Impedance Analysis of a Pot Core Inductor

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Abstract: This work develops a methodology based on the application of finite element method in the frequency domain, using the software COMSOL Multiphysics® with the ACDC module: the purpose is to evaluate electromagnetic parameters of a pot-core inductor.

This paper shows how to extract common parameters, such as the inductance (L), the equivalent series resistance (Rs), the equivalent parallel resistance (Rp) and the quality factor (Q) of a pot core inductor. The knowledge of the electromagnetic parameter is very important for several reasons, for example it is useful to choose the frequency where the device has the best performances or to predict the value of the inductance or simply to create a lumped equivalent circuit model to insert a more complex circuit.

We propose a simply and accurate method to evaluate these parameter. Finally we have compared the obtained results with measures taken with a precision RLC meter.

Keywords: Inductor, impedance analysis, ferrite core

1. Introduction

Inductances are a fundamental component in electronic field: therefore, is important to know how it can be modeled as an equivalent circuit.

Time varying electromagnetic fields in conducting media can be analyzed in terms of the current density vector, usually defined by an integral equation, whose analytical solution is possible only in simple configurations [1]. For arbitrary complex structures, numerical procedures are developed either in time domain or in frequency domain and, among them, the Finite Element Method (FEM) can be applied. The frequency domain study can be used to compute response of linear or linearized models subjected to harmonic excitation.

FEM analysis requires a convenient mesh grid study to obtain a correct and optimized solution of the model. The optimization of the mesh is related to some specific physics characteristics, like the skin depth.

In this work, it is shown how to extract the fundamental electromagnetic parameters: the inductance, the quality factor, the parallel and the series resistance of a pot core inductor. A comparison with measurements is done to validate the model.

2. Pot core inductor

The device under test is a inductor called pot core inductor (see the figure 1).

The shape geometry brings many advantages such as high quality factor and temperature stability. Moreover, the self-shielding geometry isolates the winding from external magnetic field and it forces the direction of the generated magnetic field. Typical applications for pot cores include: differential inductors, power inductors, proximity sensor, filters and telecom inductors. [2]

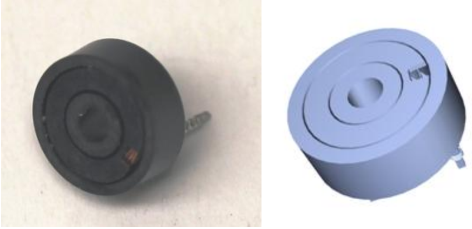


Figure 1. A photograph of a pot core inductor and its 3D representation

The ferrite core's code is EPCOS B65924_4_X22 and it is made with N22 ferrite material which is stable over a wide range of temperature and frequency excitation [3]. The coil is characterized by 66 turns of 0.1 mm copper wire diameter which is winded up in an external support allowing the weldability and the easiness to handle.

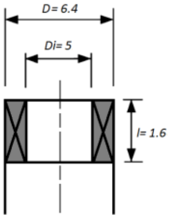


Figure 2. Structure of coil (unit: mm)

3. Use of COMSOL Multiphysics® Software

3.1 Mathematical description

The simulations have made in a frequency domain with the ACDC module and the Magnetic Field Interface. The equations (1) are computed by COMSOL Multiphysics:

$$\begin{cases}(j\omega\sigma - \omega^2\epsilon)A + \nabla \times \mathrm{H} = \mathrm{J_e} \\ B = \nabla \times \mathrm{A}\end{cases} \tag{1}$$

where: ω – the angular frequency of a magnetic field, σ – the electrical conductivity of materials, ε – permittivity of materials, A – a magnetic vector potential, H – magnetic field intensity, B – magnetic flux density, Je – externally generated current density.

This system of equations is computed to each finite element of the model. Solving the given equations allows us to obtain the magnetic flux distribution. In order to find a close solution it must be imposed a constrain in the outer boundaries:

$$n \times \mathrm{A} = 0 \tag{2}$$

This equation fixes the tangential component of the magnetic potential A to zero.

Additionally, the winding is supply by a constant voltage, this imposes the following equations:

$$J_e = \sigma \frac{V_{Coil}}{L} \tag{3}$$

where: V_{COIL} is the applied voltage specified, Je – current density in windings, σ – the conductivity of materials, L is equal to the physics interface's thickness equal to $2\pi r$ for 2D axially symmetric models [4] [5].

3.2 Model

In order to simply the analysis and to reduce the occupied memory and the computation time, all COMSOL models are made in 2D axial symmetry. A 2D axial is more light, in terms of occupied memory, than a 3D one. This is very important because the 3D model requires a lot of iterations to complete the simulation and the creation of the winding in a 3D geometry could be more difficult.

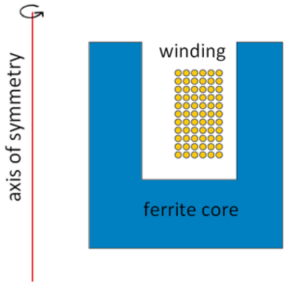


Figure 3. Geometry of the 2D axis model

As noted above, the model is developed through the ACDC module and the Magnetic Field (mf) interface. Single turn coil coupled with coil group option is a useful feature to merge the winding in one single object and it allows the computation of the impedance of the whole selected domain.

All the analysis are made in the frequency domain with range 100kHz-1MHz and the winding is supplied by a constant voltage of 1V. The model is completely drawn using COMSOL graphical tool and it is parameterized allowing a more flexibility and the material used are summarized in the table.

Material	Relative Permeability μ_r	Electrical conductivity σ (S/m)
Air	1	1
Copper	1	$5.998 \cdot 10^7$
Ferrite core N22 – Epcos	2300	1

Even if all elements are assumed to be linear, for a more detail analysis is convenient to insert the ferrite core as a non-linear material considering the magnetic losses. For our purpose it was decided to reduce the complexity, hence it is neglected also the self-resonant frequency (above the self-resonant frequency the impedance become capacitive).

3.3 Mesh settings

The appropriate settings for mesh are fundamental for a correct analysis because a single simulation model should include several physical effects, like the magnetic coupling effect between coils, the skin effect in a single wire. Therefore, two types of mesh were used: a boundary layer and a free triangular.

The boundary layers is used to mesh the wire automatic adjusting the domain thickness over the frequency in order to correctly meshing the whole domain in a wide frequency range and consequently maintain the same number of domains. This feature is possible considering the domain width as a frequency-dependence function.

The free triangular is used to mesh the remaining domain with different dimensions according to the size of the domains. The figure 3 shows the mesh of the model.

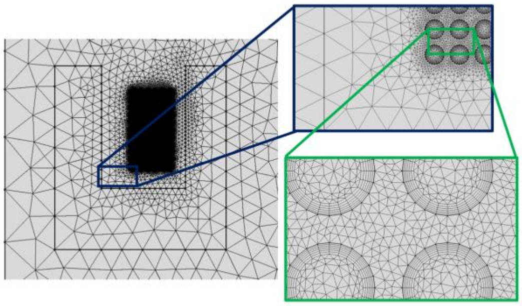


Figure 4. Mesh of the model. The details show the two typology mesh adopted. A full model is composed by 28164 domain elements and 1469 boundary elements.

3.4 Post processing

In the first instance any inductor could be represented as an equivalent circuit through lumped element model. The simplest circuit model is composed by an ideal inductor and a resistor: these components could be considered with two different topologies (as the figure shows), one with the resistor in series at the inductor (a), the other in parallel (b).

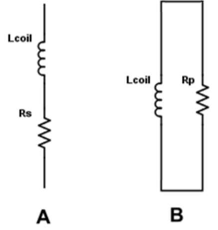


Figure 5. A- equivalent series model of an inductor; B- equivalent parallel model of an inductor

In order to extract the electromagnetic parameters it is useful plotting the variable as a global parameter over the frequency range.

The inductance L, the resistance Rs are easily to extract while parallel resistance and quality factor follow the (4) and (6) equation.

In fact, selecting the coil group in single turn section COMSOL Multiphysics allows to evaluate in the Result section many common electronics parameters [6]

$$Rp = \frac{1}{Real(1/Z)} \tag{4}$$

$$Q = \frac{Img(Z)}{Real(Z)} = \frac{X_L}{Rs} = \frac{\omega L}{Rs} \tag{5}$$

In general, the inductance L_{coil} is related to the function:

$$L_{coil} = Lp = Ls\left(1 + \frac{1}{Q^2}\right) \tag{7}$$

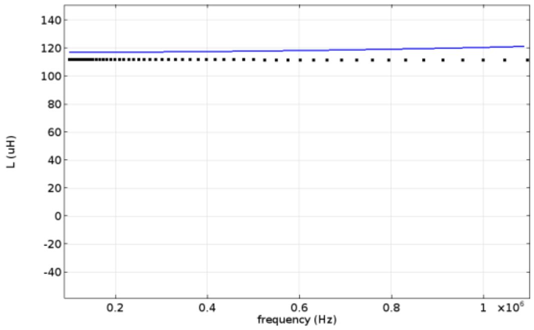
Considering a high value of the quality factor Q the inductance in both configurations is very similar, therefore the inductance $L_s \approx L_p = L_{coil}$.

If making the model more complex is necessary a small capacitor both configurations in order to introduce the self-resonance frequency should be add. In this work it was decided to neglect this accuracy and taking into account that the impedance is prevalently inductive.

4.Results

Measures compared with the simulation results allow to the validate the model.

It has been used a LCR precision meter Hp 4285A to collect the data. Figure 5 shows the comparison between the measurements and the simulation results.



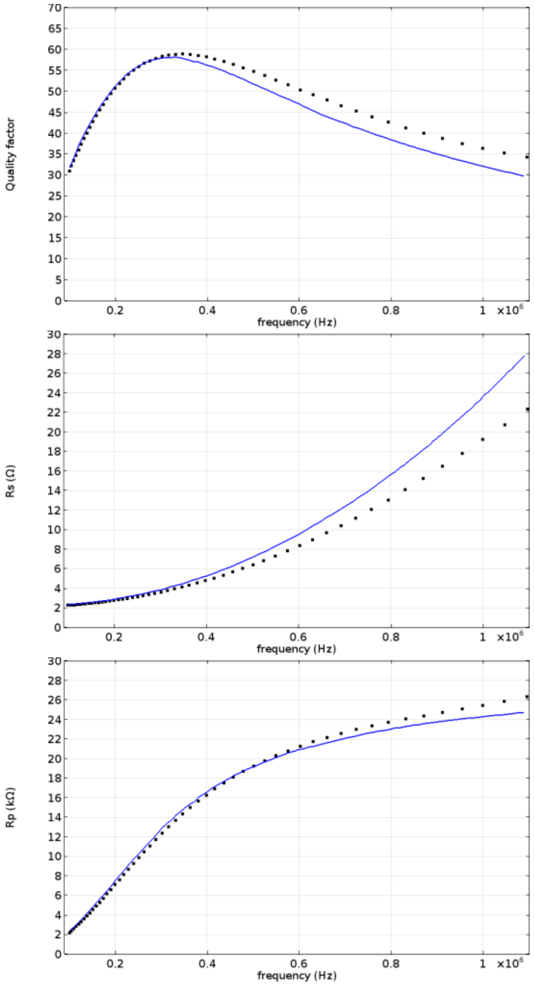


Figure 6. Comparison between measurement and simulation results for a pot core inductor with 66 turns. In order (top as first) the inductance L, the quality factor Q, the series resistor Rs, the parallel resistor Rp. The blue line are the measurements while the black dotted line are the simulation points.

It is possible to notice the measurements and the simulation results are in good agreement. In particular, until 300 kHz the resistance Rs has a different trend and therefore also the quality factor is affected. For frequencies greater than 300kHz losses are different, probably because there are some effects that we have not take into account such as the presence of the capacitor or the nonlinearities properties of the ferrite material. However, for our purpose the accuracy is acceptable for estimate each parameter at the selected frequency.

Further analysis is done changing the turns of the winding and plot the parameter over the same range of the frequency. This is useful to design checking each parameter. The figure 7 shows the trend of the parameters.

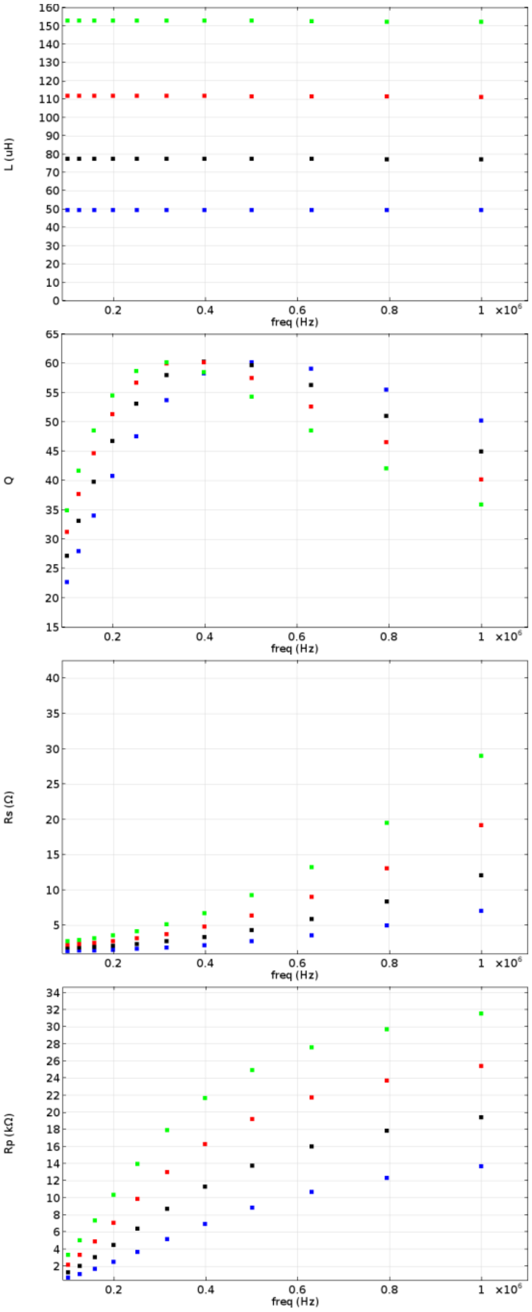


Figure 7. L, Q, Rs, Rp changing the number of turns: 44 blue, 55 black, 66 red, 77 green.

For completeness the figure 8 shows that the magnetic flux density is confined in the middle of the structure.

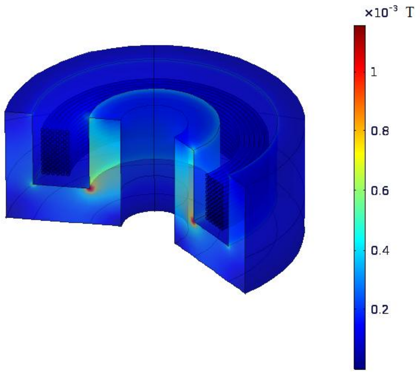


Figure 8. Magnetic flux density distribution in the pot inductor at 1MHz

The current density distribution shown in the figure 9 highlights how the current is localized in the top and in the center of the structure. This confirms that the pot core inductor thanks to the geometry confines the current as a consequence also the magnetic flux.

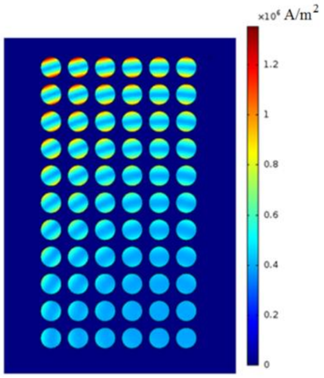


Figure 9. Current density distribution in winding at 300kHz

8. Conclusions

The analysis presented of the pot core inductor allows us to made the following conclusions:

- The COMSOL software is helpful to compute the electromagnetic calculation
- The model winding with the appropriate mesh and the post processing settings allows a good estimation of the electromagnetic parameters

The methodology shown could be a useful approach to evaluate the electromagnetic parameters.

9. References

1. T. A. G. de Tolosa and J. M. Janiszewski, "Time domain analysis of transient electromagnetic fields in conductors," *2005 IEEE Antennas and Propagation Society International Symposium*, 2005, pp. 183-186 **vol. 3A.**

2. “Ferrite cores”, Kolektor, www.kolektor.com

3. “Epcos Data book 2013, Ferrites and accessories”, Epcos, www.epcos.com

4. “ACDC Module Users Guide", COMSOL, www.comsol.com.

5. The Design of a Multilayer Planar Transformer for DC/DC Converter with a Resonant Inverter M. Puskarczyk, R. Jez, *COMSOL technical paper*, ABB Corporate Research Center, 2014

6. “RF-inductor modeling for the 21st century” Leslie Green, *Gould-Nicolet Technologies*, 2001

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