplied by two to get the final resul too.

3.4.2. Calculation of inductance and the resistance

In Annex I we explain how to create the racetrack inductor in Maxwell step by step. Now we focus on how we obtain the results.

The energy stored in a magnetic field can be expressed as:

$$E = \frac{1}{2}\int BH\, dV \qquad ($$

Where B is the magnetic field and H is the magnetic intensity.

So this is what we put into the calculator. We select B and H in Quantities and introduce 1/2 as a constant. The results are shown in 19.

```
Scl : 0.000186410904653302
Scl : *(Integrate(Volume(AllObjects), Dot(Real(<Bx,By,0>), Real(<Hx,Hy,0>))), 0.5)
```

Energy calculation in Maxwell

The energy stored by an inductor is equal to the amount of work required to establish the current through the inductor, and therefore the magnetic field. This is given by:

$$E = \frac{1}{2} L I^2 \qquad ($$

Where L is the inductance and I is the current.

We have designed with a current of 1 ampere. Therefore, we can obtain the inductance value as:

$$L = 2\frac{E}{I^2} = 2\frac{E}{1^2} = 2E \qquad ($$

In the design, the inductor is considered infinitely long, so to obtain the final value, we multiply the inductance value by the length.

To get the value of inductance in the magnetic core design, we multiply by the length of the magnetic core.

$$L_{core} = 2E \cdot Long\_core \qquad ($$

Where Long_core is the length of the core.

To get the value of inductance in the air core design, we multiply by the length of the air core, which we estimate as the length of a semicircle, using the average radius.

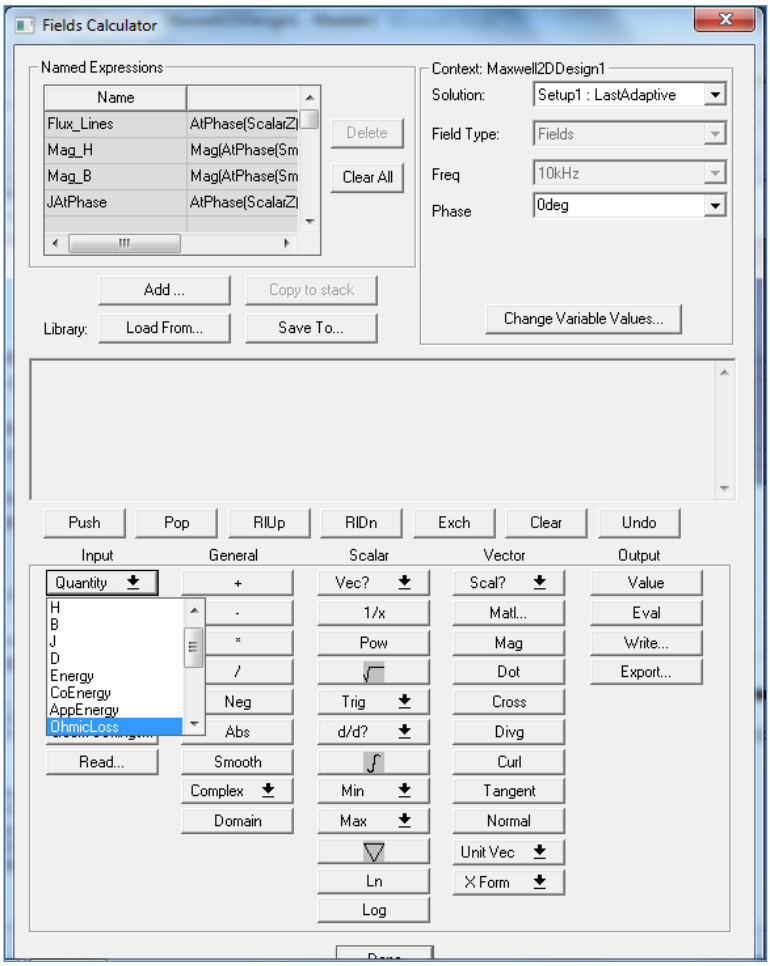
$$L_{air} = 2E \cdot Long_{air} = 2E \cdot \pi \cdot r_{average} \qquad ($$

When $Long_{air}$ is the length of the windings without core.

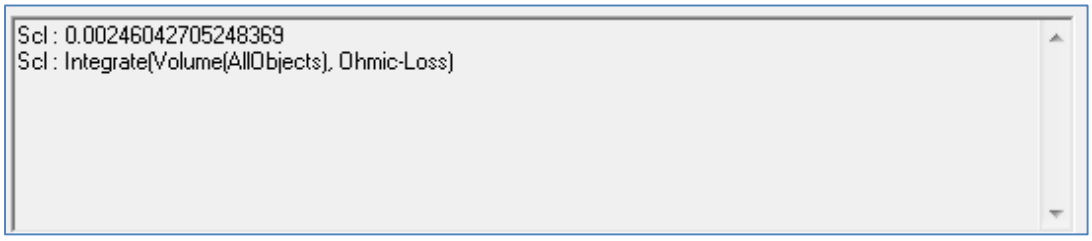
The final value of inductance is:

$$L_{total} = 2L_{core} + 2L_{air} \qquad ($$

Now we are going to get the value of the resistance. To do this we begin by calculating the Ohmic Losses in Maxwell calculator 20.



calculating the Ohmic Losses I



calculating the Ohmic Losses II

The Ohmic Losses are given by:

$$P = \frac{1}{2} R I^2 \qquad ($$

Where R is the resistance and I the current.

We have designed with a current of 1 ampere. Therefore, we can obtain the resistance value as:

$$R = 2\frac{P}{I^2} = 2\frac{P}{1^2} = 2P \qquad ($$

The inductor is considered infinitely long so we follow the process before:

$$R_{core} = 2R \cdot Long\_core \quad ($$

$$R_{air} = 2R \cdot Long_{air} = 2E \cdot \pi\, r_{average} \quad ($$

Where $Long_{core}$ is the length of the core and $Long_{air}$ is the length of the windings without core.

The final value of resistance is:

$$R_{total} = 2R_{core} + 2R_{air} \quad ($$

4. Application of the Analysis and Optimization tool

4.1. Low Voltage 220 nH inductor at 10 MHz

In this section is shown in detail the design of a 220 nH inductor at 10 MHz, whose area should not exceed 4 mm^2. The design will be performed with the tool explained in chapter 4.

The inductor is designed to operate in a converter with specifications shown in table 4. Certain parameters relating to the technology are fixed by the material and shown in table 5.

Converter specifications	
Input voltage	5 V
Output voltage	1.2 V
Output current	500 mA
Ripple current ratio	< 0.5
Switching frequency	10 MHz

Table 4: LV converter specifications

Fixed parameters	
NiFe relative permeability	280
NiFe resistivity	45 μΩ·cm
NiFe flux density	1.5 T

Table 5: NiFe physical properties

In this section is shown the design of a 220 nH inductor at 10 MHz.

The inductor is designed to operate in a converter with specifications shown in table 6. Certain parameters relating to the technology are fixed by the material and shown in table 7.

Converter specifications	
Input voltage	5V
Output voltage	1.2V
Output current	500 mA
Ripple current ratio	< 0.5
Switching frequency	10 MHz

Table 6: converter specifications

Fixed parameters	
NiFe relative permeability	280
NiFe resistivity	45 µΩ·cm
NiFe flux density	1.5 T

Table 7: NiFe phisical properties

4.1.1. Core thickness = 5um

The inductor is designed with one lamination (Core thickness = 5µm).

Table 8 presents the geometric parameters of three designed inductors.

Fixed parameters			
Parameter	**Design A** **N = 3**	**Design B** **N = 4**	**Design C** **N = 5**
Hcore	**75µm**	**75µm**	**75µm**
THcore	**5µm**	**5µm**	**5µm**
Wcore	**242.2µm**	**360µm**	**471.1µm**
Wcu	**50.74µm**	**6.25µm**	**68.22µm**
THcu	**35µm**	**35µm**	**35µm**
Lcore	**4.2mm**	**3mm**	**2.3mm**
Area	**4.23mm2**	**4.31mm2**	**4.69mm2**
Rdc	**0.341Ω**	**0.324Ω**	**0.354Ω**

Table 8: Geometric parameters of several designs for core thickness of 5µm

Table 9 is a summary of the inductances and the resistances of the designed inductors based on analytical calculations, on Maxwell and on Tyndall methodology.

N	Analytical cal. (L / Rdc)	Maxwell	Tyndall (Ls / Rac)
3	220 nH / 0,283 Ω	240,75 nH / 0,341 Ω	262,51nH / 0,331 Ω
4	197,02nH / 0,238 Ω	220,71 nH / 0,324 Ω	245,23 nH / 0,286 Ω
5	192,7nH / 0,240 Ω	221,46 nH / 0,354 Ω	255,82 nH / 0,298 Ω

Table 9: Comparison of methodologies for core thickness of 5µm

4.1.2. Core thickness = 10um

The inductor is designed with two laminations (Core thickness = 10µm).

Table 10 represents the geometric parameters of three designed inductors.

Fixed parameters			
Parameter	**Design A** **N = 3**	**Design B** **N = 4**	**Design C** **N = 5**
Hcore	**85µm**	**85µm**	**85µm**
THcore	**10µm**	**10µm**	**10µm**
Wcore	**238.46µm**	**342.1µm**	**461.58µm**
Wcu	**46.15µm**	**55.52µm**	**64.32µm**
THcu	**35µm**	**35µm**	**35µm**
Lcore	**2.1mm**	**1.6mm**	**1.2mm**
Area	**2.4mm2**	**2.7mm2**	**3.13mm2**
Rdc	**0.204Ω**	**0.221Ω**	**0.241Ω**

Table 10: Geometric parameters of several designs for core thickness of 10µm

Table 11 is a summary of the inductances and the resistances of the designed inductors based on analytical calculations, on Maxwell and on Tyndall methodology.

N	Analytical cal. (L / Rdc)	Maxwell	Tyndall (Ls / Rac)
3	220 nH / 0,173 Ω	234,83 nH / 0,204 Ω	240.77nH / 0,205 Ω
4	220nH / 0,168 Ω	237.52 nH / 0,221 Ω	246.83 nH / 0,203 Ω
5	199.23nH / 0,166 Ω	220.43 nH / 0,241 Ω	240.88 nH / 0,208 Ω

Table 11: Comparison of methodologies for core thickness of 10µm

4.1.3. Core thickness = 20um

The inductor is designed with four laminations (Core thickness = 20µm).

Table 12 presents the geometric parameters of three designed inductors.

Fixed parameters

Parameter	**Design A** **N = 3**	**Design B** **N = 4**	**Design C** **N = 5**
Hcore	**105µm**	**105µm**	**105µm**
THcore	**20µm**	**20µm**	**20µm**
Wcore	**231.31µm**	**334.77µm**	**438.32µm**
Wcu	**37.11µm**	**48.69µm**	**55.66µm**
THcu	**35µm**	**35µm**	**35µm**
Lcore	**1mm**	**0.76mm**	**0.619mm**
Area	**1.47mm2**	**1.819mm2**	**2.264mm2**
Rdc	**0.144Ω**	**0.157Ω**	**0.190Ω**

Table 12: Geometric parameters of several designs for core thickness of 20µm

Table 13 is a summary of the inductances and the resistances of the designed inductors based on analytical calculations, on Maxwell and on Tyndall methodology.

N	Analytical cal. (L / Rdc)	Maxwell	Tyndall (Ls / Rac)
3	220 nH / 0,129 Ω	233.59 nH / 0,144 Ω	215.9nH / 0,152 Ω
4	220nH / 0,126 Ω	236.3 nH / 0.157 Ω	226.13 nH / 0,153 Ω
5	220nH / 0,139 Ω	240.24 nH / 0.190 Ω	238.23 nH / 0.172 Ω

Table 13: Comparison of methodologies for core thickness of 20µm

4.2. Low Voltage 100 nH inductor at 20 MHz

In this section is shown the design of a 150 nH inductor at 20 MHz.

The inductor is designed to operate in a converter with specifications shown in table Table 14. Certain parameters relating to the technology are fixed by the material and shown in table Table 15.

Converter specifications	
Input voltage	5V
Output voltage	1.2V
Output current	500 mA
Ripple current ratio	< 0.5

Switching frequency	20 MHz

Table 14: converter specifications

Fixed parameters	
NiFe relative permeability	280
NiFe resistivity	45 µΩ·cm
NiFe flux density	1.5 T

Table 15: NiFe phisical properties

4.2.1. Core thickness = 5um

The inductor is designed with one lamination (Core thickness = 5µm).

Table 16 presents the geometric parameters of three designed inductors.

Fixed parameters			
Parameter	**Design A** **N = 3**	**Design B** **N = 4**	**Design C** **N = 5**
Hcore	**75µm**	**75µm**	**75µm**
THcore	**5µm**	**5µm**	**5µm**
Wcore	**217.9µm**	**324.2µm**	**426.1µm**
Wcu	**42.6µm**	**53.56µm**	**59.22µm**
THcu	**35µm**	**35µm**	**35µm**
Lcore	**2.7mm**	**1.8mm**	**1.4mm**
Area	**2.71mm2**	**2.84mm2**	**3.18mm2**
Rdc	**0.319Ω**	**0.328Ω**	**0.385Ω**

Table 16: Geometric parameters of several designs for core thickness of 5µm

Table 17 is a summary of the inductances and the resistances of the designed inductors based on analytical calculations, on Maxwell and on Tyndall methodology.

N	Analytical cal. (L / Rdc)	Maxwell	Tyndall (Ls / Rac)
3	150 nH / 0,225 Ω	146.12 nH / 0,319 Ω	179.34nH / 0,293 Ω
4	133.84nH / 0,192 Ω	150.75 nH / 0,328 Ω	168.19 nH / 0,263 Ω
5	130.1nH / 0,197 Ω	151.33 nH / 0.385 Ω	176.1 nH / 0.28 Ω

Table 17: Comparison of methodologies for core thickness of 5µm

4.2.2. Core thickness = 10um

The inductor is designed with two laminations (Core thickness = 10µm).

Table 18 presents the geometric parameters of three designed inductors.

Fixed parameters			
Parameter	**Design A** **N = 3**	**Design B** **N = 4**	**Design C** **N = 5**
Hcore	**85µm**	**85µm**	**85µm**
THcore	**10µm**	**10µm**	**10µm**
Wcore	**214.17µm**	**309.69µm**	**418.33µm**
Wcu	**38.1µm**	**47.42µm**	**55.67µm**
THcu	**35µm**	**35µm**	**35µm**
Lcore	**1.3mm**	**0.99mm**	**0.73mm**
Area	**1.62mm2**	**1.9mm2**	**2.28mm2**
Rdc	**0.2Ω**	**0.236Ω**	**0.283Ω**

Table 18: Geometric parameters of several designs for core thickness of 10µm

Table 19 is a summary of the inductances and the resistances of the designed inductors based on analytical calculations, on Maxwell and on Tyndall methodology.

N	Analytical cal. (L / Rdc)	Maxwell	Tyndall (Ls / Rac)
3	150 nH / 0,147 Ω	160.64 nH / 0,2 Ω	165.18nH / 0.193 Ω
4	150nH / 0,144 Ω	163.46 nH / 0,236 Ω	175.54 nH / 0,202 Ω
5	134.23nH / 0,146 Ω	150.7 nH / 0,283 Ω	163.64 nH / 0,206 Ω

Table 19: Comparison of methodologies for core thickness of 10µm

4.3. High Voltage 1 µH inductor at 10 MHz

In this section is shown the design of a 1 µH inductor at 10 MHz.

The inductor is designed to operate in a converter with specifications shown in Table 20. Certain parameters relating to the technology are fixed by the material and shown in table Table 21.

Converter specifications	
Input voltage	16V
Output voltage	5V
Output current	500 mA
Ripple current ratio	< 0.5
Switching frequency	10 MHz

Table 20: converter specifications

Fixed parameters	
NiFe relative permeability	280
NiFe resistivity	45 µΩ·cm
NiFe flux density	1.5 T

Table 21: NiFe phisical properties

4.3.1. Core thickness = 10um

The inductor is designed with two laminations (Core thickness = 10µm).

Table 22 presents the geometric parameters of three designed inductors.

Fixed parameters			
Parameter	**Design A** **N = 3**	**Design B** **N = 4**	**Design C** **N = 5**
Hcore	**85µm**	**85µm**	**85µm**
THcore	**10µm**	**10µm**	**10µm**
Wcore	**222.9µm**	**321.34µm**	**356.83µm**
Wcu	**40.97µm**	**50.34µm**	**43.37µm**
THcu	**35µm**	**35µm**	**35µm**
Lcore	**9mm**	**6.8mm**	**4.7mm**
Area	**7.76mm2**	**7.72mm2**	**6.18mm2**
Rdc	**0.777Ω**	**0.734Ω**	**0.752Ω**

Table 22: Geometric parameters of several designs for core thickness of 10µm

Table 23 is a summary of the inductances and the resistances of the designed inductors based on analytical calculations, on Maxwell and on Tyndall methodology.

N	Analytical cal. (L / Rdc)	Maxwell	Tyndall (Ls / Rac)
3	1uH / 0.686 Ω	1.05 uH / 0.777 Ω	1.058uH / 0.772 Ω
4	1uH / 0.588 Ω	1.06 uH / 0.734 Ω	1.09uH / 0.694 Ω
5	1 uH / 0.559 Ω	1.07 uH / 0.752 Ω	1.11 uH / 0.665 Ω

Table 23: Comparison of methodologies for core thickness of 10µm

4.4. High Voltage 1 µH inductor at 20 MHz

In this section is shown the design of a 1 µH inductor at 20 MHz.

The inductor is designed to operate in a converter with specifications shown in table Table 24. Certain parameters relating to the technology are fixed by the material and shown in table Table 25.

Converter specifications	
Input voltage	16
Output voltage	5
Output current	500 mA
Ripple current ratio	< 0.5
Switching frequency	20 MHz

Table 24: converter specifications

Fixed parameters	
NiFe relative permeability	280
NiFe resistivity	45 µΩ·cm
NiFe flux density	1.5 T

Table 25: NiFe phisical properties

4.4.1. Core thickness = 10um

The inductor is designed with two laminations (Core thickness = 10µm).

Table 26 presents the geometric parameters of three designed inductors.

Fixed parameters			
Parameter	**Design A** **N = 3**	**Design B** **N = 4**	**Design C** **N = 5**
Hcore	**85µm**	**85µm**	**85µm**
THcore	**10µm**	**10µm**	**10µm**
Wcore	**185.14µm**	**270.97µm**	**356.83µm**
Wcu	**28.38µm**	**37.74µm**	**43.36µm**
THcu	**35µm**	**35µm**	**35µm**
Lcore	**7.8mm**	**5.9mm**	**4.7mm**
Area	**6.11mm2**	**6.05mm2**	**6.18mm2**
Rdc	**1.02Ω**	**0.96Ω**	**1Ω**

Table 26: Geometric parameters of several designs for core thickness of 10µm

Table 27 is a summary of the inductances and the resistances of the designed inductors based on analytical calculations, on Maxwell and on Tyndall methodology.

N	Analytical cal. (L / Rdc)	Maxwell	Tyndall (Ls / Rac)
3	1uH / 0.860 Ω	1.05 uH / 1.02 Ω	1.053uH / 1.029 Ω
4	1uH / 0.683 Ω	1.06 uH / 0.96 Ω	1.07uH / 0.862 Ω
5	1 uH / 0.629 Ω	1 uH / 1.002 Ω	1.11 uH / 0.84 Ω

Table 27: Comparison of methodologies for core thickness of 10µm

5. Bibliography

[1] J. M. Rivas, O. Leitermann, Y. Han, and D. J. Perreault, “A Very High Frequency DC–DC Converter Based on a Class <formula formulatype=‘inline’><tex Notation=‘TeX’>${\bm \Phi}_{\bm 2}$</tex></formula> Resonant Inverter,” *IEEE Trans. Power Electron.*, vol. 26, no. 10, pp. 2980–2992, Oct. 2011.

[2] G. Schrom, P. Hazucha, J. Hahn, D. S. Gardner, B. A. Bloechel, G. Dermer, S. G. Narendra, T. Karnik, and V. De, “A 480-MHz, multi-phase interleaved buck DC-DC converter with hysteretic control,” in *2004 IEEE 35th Annual Power Electronics Specialists Conference (IEEE Cat. No.04CH37551)*, 2004, vol. 6, pp. 4702–4707.

[3] F. C. Lee, J. D. van Wyk, D. Boroyevich, and P. Barbosa, “Technology trends toward a system-in-a-module in power electronics,” *IEEE Circuits Syst. Mag.*, vol. 2, no. 4, pp. 4–22, 2002.

[4] S. C. Ó. Mathúna, T. O. Donnell, N. Wang, and K. Rinne, “Magnetics on Silicon : An Enabling Technology for Power Supply on Chip,” vol. 20, no. 3, pp. 585–592, 2005.

[5] M. Wang, “Integrated Power Inductors in Silicon for Compact DC-DC Converters in Portable Electronics,” UNIVERSITY OF FLORIDA, 2010.

[6] T. O. Donnell, N. Wang, R. Meere, F. Rhen, S. Roy, D. O. Sullivan, C. O. Mathuna, L. Maltings, and P. Row, “Microfabricated Inductors for 20 MHz Dc-Dc Converters,” pp. 689–693, 2008.

[7] Y. Katayama, S. Sugahara, H. Nakazawa, and M. Edo, “High-power-density MHz-switching monolithic DC-DC converter with thin-film inductor,” in *2000 IEEE 31st Annual Power Electronics Specialists Conference. Conference Proceedings (Cat. No.00CH37018)*, 2000, vol. 3, pp. 1485–1490.

[8] C. Kim, S. Bae, Hee-jun Kim, S. Nam, and H. Kim, “Fabrication of high frequency DC-DC converter using Ti/FeTaN film inductor,” *IEEE Trans. Magn.*, vol. 37, no. 4, pp. 2894–2896, Jul. 2001.

[9] R. Meere and T. O’Donnell, “Analysis of microinductor performance in a 20-100 MHz dc/dc converter,” *Power Electron. …*, vol. 24, no. 9, pp. 2212–2218, 2009.

[10] T. M. Andersen, C. M. Zingerli, F. Krismer, J. W. Kolar, N. Wang, and C. Mathuna, “Modeling and Pareto Optimization of Microfabricated Inductors for Power Supply on Chip,” *IEEE Trans. Power Electron.*, vol. 28, no. 9, pp. 4422–4430, Sep. 2013.

[11] R. Meere, T. O’Donnell, N. Wang, N. Achotte, S. Kulkarni, and S. C. O’Mathuna, “Size and Performance Tradeoffs in Micro-Inductors for High Frequency DC-DC Conversion,” *IEEE Trans. Magn.*, vol. 45, no. 10, pp. 4234–4237, Oct. 2009.

[12] R. Meere, T. O'Donnell, S. Kulkarni, S. Roy, and S. C. O'Mathuna, "Magnetic-Core and Air-Core Inductors on Silicon: A Performance Comparison up to 100 MHz," *IEEE Trans. Magn.*, vol. 47, no. 10, pp. 4429–4432, Oct. 2011.

[13] D. V. Harburg, Xuehong Yu, F. Herrault, C. G. Levey, M. G. Allen, and C. R. Sullivan, "Micro-fabricated thin-film inductors for on-chip power conversion." pp. 1–6, 2012.

[14] C. Yang, A. Member, F. Liu, X. Wang, J. Zhan, A. Wang, T. Ren, S. Member, L. Liu, H. Long, Z. Wu, and X. Li, "Investigation of On-Chip Soft-Ferrite-Integrated Inductors for RF ICs — Part I : Design and Simulation," vol. 56, no. 12, pp. 3133–3140, 2009.

[15] C. Yang, F. Liu, X. Wang, J. Zhan, A. Wang, T.-L. Ren, L.-T. Liu, H. Long, Z. Wu, and X. Li, "Investigation of On-Chip Soft-Ferrite-Integrated Inductors for RF ICs—Part II: Experiments," *IEEE Trans. Electron Devices*, vol. 56, no. 12, pp. 3141–3148, Dec. 2009.

[16] X. Fang, R. Wu, L. Peng, and J. K. O. Sin, "A Novel Silicon-Embedded Toroidal Power Inductor With Magnetic Core," *IEEE Electron Device Lett.*, vol. 34, no. 2, pp. 292–294, Feb. 2013.

[17] D. Yao, C. G. Levey, R. Tian, and C. R. Sullivan, "Microfabricated V-Groove Power Inductors Using Multilayer Co–Zr–O Thin Films for Very-High-Frequency DC–DC Converters," *IEEE Trans. Power Electron.*, vol. 28, no. 9, pp. 4384–4394, Sep. 2013.

[18] C. R. Sullivan, D. V. Harburg, J. Qiu, C. G. Levey, and D. Yao, "Integrating Magnetics for On-Chip Power: A Perspective," *IEEE Trans. Power Electron.*, vol. 28, no. 9, pp. 4342–4353, Sep. 2013.

[19] J. Qiu and C. R. Sullivan, "Design and Fabrication of VHF Tapped Power Inductors Using Nanogranular Magnetic Films," *IEEE Trans. Power Electron.*, vol. 27, no. 12, pp. 4965–4975, Dec. 2012.

[20] J. Mühlethaler and J. W. Kolar, "Optimal Design of Inductive Components Based on Accurate Loss and Thermal Models," in *IEEE Applied Power Electronics Specialist Conference APEC Tutorial*, 2012.

Annex I. Design oriented optimization tool

This chapter will show a tool developed in MATLAB to design racetrack inductors. The objective of the tool is to provide an interface to introduce:

- Electrical specifications: the input voltage (Vin) and output voltage (Vout), current (Idc), the value of inductance (L), frequency (F), and relative permeability, conductivity, maximum magnetic field (Bmax) and saturation (Bsat) of the core.
- Geometrical specifications: maximum area.
- Technological constraints: Core Thickness, Separation (between the core), Cu thickness, spacing (between the windings).

It will present a flowchart which represents the operation of the tool. Then it will show the graphical interface (also developed in MATLAB) that allows communication between user and the tool.

Next, the programming functions will be explained. We clarify how the results are displayed. The results are:

- Geometric design of the inductor
- Electrical values L and R

Finally, we explain other applications of the functions and possible improvements of the tool.

Flowcharts

The following diagram shows the general operation of the tool.

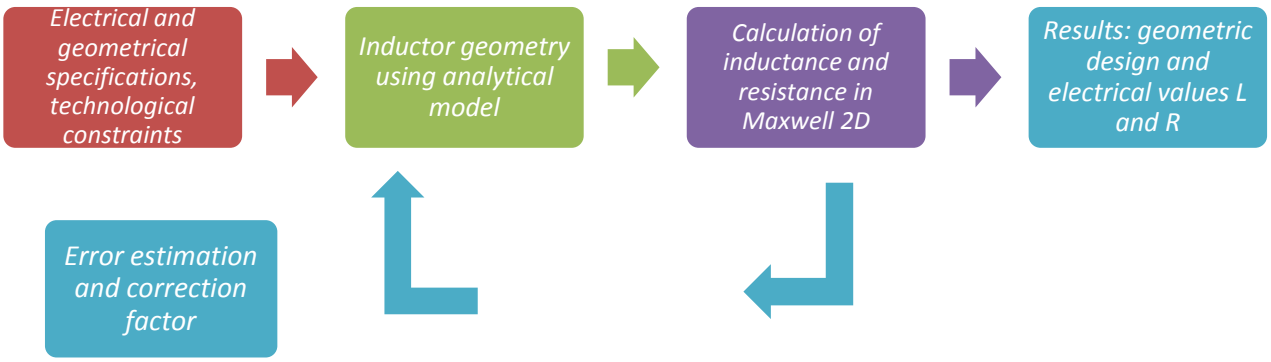


Figure 1: Flowchart of overall tool performance

1. We use the analytical model explained in section 3.3 for the initial design of the inductor. Then, the tool generates a script that will be interpreted by Maxwell. This script contains not only information for inductor design but also includes all necessary instructions for performing simulation.
2. Postprocessing the electromagnetic field results, as it was explained in the previous chapter, to calculate the stored magnetic energy and ohmic losses at the frequency of interest.

3. The results are stored and it allows to obtain the values of inductance L and resistance R at the frequency of interest.
4. A comparison is made between the desired inductance value and the inductance value obtained by finite element tool. If the inductance obtained with Maxwell is different than the desired inductance by an error higher than 10%, we recalculate the design of the analytical model applying the following correction factor to the inductor:

$$Lo = \frac{L^2}{Lf} \qquad (37)$$

where L is the initially desired inductance, Lf is obtained by Maxwell and Lo is the corrected inductance.

Example: we wish to create a design of a 150 nH inductor at 20 MHz. After making the design by the analytical model, Maxwell gets an inductance of 167 nH. As 167 nH is greater than 1.1 · 150 nH, a new analytical design will be perform with an objective inductance value given by:

$$Lo = \frac{150^{\,2}}{167} = 134{,}73\ nH \qquad (38)$$

5. Once we have applied this correction factor, the analytical model is performed again, recalculating all and creating a new script for Maxwell. In this iteration we obtain the desired result in Maxwell, so it will always be a process that is repeated once.
6. Now that we have a model similar to the desired, we generate the input file needed by the analytical tool developed by Tyndall in order to compare results.

The following diagram shows in more detail the internal working of the tool:

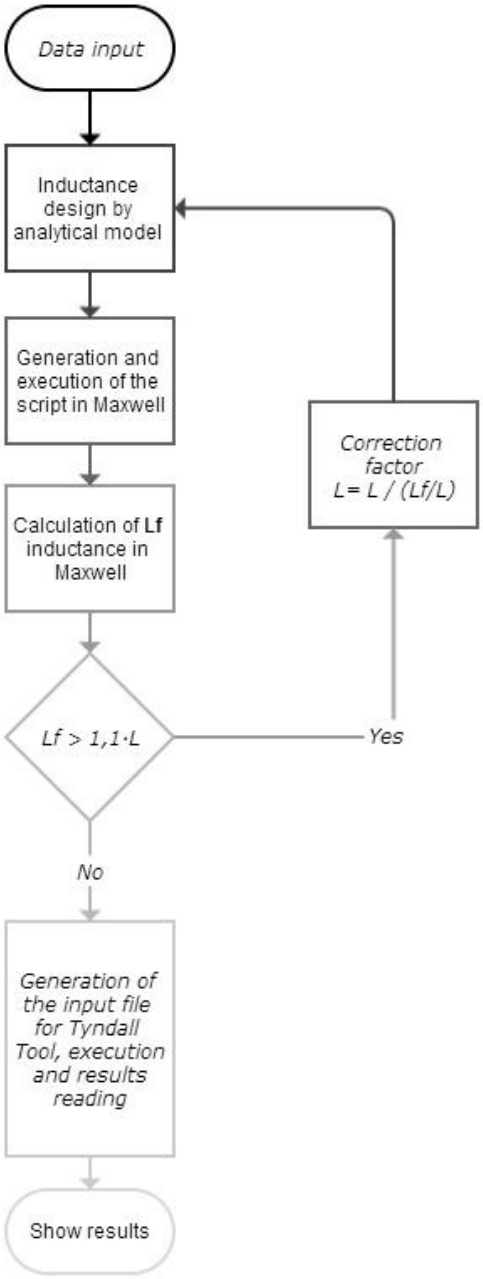


Figure 2: detailed flowchart

Graphic interface

The following figure shows the graphical interface (also developed in MATLAB) that allows communication between user and the tool.

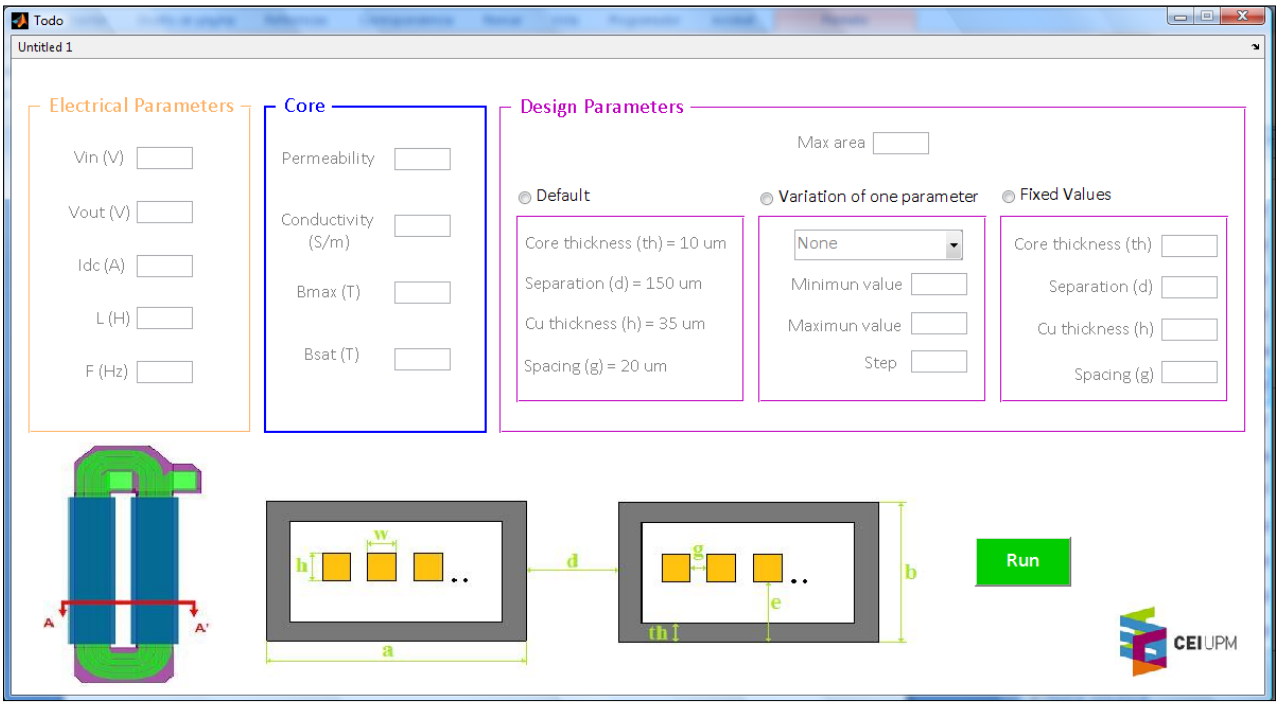


Figure 3: Tool interface

As we can see in the previous figure, the interface is divided into three parts. The first corresponds to the electrical parameters:

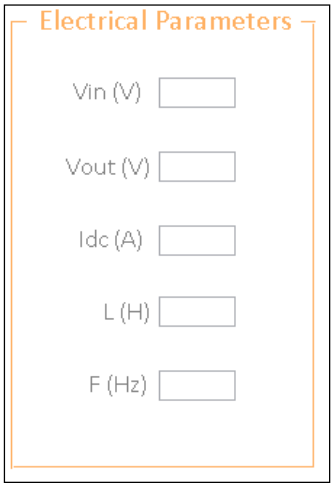


Figure 4: electrical parametersin the interface

which includes: the input voltage (Vin) and output voltage (Vout), current (Idc), the value of inductance (L) and frequency (F).

The second part corresponds to the magnetic core data.

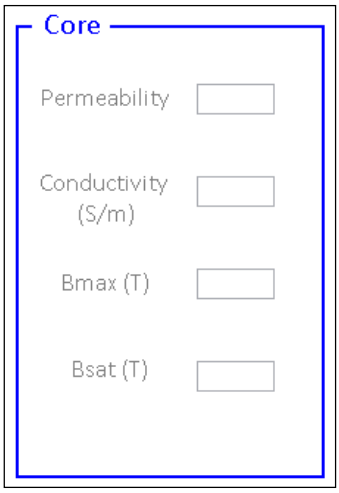


Figure 5: magnetic core data in the interface

It will be required the relative permeability, conductivity, maximum magnetic field (Bmax) and saturation (Bsat).

The third and final part corresponds to the geometric parameters of the inductor design.

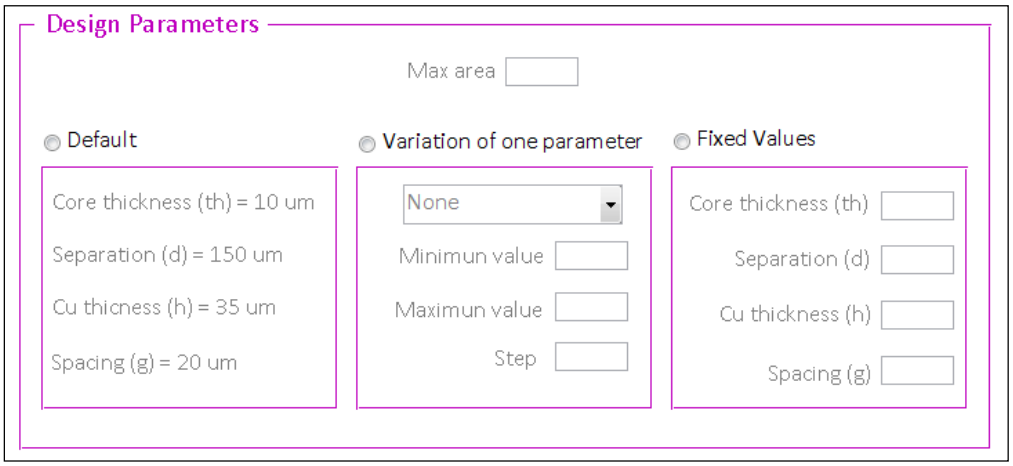


Figure 6: geometrical parameters in the interface

It should specify the maximum area to be occupied. Then there are 3 possible ways to design:

- ***Default: some parameters are fixed for current technology process. These parameters are the Core Thickness, Separation (between the core), Cu thickness (winding thickness) and spacing (between the windings).***

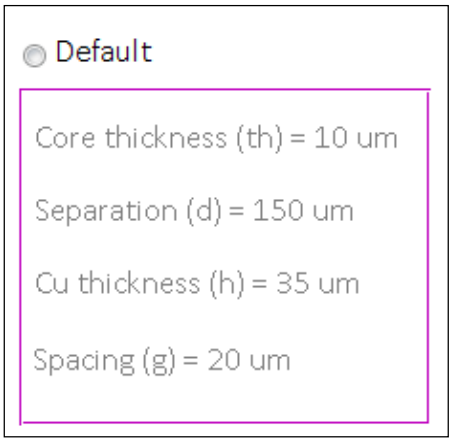


Figure 7: design example with default parameters

- ***Variation of one parameter: some parameters are fixed for current technology process, but in contrast to the previous case, you can select one of them and include a range of values (maximum, minimum and step). This allows us to identify how that particular parameter affects the design.***

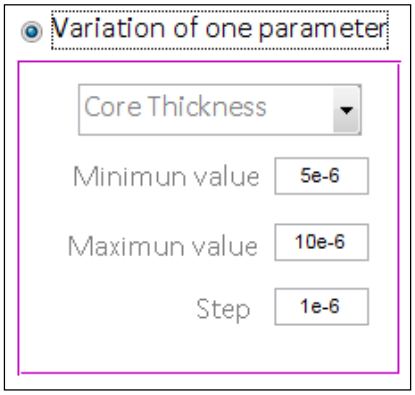


Figure 8: Example of variation of one parameter in a range in the interface

The figure above is an example of a parameter variation. In this case it was decided to vary the thickness of the magnetic core. The minimum value that will take this variable is 5 microns, increasing 1 micron up to 10 microns. With this selection, we will perform six different inductor designs for a corethickness of 5, 6, 7, 8, 9 and 10 microns.

- ***Fixed Values: it can enter the desired values for the parameters that have geometric constraints.***

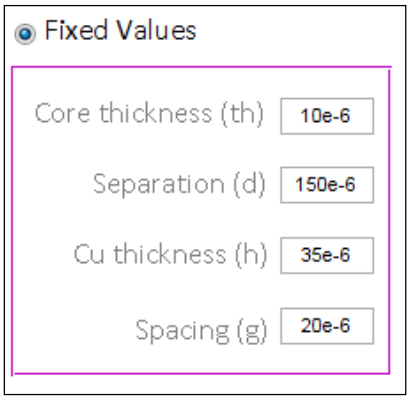


Figure 9: Example of fixed values in the interface

Functions

A Matlab function includes in the first line of the file, a header which specifies its name, which and how many arguments have (the parameters that it receives), and what and how many values it returns. Said header is identified also by the '**function'** word as shown in the following example:

function a=product(x,y)

which defines a function named product, which has two arguments (x and y) and returns a value (a).

We will now detail the main functions created for the development of the tool.

Analytical design function

Function [R, vueltas, H_CORE, W_CORE, W_CU, Y, LONG_CORE, LONG_AIR, AREA_FINAL] = **fidesign** (L, Vin, Vo, f, Io, AREA, MU_R, Conductivity, TH_CU, TH_CORE, S, separation, overlap, distance, Bmax, space_centre)

This function receives all the parameters entered through the interface and returning the remaining geometric parameters, which are obtained through the analytical model. So it returns a complete design of the inductor.

Maxwell function

Function [Lf, Rf] = **fmaxwell_1f** (aux, WCORE, HCORE, THCORE, distance2, 0, MU_R, vueltas, WCU, HCU, S2, space, Y2, LONGCORE, LONGAIR, f)

This function receives the complete design of the inductor,it means all information entered via the interface, in addition to the parameters obtained in the analytical design.

Then, it generates the script that Maxwell needs, with all the information, executes and stores the results (Energy and Ohmic Losses). Finally, it calculates and returns **Lf** inductance and **R** resistance values.

Function for the executable of Tyndall

Function [Le, Re] = **fexe** (AREA_FINAL, Conductivity, MU_R, f, Io, vueltas, TH_CU, H_CORE, Vo, Vin, AREA, separation, overlap, space_centre, W_CU, S, TH_CORE)

This function takes the complete design of the inductor, as the above function. Then it generates the input file needed by the executable developed by Tyndall and executes it. Next, it reads the output file where the results are stored to read and display the values of inductance **Le** and resistance **Re**.

Results

This section explains how to display the results based on the selected design.

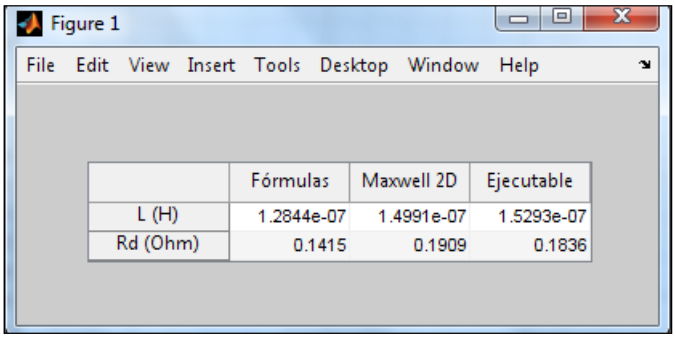
If the designer choose a Default design, it is understood that the interest is to obtain **electrical parameters R and L** displayed by the tool, and the **design of the inductor** and the **electromagnetic field results** in Maxwell, since they are stored in the directory specified by the user, when the tool is installed, following the Reference Manual in Annex II.

In Variation of one parameter, the designer is interested in **the evolution of the electrical parameters L and R** when a parameter that is fixed for current technology process varies in a range. This allows to find out the influence of these restrictions separately.

Finally in Fixed Values, the objective is the same as in the previous case, but now **there is an interest in changing two or more fixed parameters**, in order to find out their influence together.

Below there is an example of each case:

- ***Default: it will see a table with the results obtained for the three functions (analytical design, Maxwell and Tyndall executable).***



	Fórmulas	Maxwell 2D	Ejecutable
L (H)	1.2844e-07	1.4991e-07	1.5293e-07
Rd (Ohm)	0.1415	0.1909	0.1836

Figure 10: results obtained for a Defaultdesign

- ***Variation of one parameter: it graphically displays the evolution of the inductance and resistance for the three functions.***

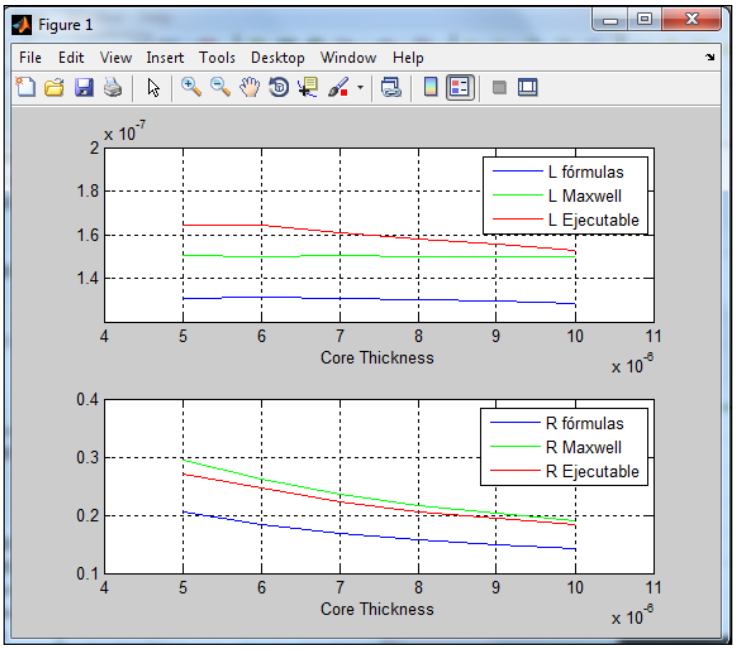


Figure 11: results obtained for Variation of oneparameterdesign

- ***Fixed Values: it will display a table with the results obtained for the three functions identical to the Default case.***

Other applications and improvements

This tool allows us to optimize the design of an inductor. However, its functions may be used independently if it is required for a new purpose.

Analytical design function

For example, if you require an estimate of inductance and resistance where you need a short calculation time, it could be employed the analytical design function, since the outcome is immediate.

In addition, we could add features to provide more information. For example, it could represent the evolution of any parameter with the number of turns. Examples:

Representation of the area

The figure shows an example representing the area where the blue curve shows the evolution of the area with the number of turns and the red line represents the maximum area entered by the user through the interface. The intersection of the two gives us the maximum number of turns (N) to not exceed the maximum area requested.

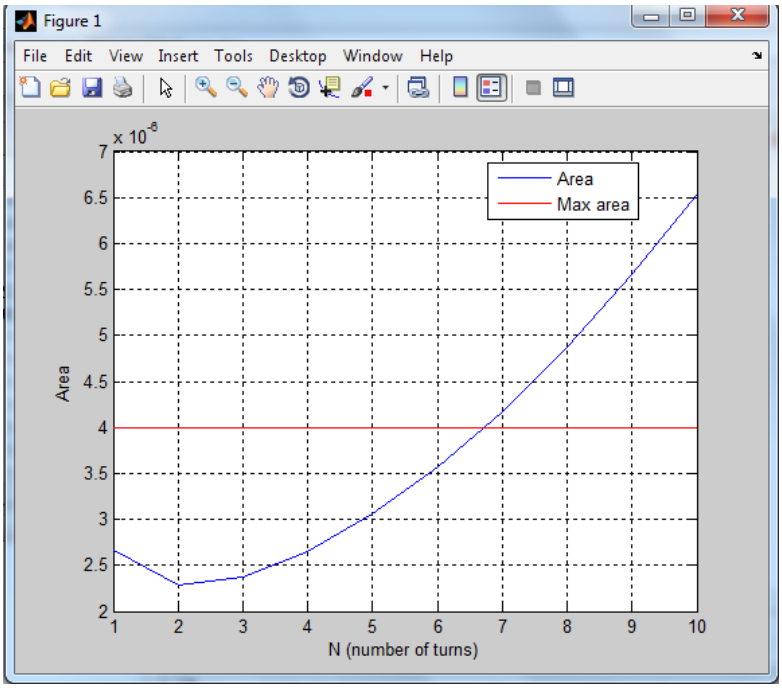


Figure 12: area representation based on the number of turns

Representation of the length and width of the core

The figure shows an example where the green curve shows the evolution of the length of the core and the red curve shows the evolution of the width of the core, both with the number of turns. The intersection of these two curves indicates when the device becomes wider than long, and then it would be better to consider a multilayer design.

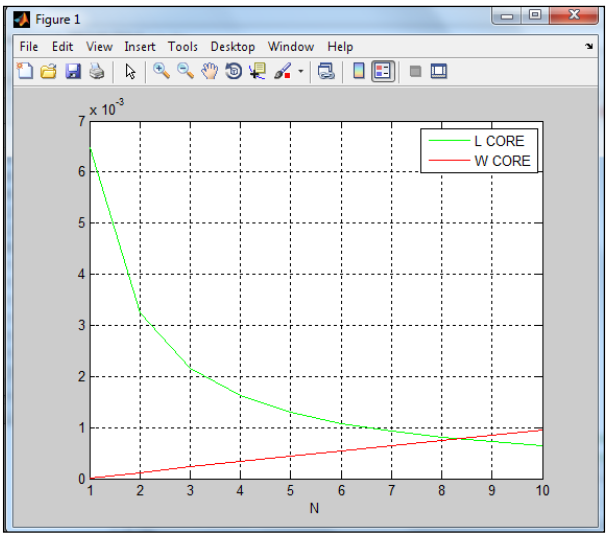


Figure 13: Representation of the length and width of the core based on N

Representation of the resistance

The figure shows the evolution of the resistance with the number of turns, where the designer can determine how far the resistance increases.

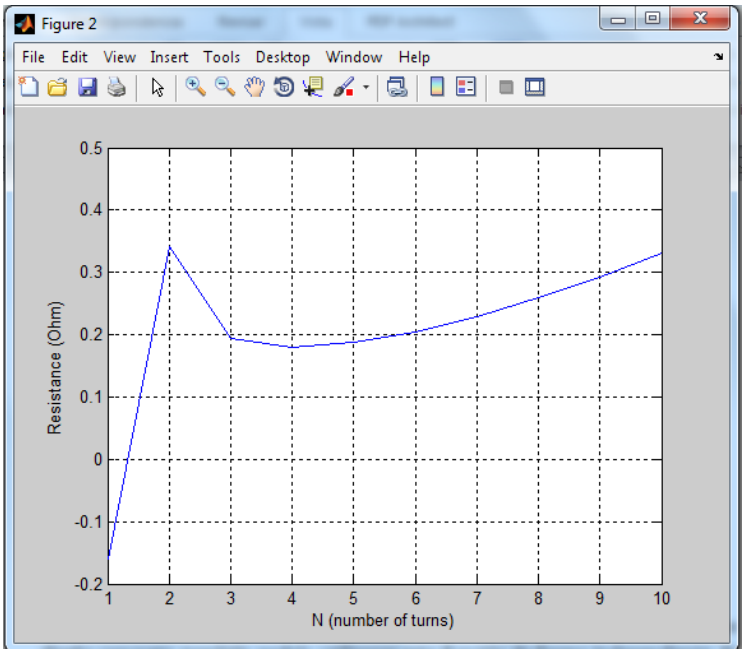


Figure 14: representation of the resistance as a function of N

In addition to the representation of the evolution of the parameters, we could get other information such as the estimated losses in the core and in the windings.

The code required to implement these additional features is already implemented, so it would only be necessary to activate it or modify it (see Reference manual in Annex II)

Maxwell function

This function calls the finite element tool and obtained, as shown in the previous chapter, an inductor design and its electromagnetic field results.

It would only be necessary to assign a value to the input parameters employing the function, and it would display the value of inductance and resistance, and the design an electromagnetic field results would be saved (see Reference Manual in the Annex II).

If we were interested in other information provided by Maxwell, for example, the distribution of magnetic field in the inductor, it would only be necessary to modify the code following the same procedure that was used in obtaining the Energy and the Ohmic Losses.

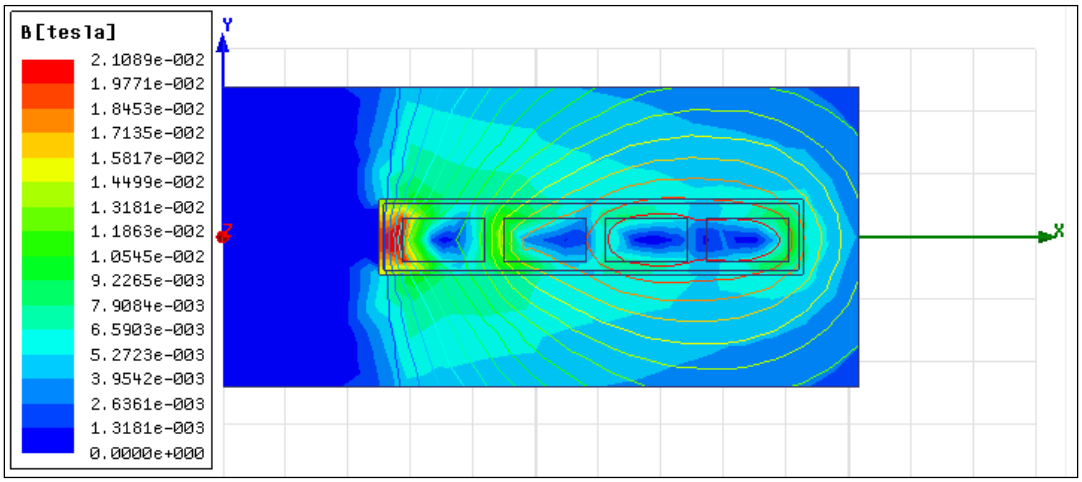


Figure 15: an example of the distribution of magnetic field in the inductor

By contrast, it may be interested in other analyzes, such as analyzing the design to a range of frequencies. To do this, we have developed a similar function for Maxwell, where instead of receiving a single frequency as an argument, it requires a range, which is determined by a minimum frequency, maximum frequency, and step.

Function [Lf, Rf] = **fmaxwell** (aux, WCORE, HCORE, THCORE, distance2, 0, MU_R, vueltas, WCU, HCU, S2, space, Y2, LONGCORE, LONGAIR, Fmin, Fmax, step)

When this function is used, the results are displayed graphically. In the next figure there is an example.

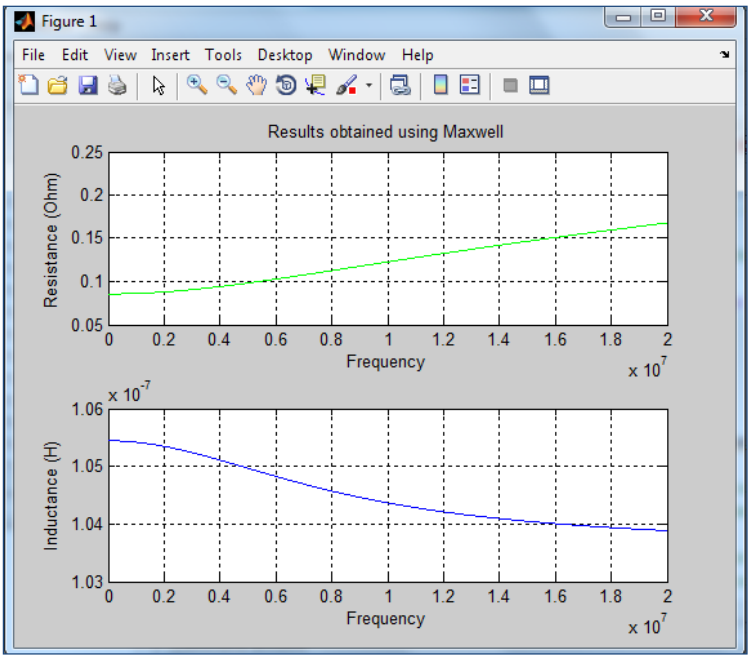


Figure 16: An example of Maxwell function for a range of frequencies.

Improvements

It might be interesting to implement a design with more accurate formulas, thus avoiding the necessity of using a correction factor and eliminating iteration, so that the execution time is reduced significantly.

Annex II. Creating the geometric model in Maxwell

Below we detail how to design a racetrack inductor in Maxwell, with magnetic core. The second design process is the same, but by assigning air as the core material.

We started by creating a new project 2D. To do this, go to **File** >> **New** and then we click on the icon 2D model as the following figures.

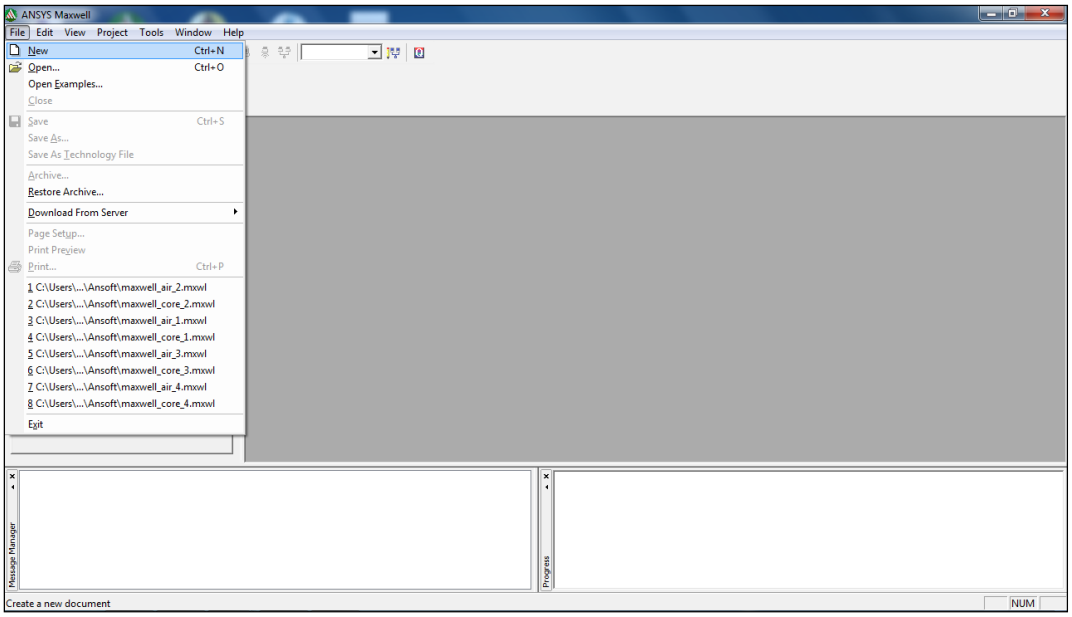


Figure 17: how to create a new project in Maxwell

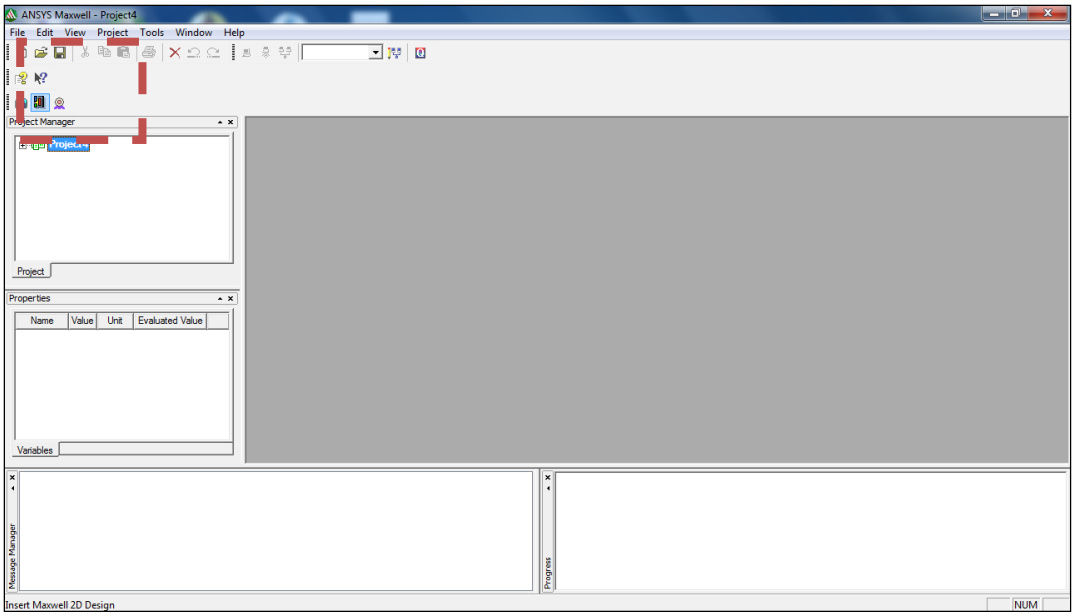


Figure 18: how to create a 2D model in Maxwell

The Ansoft Maxwell window has several optional panels:

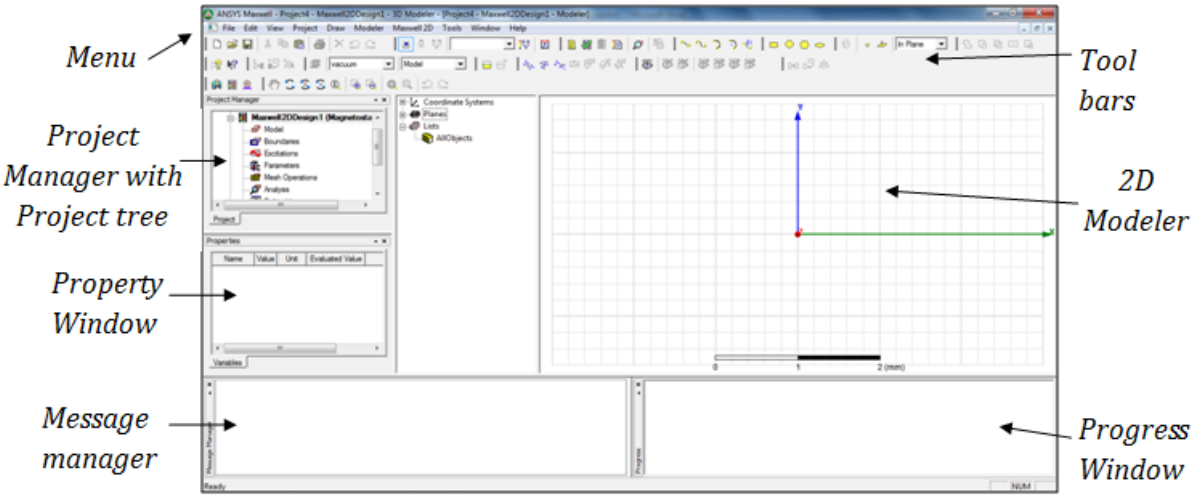


Figure 19: Maxwell window

We create the outer rectangle of the magnetic core. To do this, we click on the rectangle icon. Then, we introduce the X and Y coordinates of the lower left corner and the increase in X and Y as shown in the following figures.

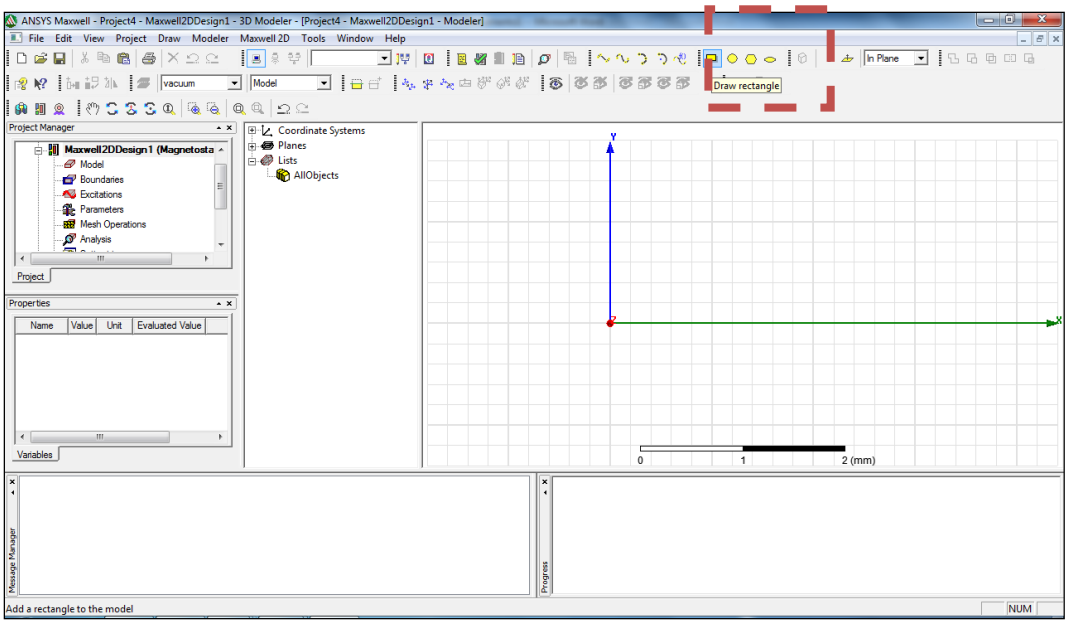


Figure 20: rectangle icon in Maxwell window

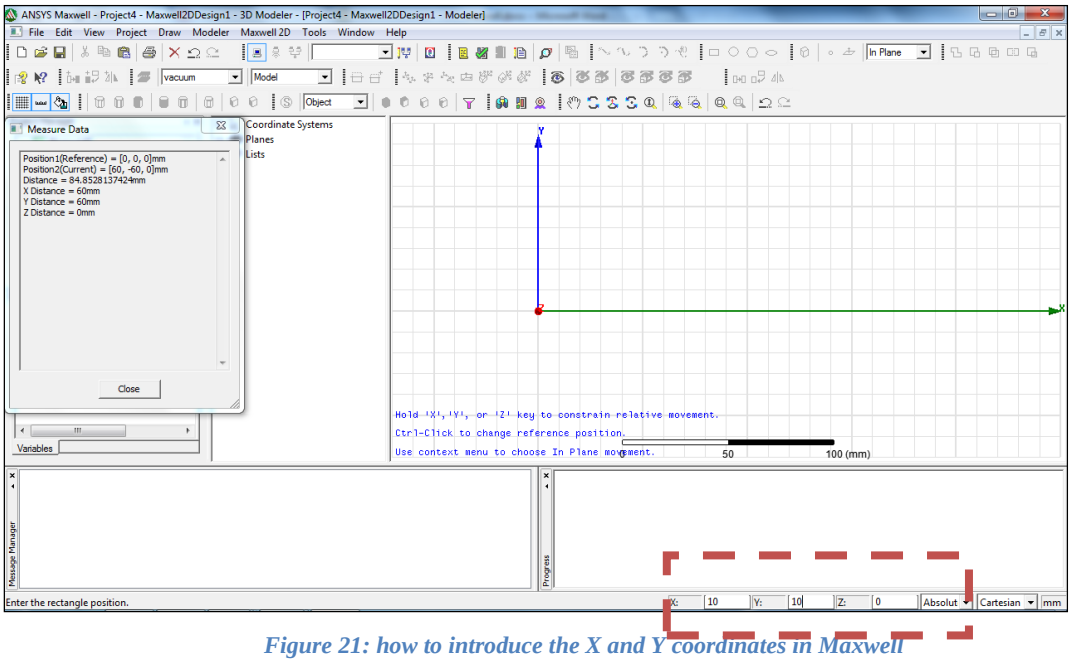


Figure 21: how to introduce the X and Y coordinates in Maxwell

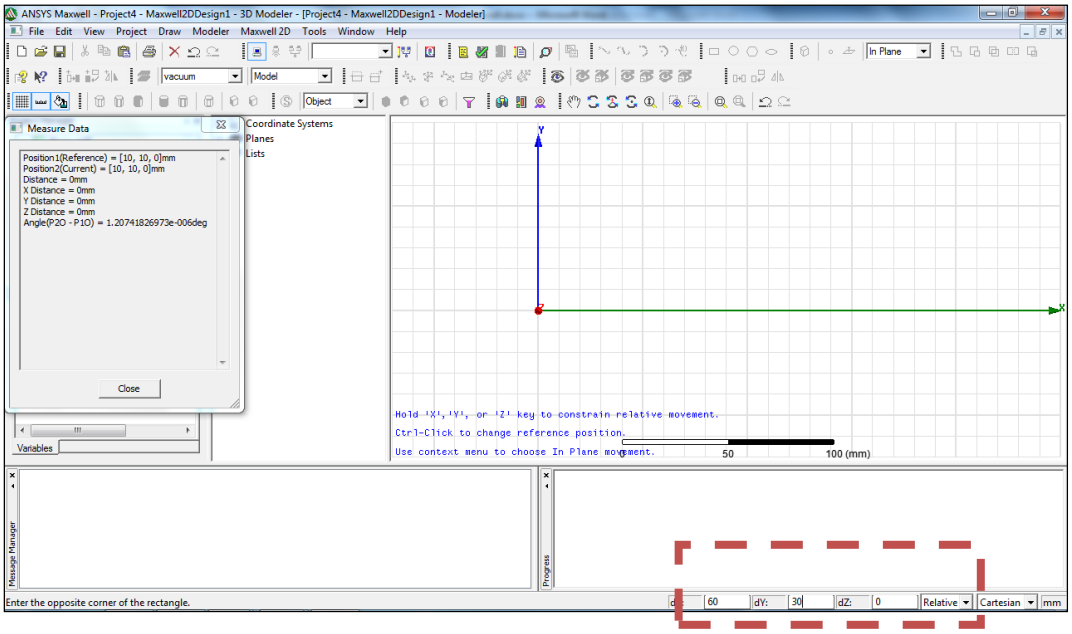


Figure 22: how to introduce the increase in X and Y in Maxwell

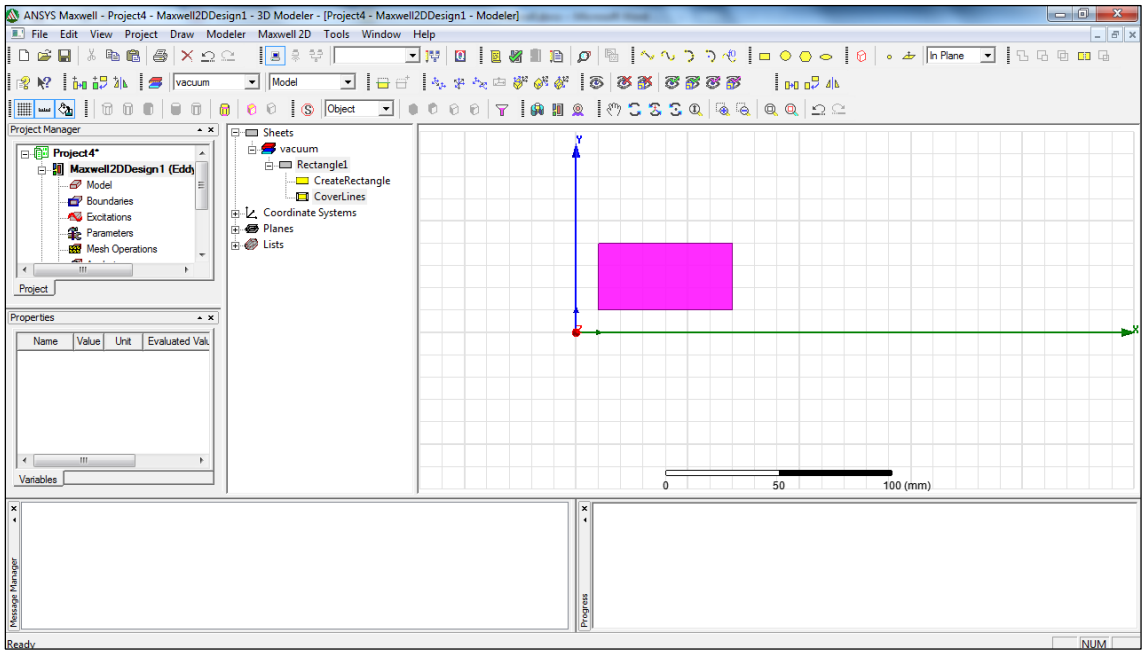


Figure 23: the outer rectangle of the magnetic core in Maxwell

Next, we follow the same process to create the inner rectangle. Once done,we use the tool for subtracting to obtain the magnetic core as shown by the following figures.

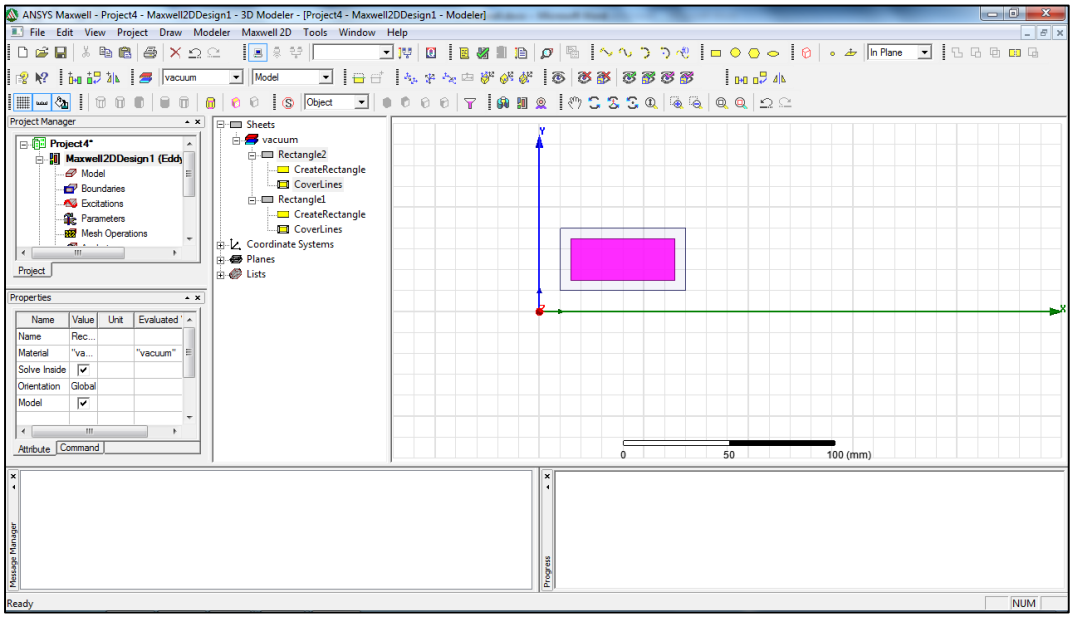


Figure 24: the inner rectangle of the magnetic core in Maxwell

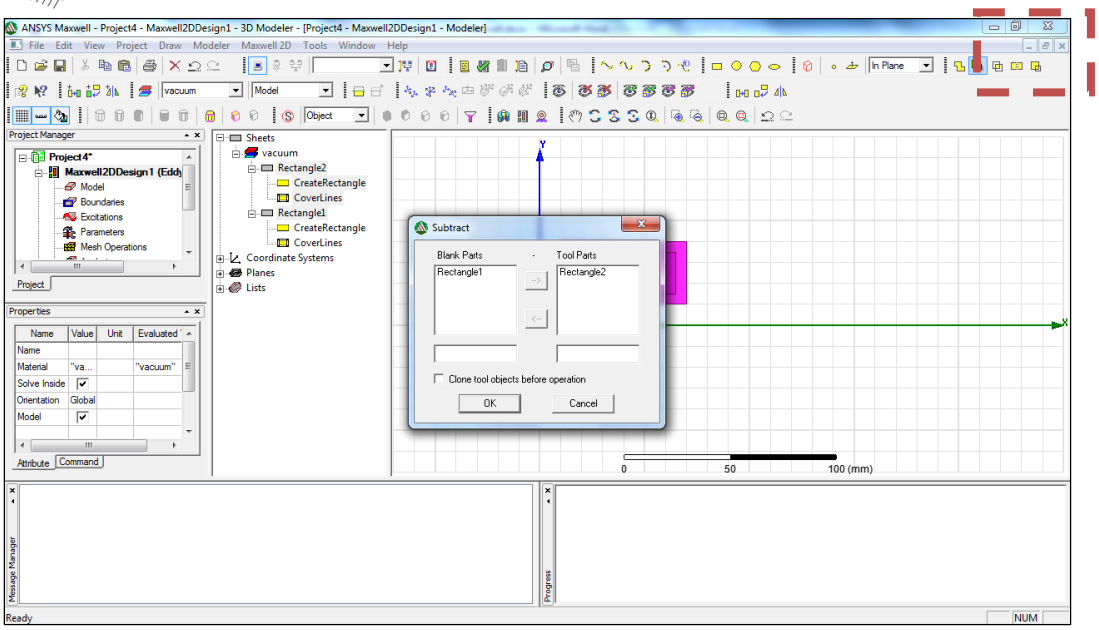


Figure 25: using the tool for subtracting in Maxwell

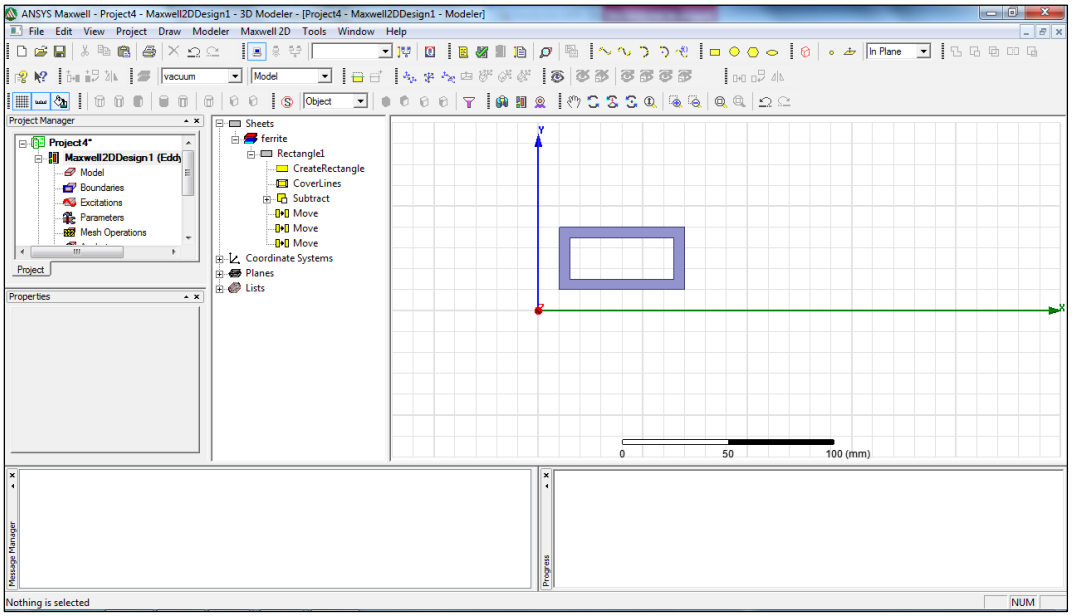


Figure 26: the magnetic core of the inductor in Maxwell

And then we follow the same process to create the windings. First, we create one rectangle and duplicate it as many times as we need.

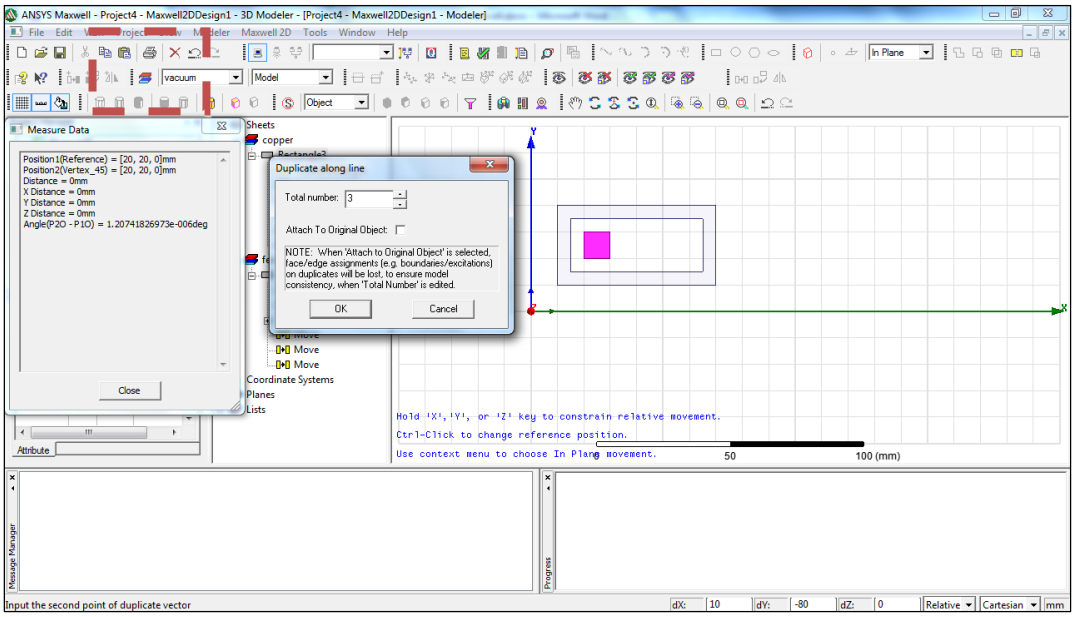


Figure 27: implementation of the windings by duplication in Maxwell

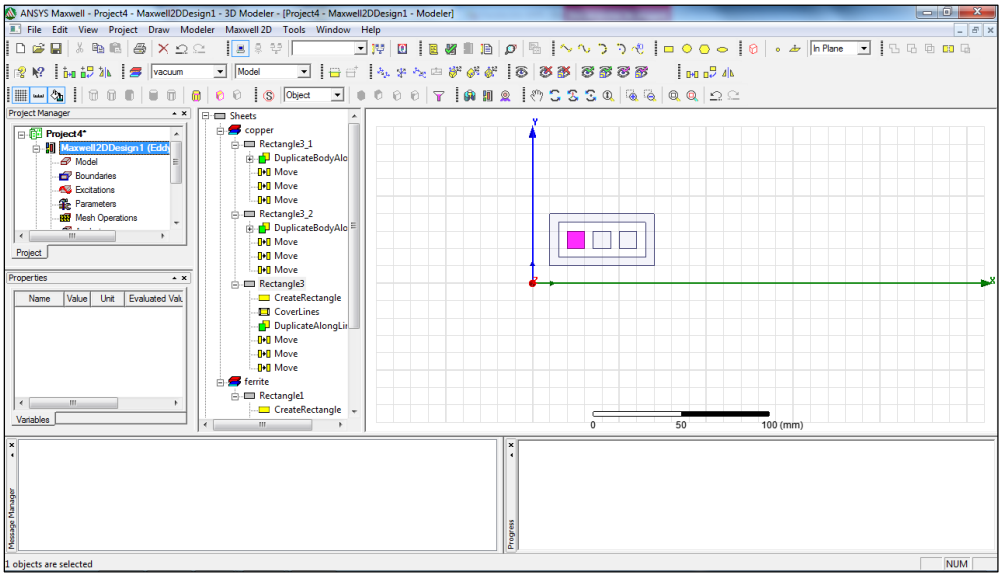


Figure 28: geometric model in Maxwell

Set up boundaries and currents

The structure is a magnetically isolated system. Therefore, it must create an outer region by assigning boundaries to the outside edges of this object.

There are two types of boundary conditions that we will use in this problem:

- ***Balloon boundaries: can only be applied to the outer boundary.***

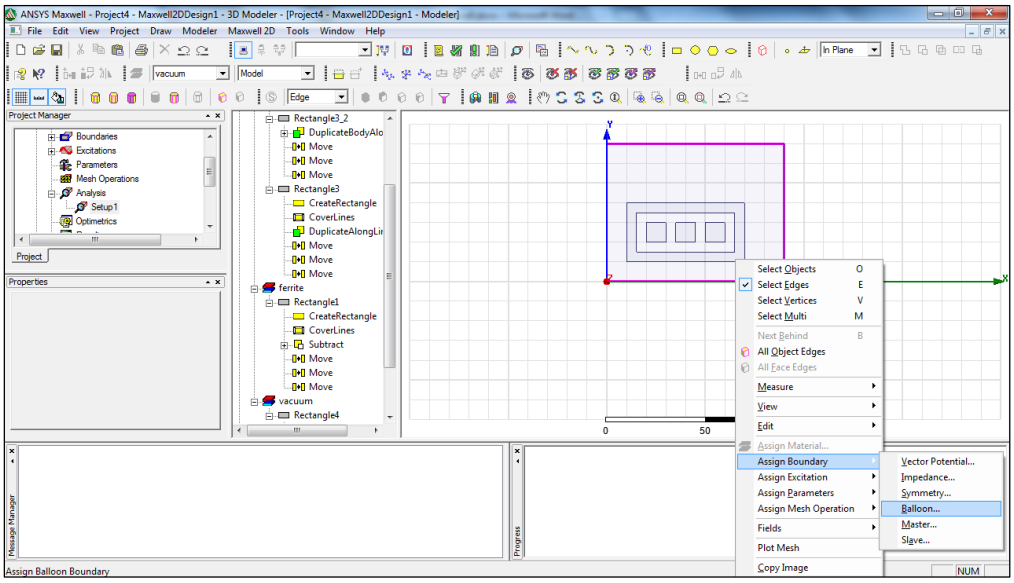


Figure 29: assigning balloon boundaries in Maxwell

- ***Symmetry: itenables to model only part of a structure, which reduces the size or complexity of your design.***

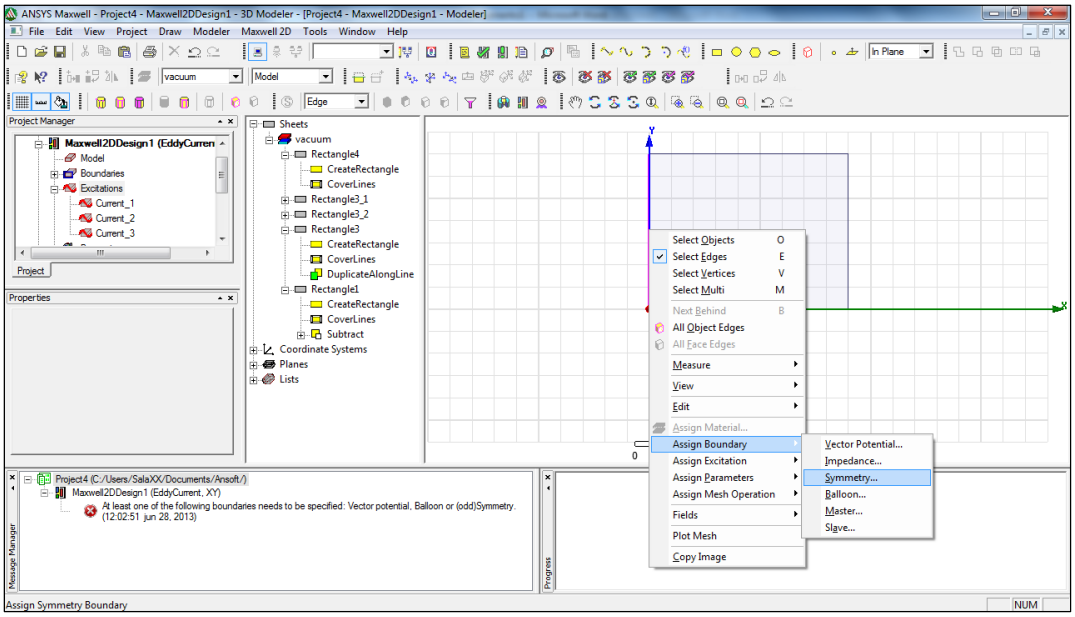


Figure 30: assigning symmetry boundary in Maxwell

Next, we assign a current of 1 amp for each winding.

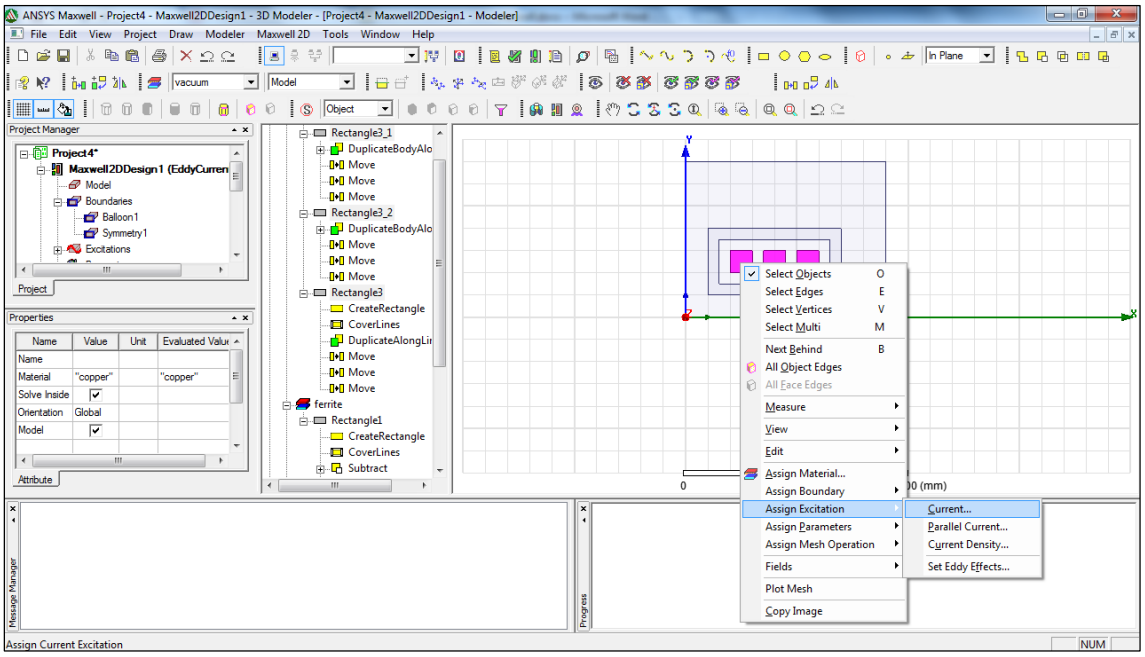


Figure 31: assigning currents in Maxwell

Assign materials to objects

The next step is to assign materials to the objects in the model via the Properties Window. We will do the following:

- Assign copper to the windings.

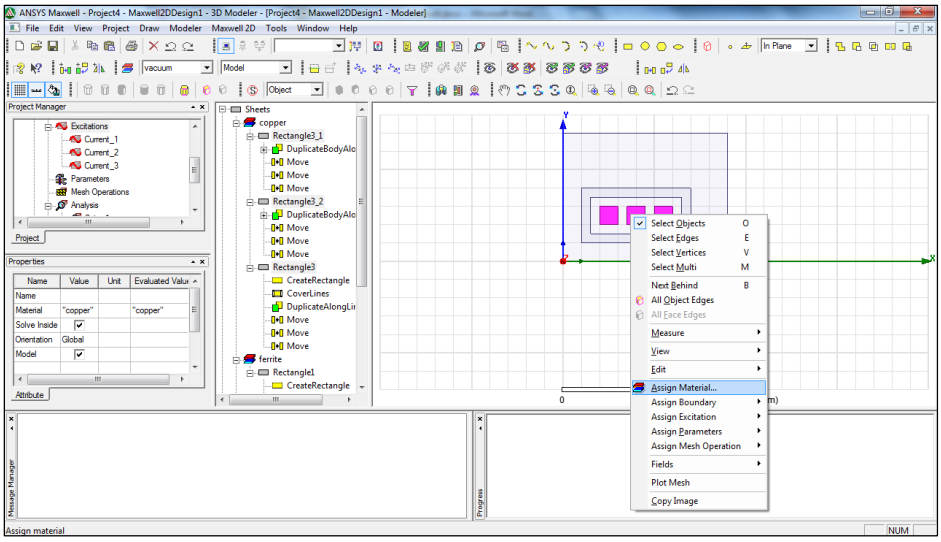


Figure 32: assigning material to the windings I

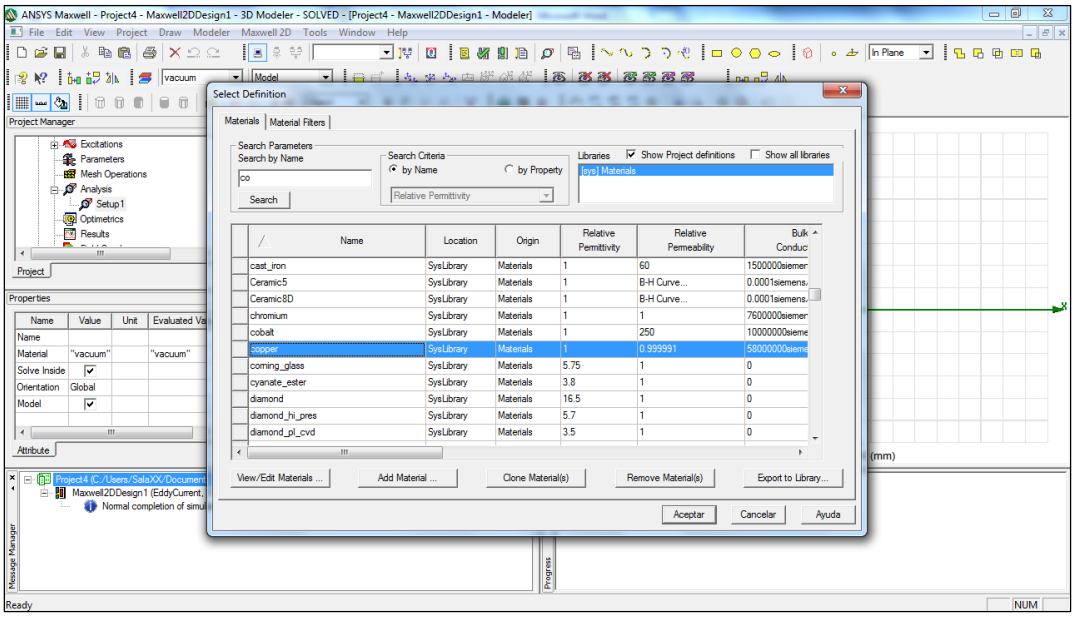


Figure 33: assigning material to the windings II

• Assign ferrite/air to the core.

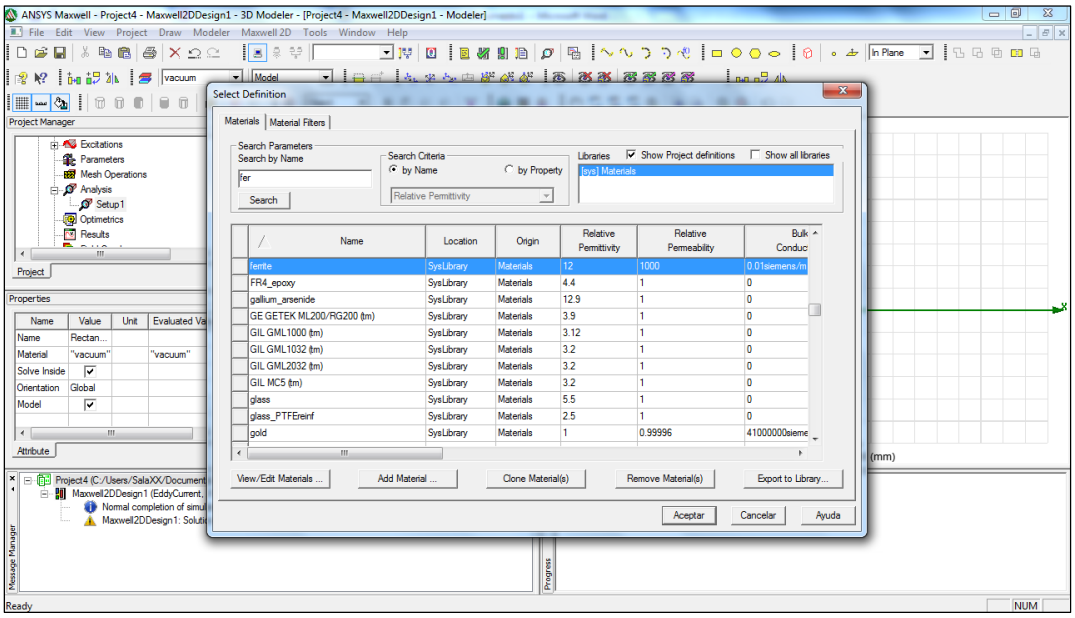


Figure 34: assigning material to the core in Maxwell

• Accept the default material that is assigned to the background object, which is vacuum.

Add solution setup

Use the default criteria to generate the solution. We click on **Maxwell 2D >> Solution type>> Eddy current.**

In the Project tree right-click Analyze and select **Add Solution Setup**.

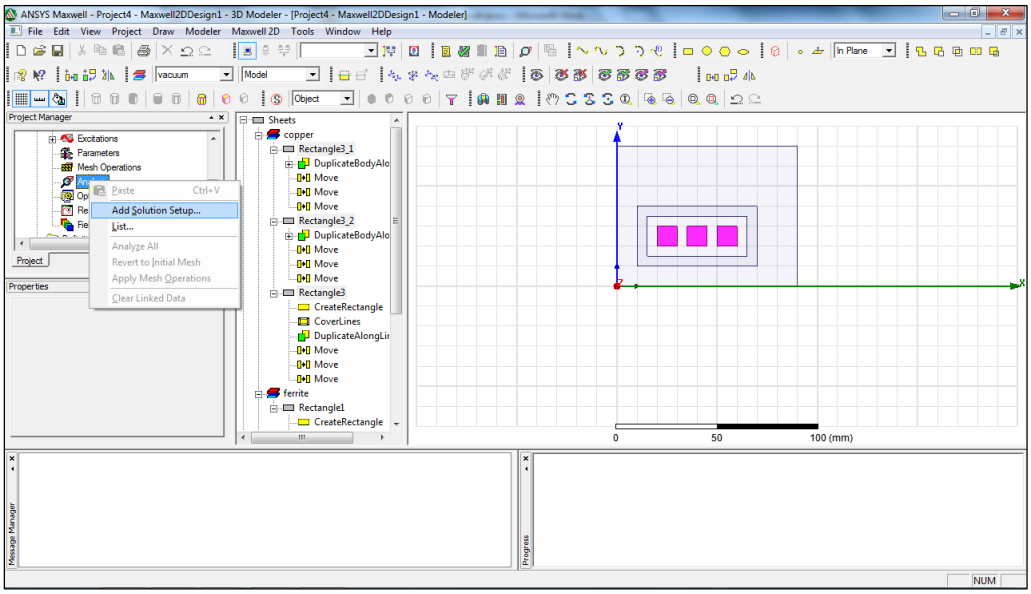


Figure 35: how to add a solution setup in Maxwell

If we want a single frequency, we go to the Solver tab and enter its value.

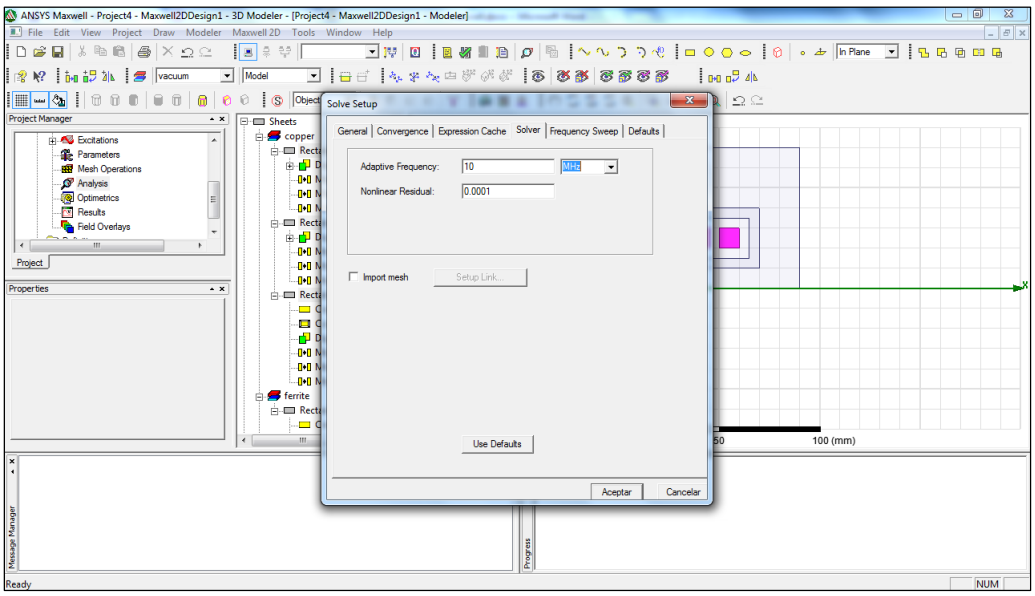


Figure 36: how to simulate with a single frequency

By contrast, if we want a range of frequencies, we go to the Frequency Sweep tab and enter the required values.

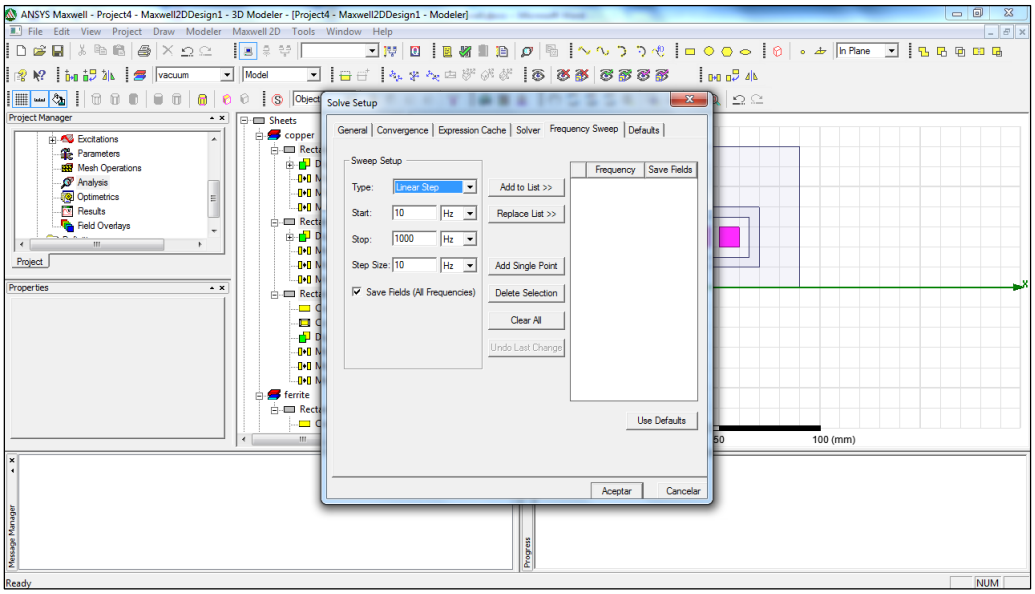


Figure 37: how to simulate with a range of frequencies

Start the Solution

Now that we have set up the solution parameters, the problem is ready to be solved. To start the solution, right-click **Setup1** >> **Analyze** in the Project Manager window. A progress bar appears in the Progress box at the bottom of the screen.

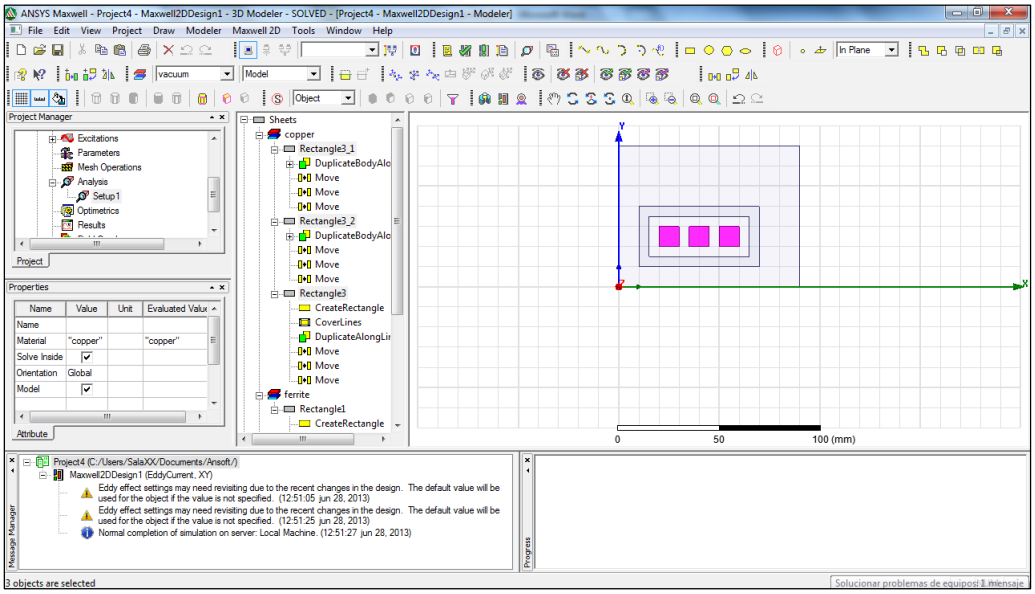


Figure 38: generating a solution in Maxwell 2D

Analyzing the solution

Now that we have generated a solution forour problem, we can analyze itusing Maxwell 2D's post processing features.

We will use the field calculator to obtain the Energy and the Ohmic losses, selecting the menu item **Maxwell >> Fields >> Calculator**.

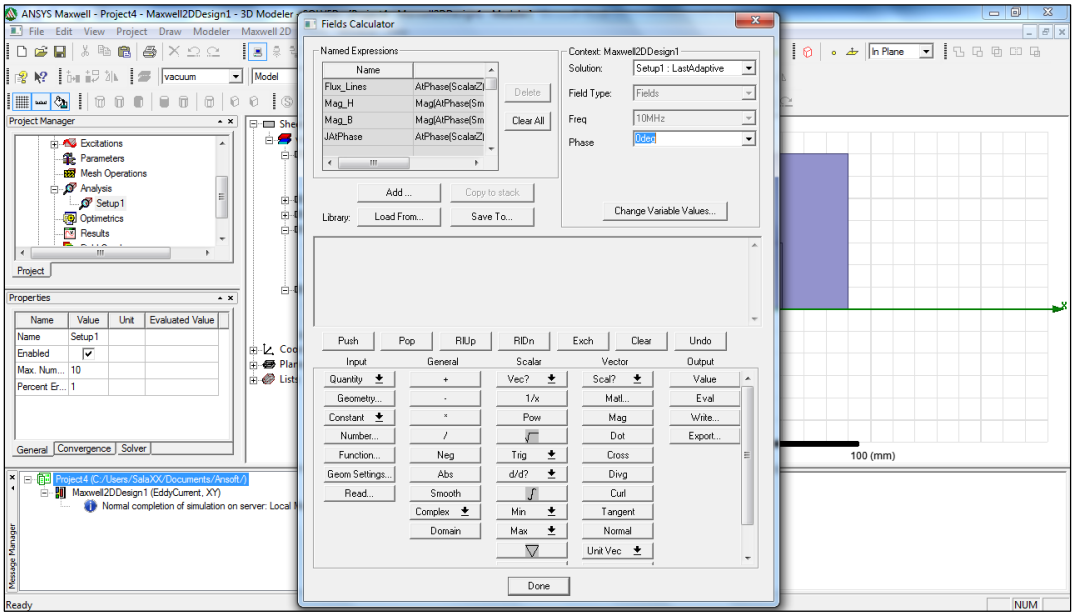


Figure 39: calculator in Maxwell

Annex III. Reference Manual of the tool

We have explained in chapters 4 and 5 how the interface is done and how it works, so these sections can be used as User Manual tool. With the Reference Manual we explain the previous steps to use the tool and we go deeper into the implementation of the code, hoping it will be useful for developers who want to extend or modify its functionality.

Installation

The tool consists of the following files:

File	Function
Todo.m	This file contains the MATLAB interface code and the main code where calls are made to the different functions.
Todo.fig	This file is the GUI.
Unidades.m	This files are the functions that we have explain in section 4.3
Fmaxwell_1f.m	
Fidesign.m	
Fexe.m	
Magic_32.exe	This executable is the tool of Tyndall.
Nucleo.jpg	These are the images of the interface.
CEI.jpg	
Racetrack.jpg	

Table 28: files of the Matlab tool

We will need to install Matlab and Maxwell 2D in order to use the tool.

We have to create a **working directory** (which we will use in MATLAB), where we have all the files mentioned above.

Code modifications

We have to modificate line 31 and line 152 of the code in Fmaxwell_1f.m function, in order to indicate where we can save the Maxwell design.

32. fprintf(codigo,'oProject.SaveAs "C:\\ Users\\ SalaXX\\ Documents\\ Ansoft \\%s_core_%d.mxwl", true\n',Nombre,aux);

152. fprintf(codigo2,'oProject.SaveAs "C:\\ Users\\ SalaXX\\ Documents\\ Ansoft \\%s_air_%d.mxwl", true\n',Nombre,aux);

So we have to modificate de line from “Save As” to “\\%s_core_%d.mxwl".

After that, we have to modificate lines 111, 119, 229 and 237 of the code in Fmaxwell_1f.m function, in order to indicate our Working Directory.

111. fprintf(codigo,'oModule.CalculatorWrite "E:\\ PROYECTO\\ Formulas\\ energ_core.fld", Array("Solution:=", "Setup1 : LastAdaptive"), Array("Freq:=", "%fHz", "Phase:=", "0deg")\n',Fmin);

119. fprintf(codigo,'oModule.CalculatorWrite "E:\\ PROYECTO\\ Formulas\\ res_core.fld", Array("Solution:=", "Setup1 : LastAdaptive"), Array("Freq:=", "%fHz", "Phase:=", "0deg")\n',Fmin);

229. fprintf(codigo2,'oModule.CalculatorWrite "E:\\ PROYECTO\\ Formulas\\ energ_air.fld"

237. fprintf(codigo2,'oModule.CalculatorWrite "E:\\ PROYECTO\\ Formulas\\ res_air.fld", Array("Solution:=", "Setup1 : LastAdaptive"), Array("Freq:=", "%fHz", "Phase:=", "0deg")\n',Fmin);

So we have to modificate de lines from “CalculatorWrite” to “\\energ_core.fld".

Tool execution

In order to start the tool, we need to open Matlab, select our working directory and in the command line, whe have to write the name of the interface, in this case:

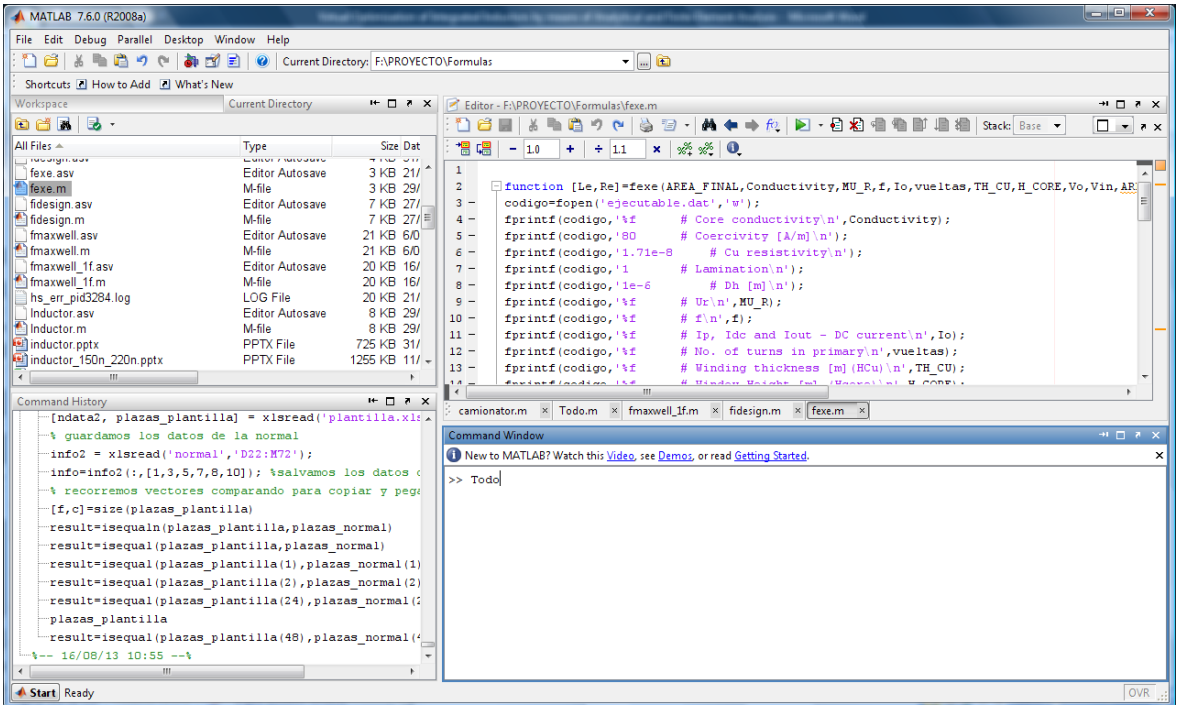


Figure 40: how to execute the tool in Matlab

After that, the GUI appears:

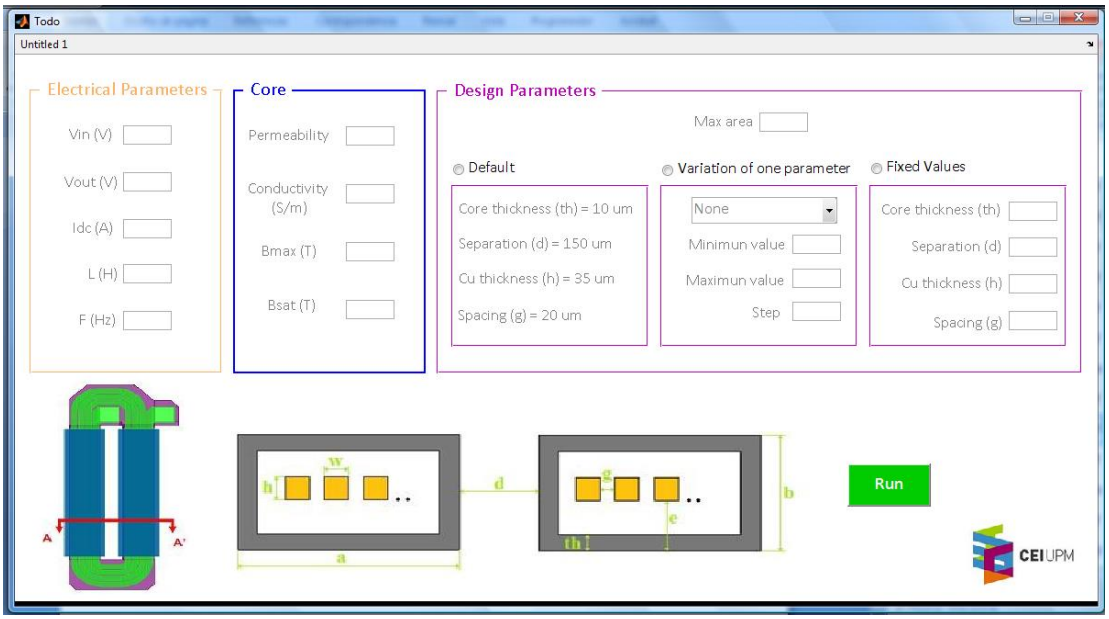


Figure 41: GUI

Implementation of the code

The main function code "Todo.m" follows a structure which is repeated as many times as design options are in the interface. That is:

Option number X (from line Y to Z):

- We assign values to the parameters that are kept fixed. This assignment can be done in two ways: the parameters can have a default value assigned, or can obtain its value through the values entered in the interface.
- We call the function **Fidesing**. We send these parameters and receive the rest. We obtain the complete design of the inductor.
- We call the function **unidades**. This function only transforms the parameters from meters to **millimeters**, because **we configured Maxwell to enter data in these units.**
- We call **fmaxwell_1f** function in orden to obtain the Maxwell Design.
- Correction code: we compare the value of inductance used in analytical design (**L**) inductance value obtained in Maxwell (**Lf**). If this is 1.1 times higher, apply the correction factor to L, we again call the function **Fidesign** to redesign the inductor, and the functions **unidades** and **fmaxwell_1f.**
- Now we have an accurate design in Maxwell, we call **fexen** function in order to obtain de Tyndall model.
- After that, the rest of the code is used to display the results.

We show a table below to indicate where each option is in the code:

Option	Code lines
Option number 1: Default	from line 1041 to 1088
Option number 2: **Variation of one parameter** **Core Thickness**	from line 1091 to 1168
Option number 2: **Variation of one parameter** **Cu Thickness**	from line 1170 to 1249
Option number 2: **Variation of one parameter** **Separation**	from line 1251 to 1332
Option number 3: **Fixed Values**	from line 989 to 1088

Table 29: Design options and its code lines

Using functions independently

If our goal is to use only one of the functions independently of the GUI, the steps would be (in the command line):

1. Assign the value to the input parameters in
2. Call the function

Then the results would show.

Example: Fidesign

Step 1: Assign the value to the input parameters

L=220e-9;

Vin=5;

Vo=1.2;

f=10e+6;

Io=0.5;

AREA=4e-6;

MU_R=280;

Conductivity=181818;

TH_CU=35e-5;

TH_CORE=10e-6;

s=20e-6;

separation=150e-6;

overlap=50e-6;

distance=250e-6;

Bmax=1.2;

space_centre=15e-6;

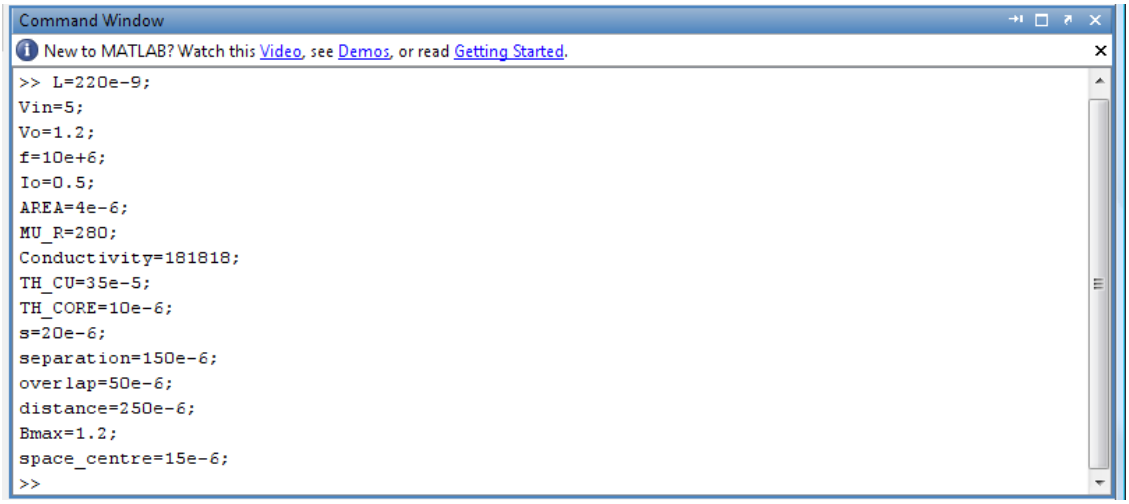


Figure 42: introducing parameters in the command line

Step 2: call the function

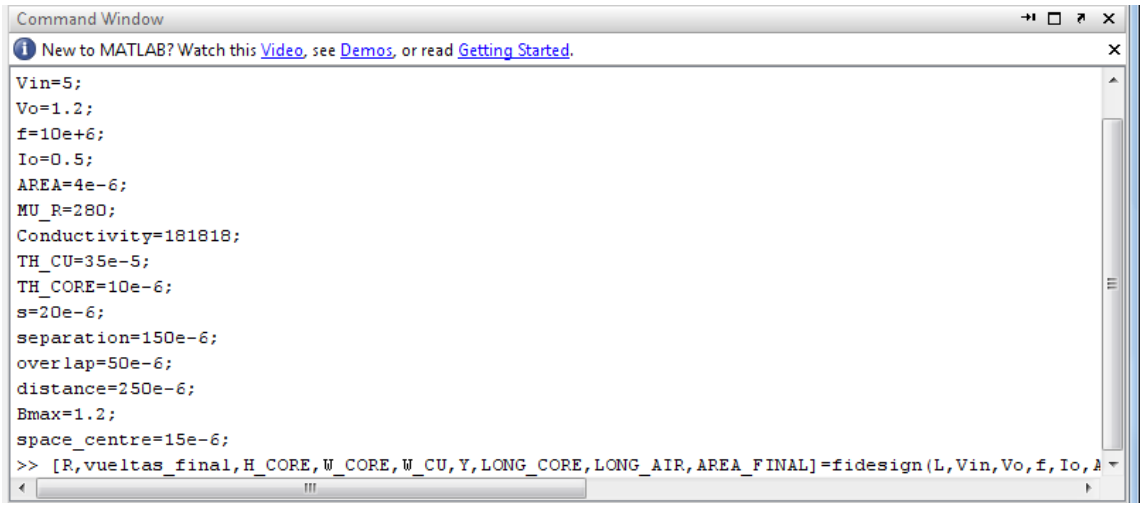


Figure 43: calling the fucntion in Matlab

And the results are shown just in the same way that when we use the GUI.

Annex IV. Losses in magnetic components

Losses

The power dissipated in the inductor arises from two separate sources: the losses associated with the inductor core and those associated with the inductor windings. Although exact calculations of these losses can be complex and difficult, they can be estimated.

Power losses in the **winding** are the result of DC conducting losses and AC conducting losses. AC conducting losses are due to two different effects: skin and proximity.

Power losses in the **core** are related with eddy losses and hysteresis losses.

These mechanisms of losses are discussed below.

Eddy currents

The magnetic fields created by the conductors affect other conductive materials such as other conductors, silicon die substrates, ground planes, some dielectric materials, and magnetic materials. A magnetic field created by a conductor can intersect a nearby conductor and induce small circular currents ("eddy currents") within the new conductor. These eddy currents in turn produce a magnetic field that opposes the original field, generating a loss in the efficiency with which the field can change direction (as it does often in the case of high frequency alternating current). Additionally, these eddy currents dissipate energy in the form of heat as they flow through the conductor, further decreasing the efficiency of energy storage [5].

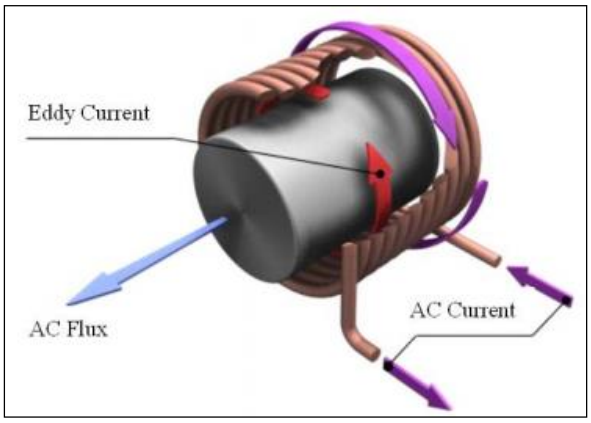


Figure 44: Schematic of induced eddy current loss [5]

Losses due to eddy currents are given by:

$$P_e = R \cdot {i_e}^2(t) = \frac{Ve^2(t)}{R}$$

$$V_e(t) = \frac{d\phi(t)}{dt} = A_c \frac{dB(t)}{dt}$$

The induced voltage Ve(t) is proportional to the derivative of the flux density Φ(t). In consequence, the magnitude of the induced voltage is directly proportional to the excitation frequency f. Therefore, the eddy current loss is proportional to f^2. Also the magnitude of the magnetic core's electrical impedance decreases with increasing frequency. So the eddy currentloss typically increases faster than f^2, which would become a serious problem in high frequency.

The way to suppress eddy current loss is to reduce the thickness of the magnetic core close to or smaller than its skin depth. When the thickness of the magnetic core is in the same scale with the skin depth, there will be not enough space for large eddy currents to be generated due to the skin effect [8].

Another way to reduce the core loss at high frequency, while maintaining sufficient core thickness, is using multilayer structures with magnetic thin films to decrease eddy-current losses, since the dielectric layers between the magnetic layers confine the induced eddy current to each individual layer. For micro magnetic devices, lamination is a big challenge for conventional microfabrication technologies. Several approaches have been proposed and different laminated cores have been demonstrated in [10-18].

Hysteresis losses

Hysteresis loss is due to power that is consumed in reversing the magnetic field of the inductor core each time the direction of current in the inductor changes. This wasted energy in the form of heat is proportional to the area of the magnetic hysteresis loop.

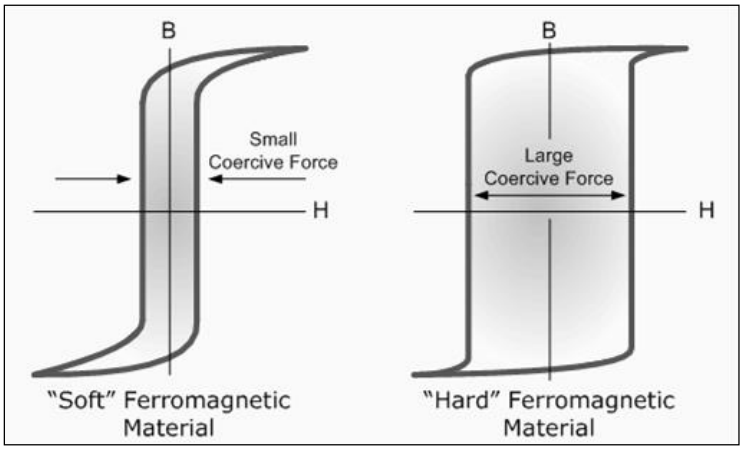


Figure 45: Magnetic Hysteresis Loops for Soft and Hard Materials [50]

Consider an n-turn inductor excited by a periodic waveform. The net energy that flows into the inductor over one cycle is:

$$W = (A_c \cdot l_m) \oint H db$$

where the term ($A_c \cdot l_m$) is the volume of the core and the integral is the area of the B-H loop. Then the hysteresis power loss is the energy loss per cycle multiplied by the frequency f , i.e.;

$$P_H = W \cdot f$$

So the hysteresis loss is proportional to the area of the hysteresis loop of the inductor and the switching frequency f.

DC conducting losses

The majority energy loss of an inductor comes from its DC resistance (R_{DC}). The power loss due to DC resistance is given by:

$$P_{dc} = R_{dc} \cdot {I_{L\_rms}}^2$$

where, P_{dc} is the power loss due to DC resistance, and I_{L_rms} is the rms current of the inductor. For high performance inductors, DC conducting loss dominates and other losses need to be suppressed [8].

AC conducting losses: skin effect

Eddy currents are also responsible for the skin effect, in which changing magneticfields produced by a conductor induce eddy currents inside the center of that conductor.

At high frequencies, the opposing fields created by eddy currents are strongestin the center of the conductor, causing the current density in this region to decreasesharply. Most of the current flows much more strongly near the surface of the conductor, causing the apparent cross-sectional area of the current-carrying conductor todecrease (and consequently causing the AC resistance to increase). The next figure shows an example of the skin effect on current densities within a conductor.

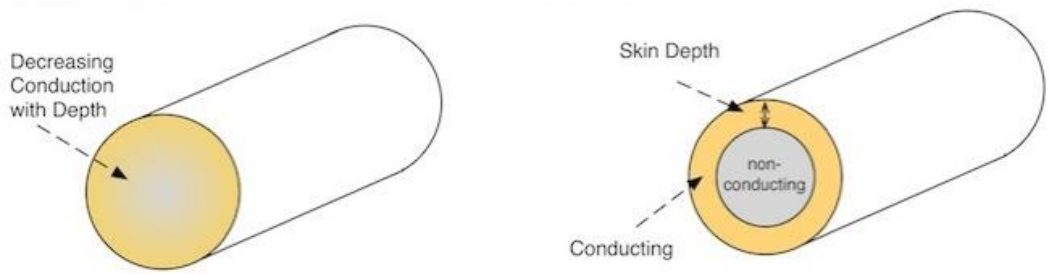


Figure 46: an example of the skin effect on current densities [51]

An approximation of the skin depth can be calculated using the magnetic permeability, μ, and the electrical resistivity, ρ, of the material, as well as thefrequency of operation, f, using the following equation:

$$\delta = \sqrt{\frac{\rho}{\pi f \mu}}$$

AC conducting losses: proximity effect

The proximity effect is a phenomenon that a conductor that carries a high frequency AC current will increase the AC resistance of an adjacent conductor. This proximity effect is pronounced in high frequency conductors, especially in high frequency AC converters.