



Simplifications in 3D High-Low Frequency Models of Multi-winding Magnetic Components (EE & Toroidal Cores)

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Abstract

Not every magnetic component can be simulated with 3D finite elements tools. Nowadays, there are hard difficulties to simulate 3D models because of computer limitations and the 2D models have not enough accuracy [1,2].

The proposed method will simulate the magnetic component (EE and Toroidal core) in 3D and decrease the needed processing time. The method consists of several simplifications and adjustments to determine the sought parameters (resistance & inductance) in low/high frequency without losing accuracy when compared with the real 3D model simulation.

Keywords

DC power conversion, finite-element methods, inductors, modelling, voltage transformers, 3 dimensions

Introduction

Currently, there are computer limitations that make impossible to process 3D magnetic component models with Finite Elements Analysis (FEA). In fact, it is necessary to make simplifications in the model to process the model.

Sometimes, the 2D model of the magnetic component is not appropriate due to the asymmetry of the component [3].

Therefore, a method with 3D simplifications has been developed to obtain the sought parameters of resistance and inductance with a similar accuracy to the real 3D model and to decrease the simulated time of the FEA program.

There are several assumptions, methods and models, aided program to simulate different components with more or less accuracy [4-13], but not with the final objective for this manuscript.

Finite Elements Study

In any 3D simulation, the main factor that limits the study of the component is the number of Finite Elements (FE). Most magnetic component models are composed of air, core and coils.

In determining the number of FE, the coils are the most important component. The number of coils, the shape, distance among them and the geometry can significantly impact the number of Finite Elements [14].

Among these factors, the critical one is the coil section. A study in

detail has been developed in Maxwell to know more precisely how the number of FE varies with the cross-sectional shape of the coil.

The same model (EE core) has been processed several times while changing the coil cross-section (number of edges in the section). A similar study was developed using a Toroidal core. Figure 1 is obtained results. Conclusion for this study is:

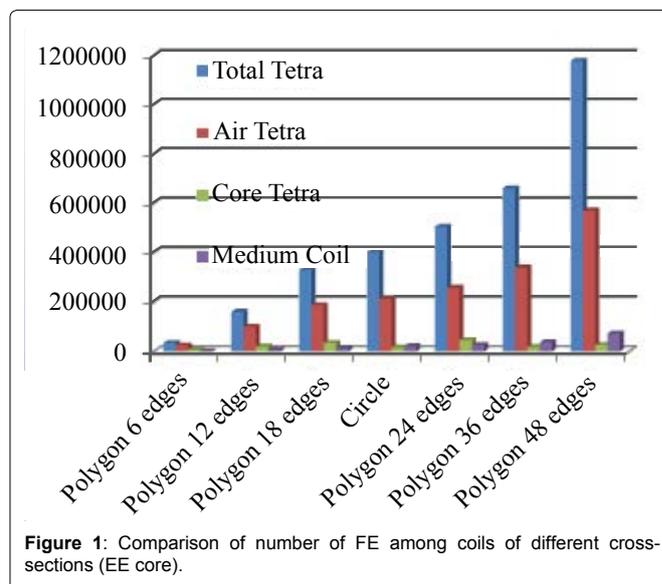


Figure 1: Comparison of number of FE among coils of different cross-sections (EE core).

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1. The number of FE increases with the number of edges. The only exception is a coil with a circular cross-section where the number of FE is between 18 to 24 edges cross-section

2. The air zone which reflects space between coils causes an increase in the number of FE. (It is aware because each section has different area and this produces different air zones)

3. The differences between the hexagon coil section and a circular section are significant.

As it is known, the memory limitations of the computer are due to the number of FE.

The most important conclusion is that most of the FE tools uses the same logic (mesh/resolution/checking the error estimator), and

thus, imposed a determinate value of error estimator, independent of the mesh had been created; there is a reduction of FE changing the coil section [14].

From this point, the purpose of this study is to reduce the number of FE without losing accuracy.

Approach Proposal

In a comparison between a real 3D model and the model (coil with polygonal section), the results are not comparable, even at low frequency. One of the main reasons is the different cross-section of the coils (circle versus polygonal section).

One of the original contributions is to change the properties of the modelled material (usually copper) in order to have the same resistance as the actual coil at low frequency, regardless of the cross-sectional shape (Figure 2).

Coil Section Study

It is necessary to choose the best polygonal section (less than 18 edges) that maintains the same accuracy in determining the resistance and inductance and minimizes the time needed to perform an FEA analysis.

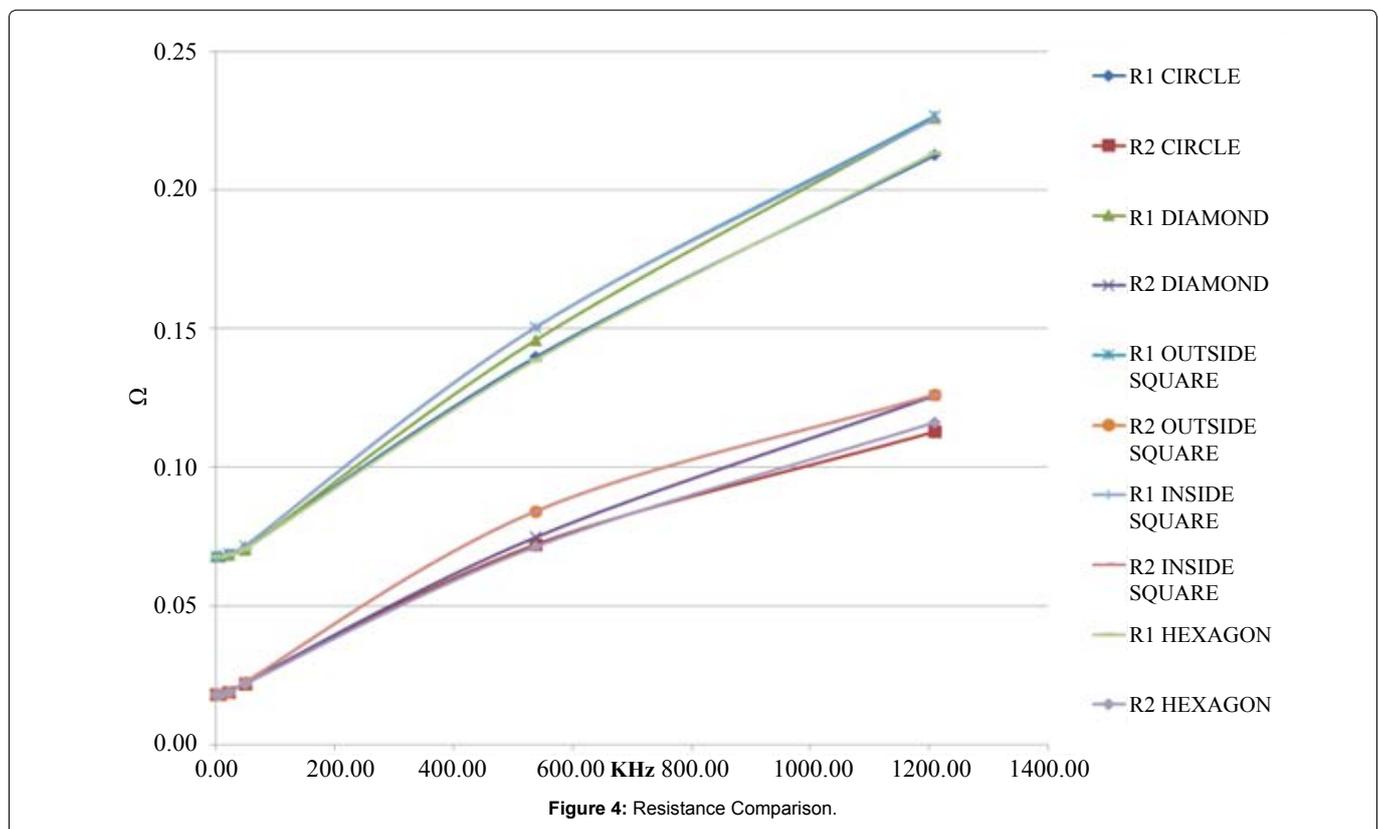
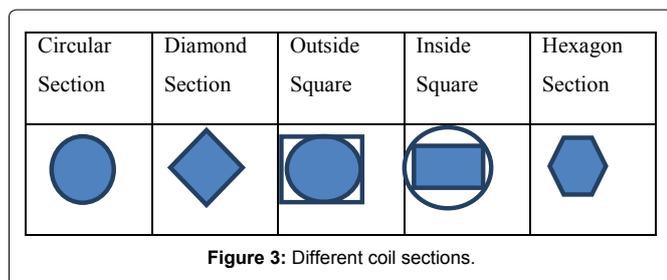
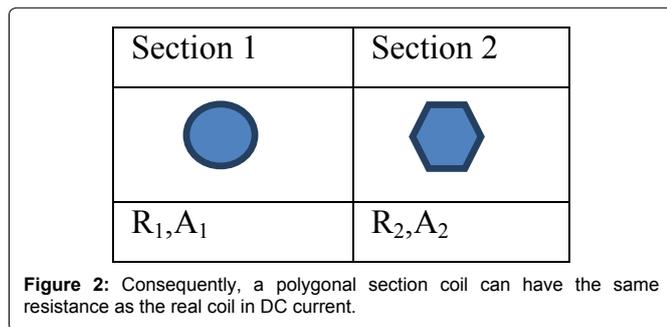
The best approach is to compare several cross-sections. Figure 3 showed the used section.

The study consists of simulating several models without core and same coils (only changing the coil section shape).

After parameter extraction of the all simulations, it is possible to compare the resistance and inductance among models. In Figure 4 and Figure 5 are the resistance and inductance comparison.

As supported by these figures:

1. The best option is to use a hexagon cross-section because it best resembles the original circular cross-section.
2. The error in high frequency between a circle and hexagon



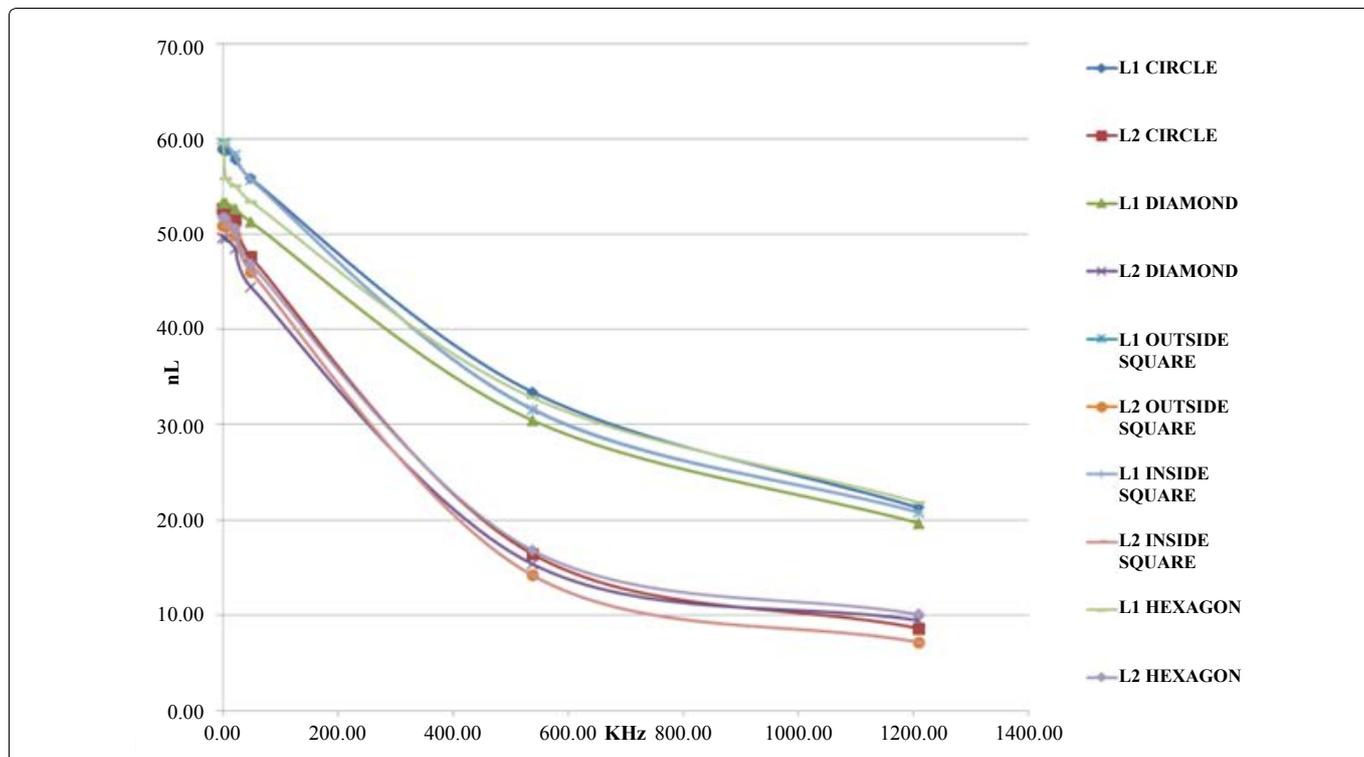


Figure 5: Inductance Comparison.



These models will have a primary and a secondary.

- Primary: variable number of turns. AWG 18, copper
- Secondary: variable number of turns. AWG 24, copper

The selection of the coils has been arbitrary to establish a method to analyze models with polygonal sections in high frequency (Table 1).

Several simulations where only the number of coils varies (from one to four coils on each side) are done to compare the resistance and inductance between the real model and the model with hexagon cross-section.

For this study, many simulations are done, however only the most representative results are shown to understand the process and methodology. The following are examples of results using a Toroidal core (four turns in each coil).

The controlled parameters are the short circuit and the leakage impedance. The magnetizing impedance has not been used because it is independent of the coil cross-section shape.

The results Figure 7 and Figure 8 demonstrate that:

- Due to the material properties changes, in low frequencies, the resistive values are equal in every simulation.
- The precision of the inductance results are sufficient for this study. However, to increase the accuracy, the cross-section of the coil should be octagonal. For inductance, one of the most important factors is the distance between coils and turns themselves. The distances in an octagonal cross-section are more similar to an actual coil (circular) than a modelled hexagon section.

Changing the properties of the coil material suffices to model EE & Toroidal cores with hexagon coil cross-section for low frequencies.

High Frequency Study

The truncated model with a hexagon cross-section works in low frequencies but differs in medium and high frequencies. For this method, it is necessary to find a factor that modifies the resistance values to obtain similar values to the real coil.

section is 0,4 % for the resistance and 2,6 % for the inductance

Thus, the choice for the coils is a hexagon cross-section.

The next step is to develop a study of simulations using the models in the following figure 6.

These models have been chosen because EE & Toroidal core are more common in transformers and power converters and their core does not have 3D symmetry. These models are a good choice because this study focuses on magnetic components that cannot be properly studied in 2D.

Table 1: Information about skin effect.

	AWG18	AWG24	Hz
r/δ	0,0234572	0,0120456	1
r/δ	1,7199124	0,8831983	5376
r/δ	3,4400648	1,7665197	21507
r/δ	5,1601105	2,6497865	48391
r/δ	17,200372	8,8326233	537678
r/δ	25,800563	13,248938	1209776

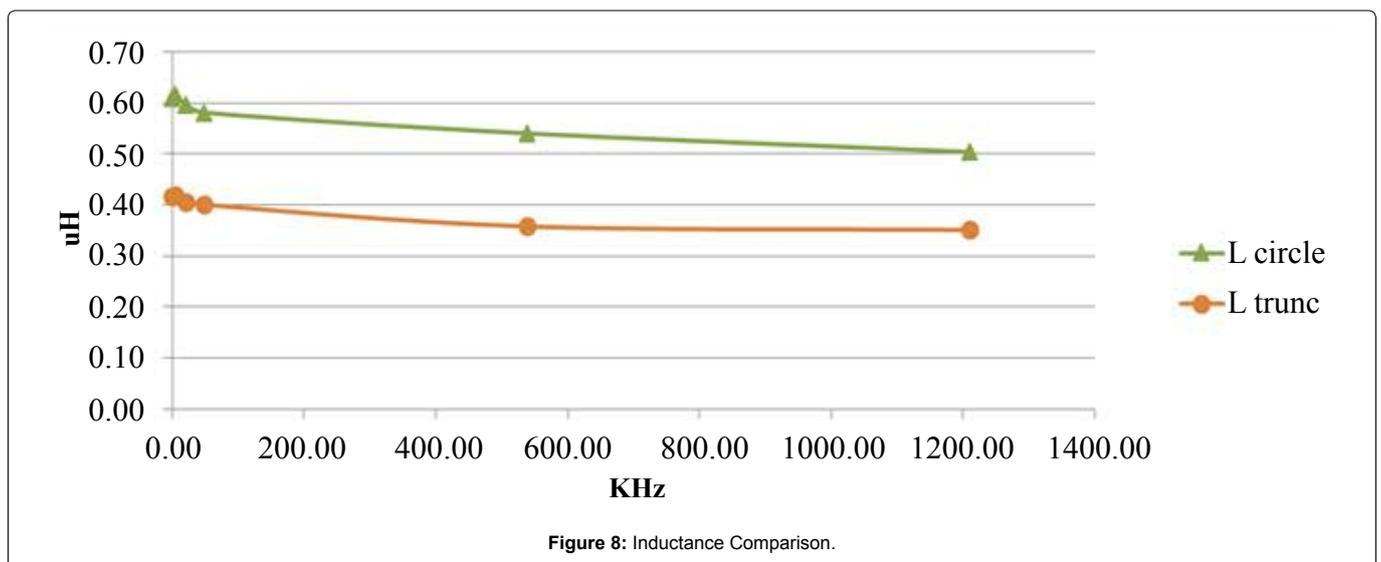
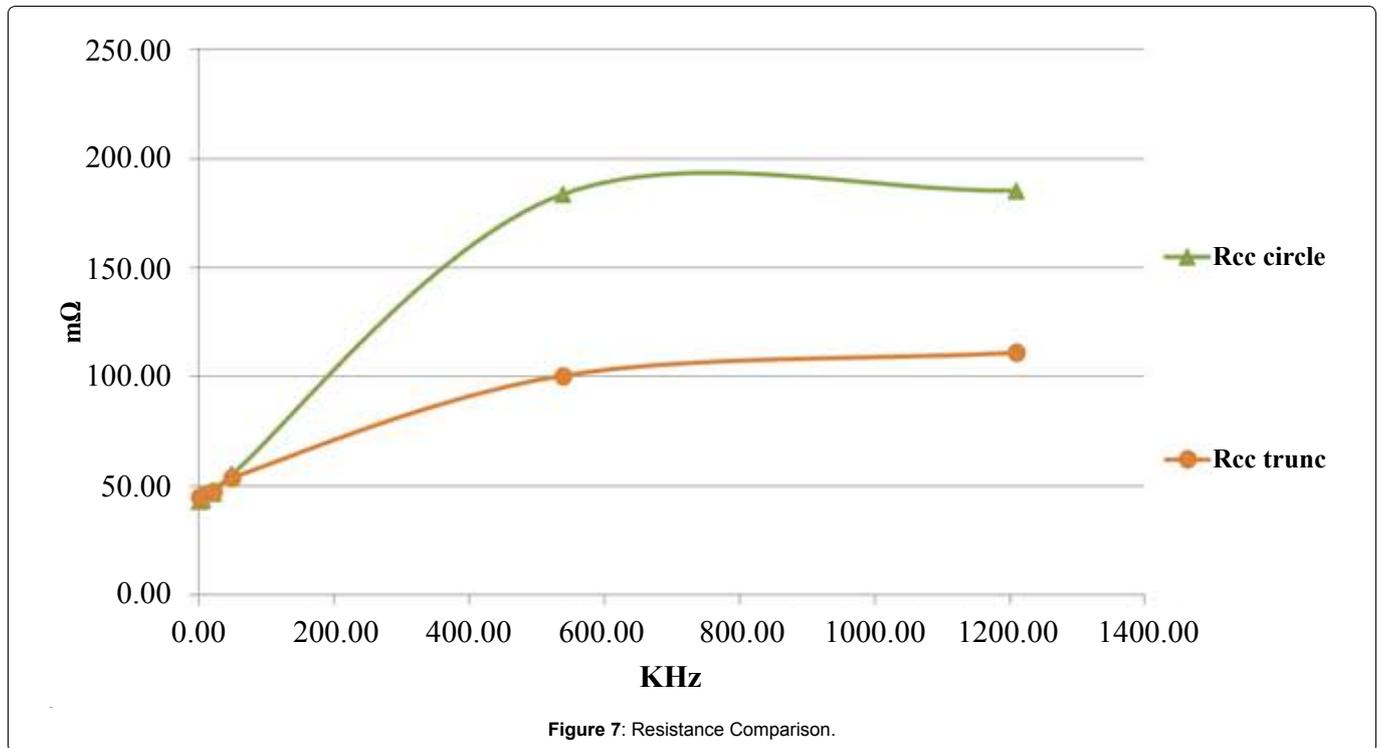


Table 2: The separated ranges.

Lowfrequencies	< 20 KHz
Medium Frequencies	20 - 50 KHz
High Frequencies	<1,2 MHz

To accomplish this, several frequency ranges are separated and the sought parameters are extracted to look for a linear behaviour (Table 2).

The next step in this study is to represent the difference between the truncated model and the real simulated model.

- EE core (1, 2, 3, 4, 8 turns in each coil)
- Toroidal core (1, 2, 3, 4 turns in each coil)

As is known, the relationship between resistance and frequency is of the 3rd order. Thus, to find the linear behaviour in these ranges the plotted against the cubic frequency [15].

The next graphs (Figure 9, Figure 10 and Figure 11) show the

results of this study for an EE core with eight turns in each side (also the slopes).

Using the method of this study, linear relationships are achieved in all studied cases:

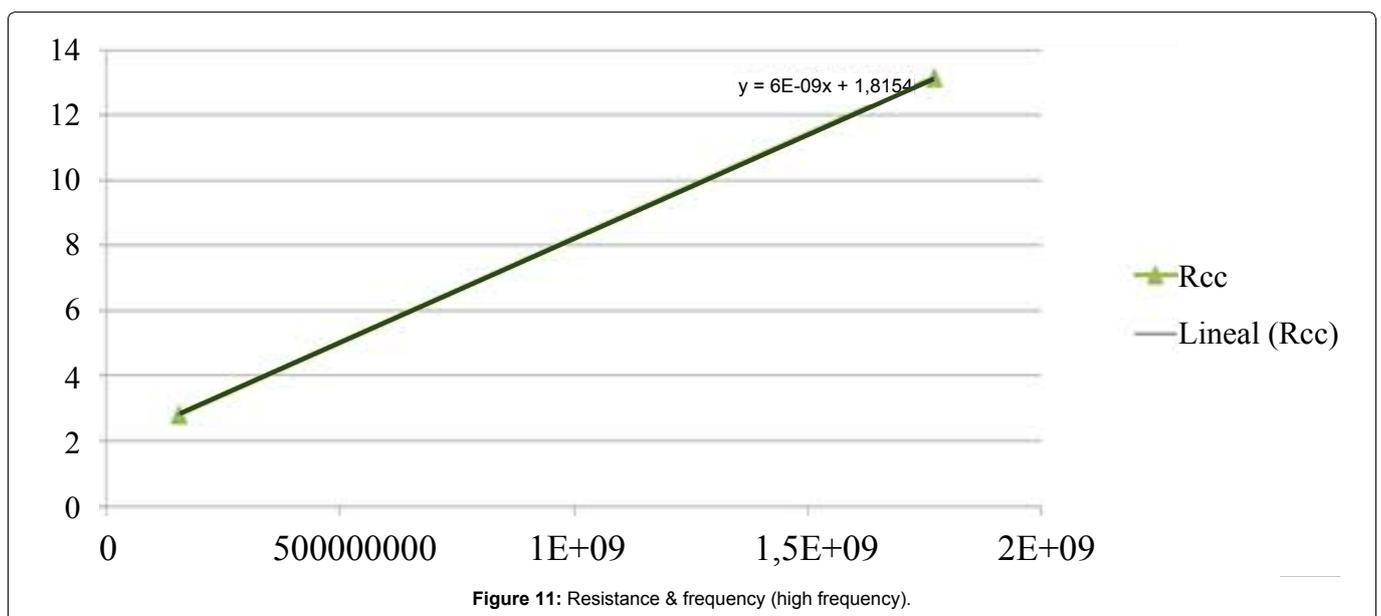
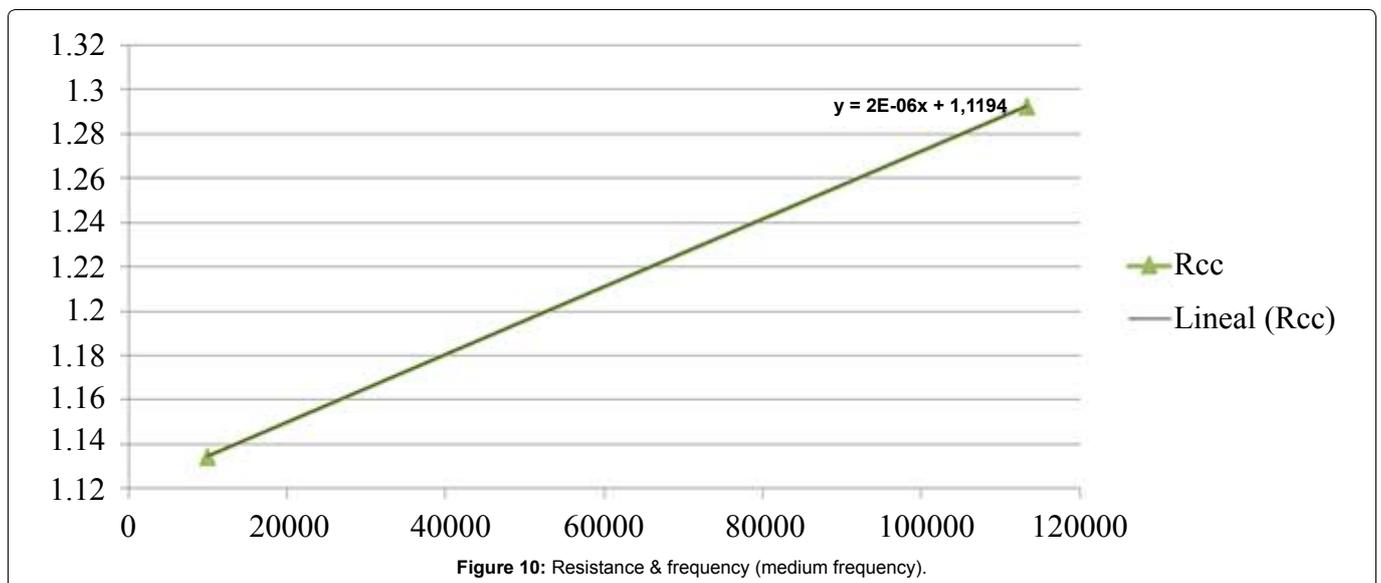
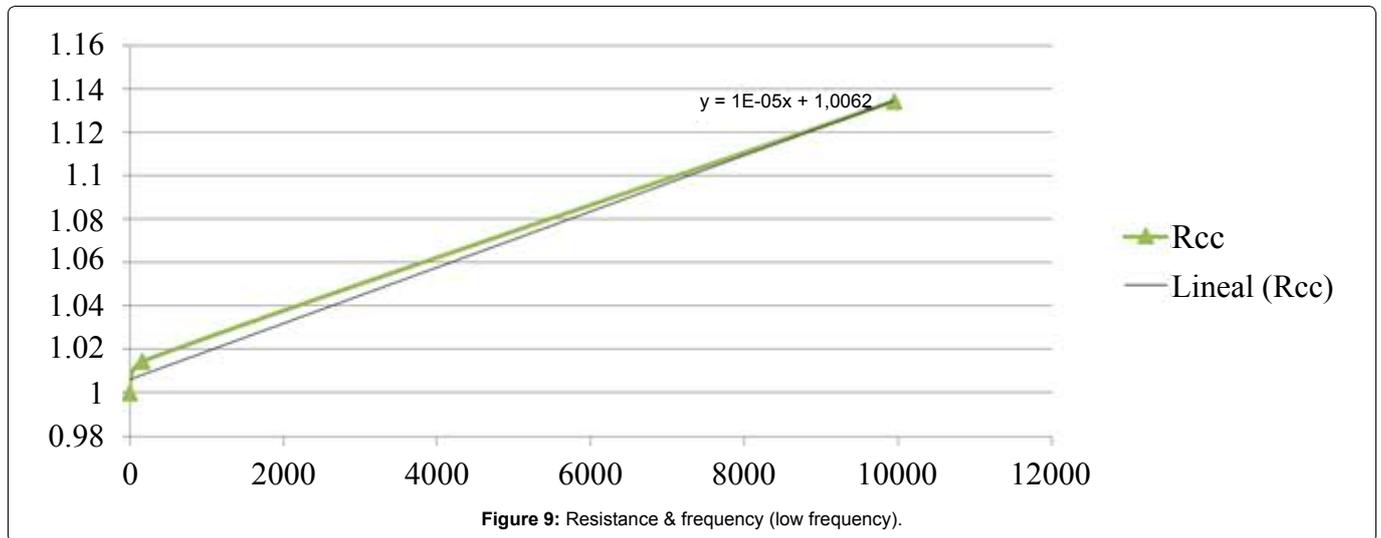
- EE core (1, 2, 3, 4 and 8 turns)
- Toroidal core (1, 2, 3, 4 turns)

With this information, a table is built to compare the slopes with the number of turns for each core. This allows a linear relationship to be found for each frequency range for both models (EE & Toroidal core).

Method

Step I: Change the cross-section of the coils

The cross-section of the coil is modelled as a hexagon cross-section inside the original circle of the coil.



- The coil will be modelled as rings, not as a single spiralled coil. the same resistance as the real component in DC.
- The properties of the coil material will be changed to have **Step II: Simulation of the component**

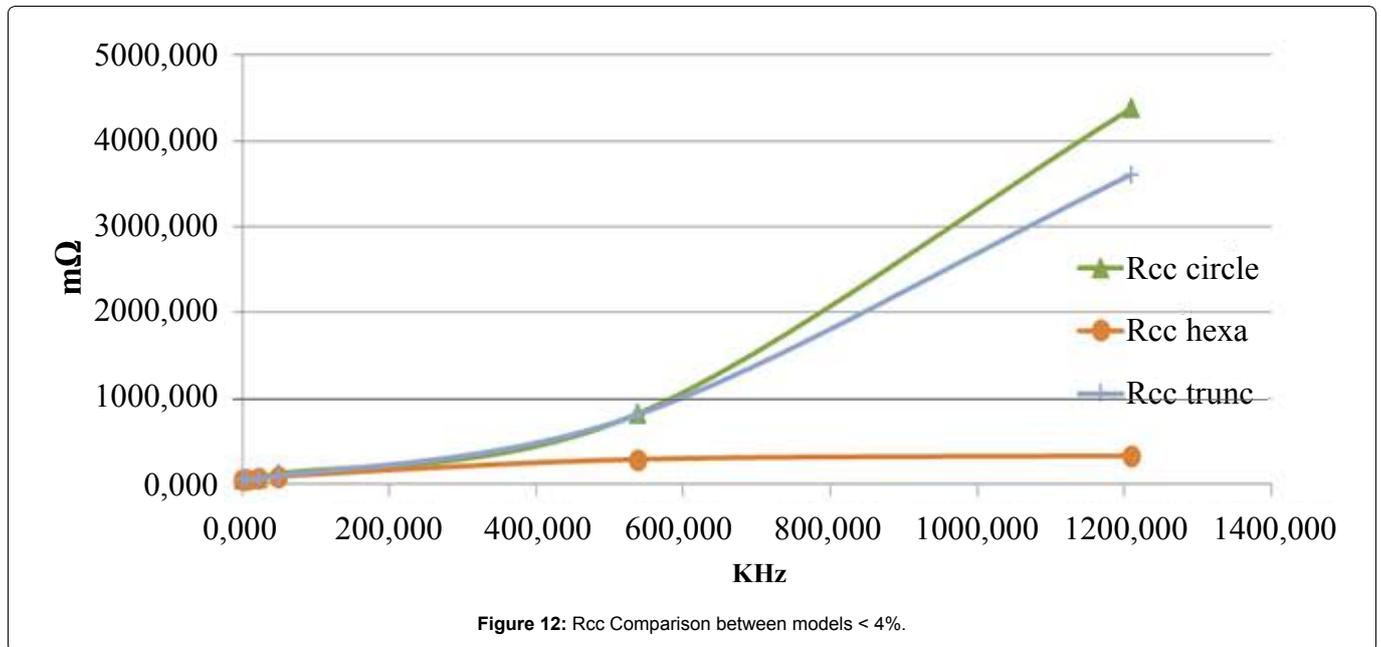


Figure 12: Rcc Comparison between models < 4%.

Table 3: Correction factor.

For an EE core	
Medium Frequencies	a=0,25 x 10 ⁻¹⁵
High Frequencies	a=5 x 10 ⁻¹⁸
For a Toroidal core	
Medium Frequencies	a=0.1/10E-15
High Frequencies	a=0.3/10E-18

Table 4: The proposed component was a transformer.

Core	Coils	
EE. 42.21.15	Primary 8 turns, copper	Secondary 8 turns, copper
Ferroxcube	AWG 18	AWG 24

- The post process will be done by the Application FEA with parameter extraction (energy analysis for multiwinding magnetic components [1]). In this case, the parameter extraction has been developed in 3D.

Step III: Correlation for the resistance and inductance

- The inductance is the same as the post-process (<5 % error, even in high frequencies)
- The resistance at Very Low Frequencies is the same as post-process.
- The resistance at higher frequencies is determined using a correction factor (the second original contribution) as follows:

The correction factor, y, is as follows:

$$y = af^3$$

(Table 3)

Validation

In order to validate the modeling process, several magnetic components were simulated. Two of them are presented here to illustrate the accuracy of the proposed method.

Simulation #1

The proposed component was a transformer with the following characteristics (Table 4)

Table 5: The real model simulation.

Freq (Hz)	Relative Error %
5376	1,4
537678	1, 21
1209776	17,6

Table 6: The second model was of another transformer.

Core	Coils	
C107.65.25	Primary 3 turns, copper	Secondary 3 turns, copper
Ferroxcube	AWG 18	AWG 24

Table 7: The real model needed 320898 FE and the truncated model 13480, FE, thus a less than 4,5% difference.

Freq (Hz)	Relative Error %
5376	1,3
537678	6,5
1209776	9,5

It compares the results of three simulations, the real model with a circular cross-section, the model with a hexagonal cross-section, and the model with changed properties for the coil and with the method applied.

The real model simulation had 811411 FE and the truncated model only 30202 FE, so < 4% (Figure 12, Table 5).

Simulation #2

The second model was of another transformer with the following characteristics (Table 6):

Again, it is compared the results among the 3 models.

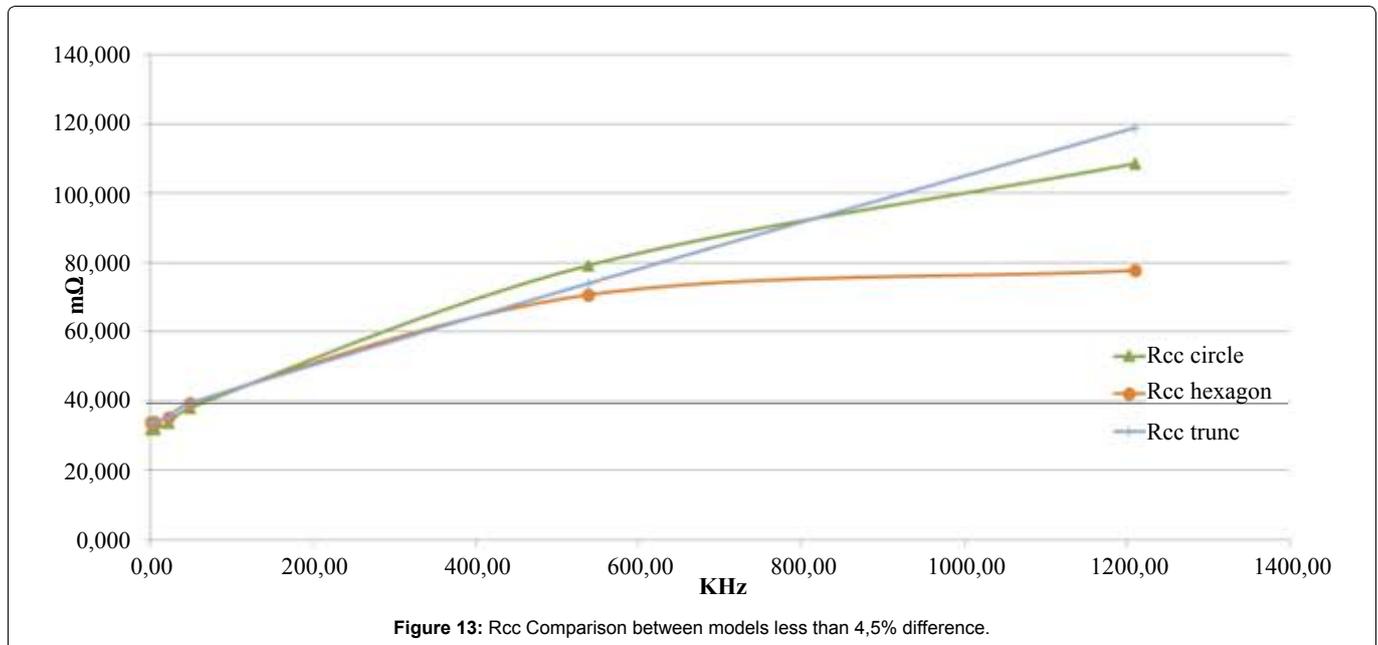
The real model needed 320898 FE and the truncated model 13480, FE, thus a less than 4,5% difference (Figure 13, Table 7).

Conclusions

The main conclusion of this study is a method to model any magnetic component (either EE core or Toroidal core) which maintains key parameters (Resistance & Inductance), accuracy and reduces the amount of time to perform an FEA analysis.

Additionally, this study has found the following conclusions:

- 1) The main factor to increase the number of finite elements in a



magnetic component simulation is the number of turns and the coil cross-section.

2) By changing the properties of the copper, a polygonal cross-section inside the original circular cross-section can have the same resistance in DC current as the real coil. To model the behaviour of the inductance, this is a better approach when compared to a polygonal cross-section with the same area of the original circular cross-section.

3) The hexagon cross-section inside the coil is the best option when compared to a diamond or square cross-section.

4) For the purposes of this study, the values of inductance are very similar. To increase the accuracy of the model, it is necessary to increase the number of edges of the coil cross-section.

5) A correlation between resistance and frequencies is found when frequencies are separated into very Low, Medium and High ranges.

6) A method has been developed to obtain the parameters of resistance of inductance for transformers (EE core and Toroidal core) in low/medium and high frequency. This method is the most important original contribution in this publication.

Future works

With these conclusions in modelling and time computing for transformers, we can performance similar studies for other kind of transformers, it means with different core shapes. Even, this study could be developed for other magnetic components like coils.

Another different task would be to understand the effect of the shape coil, distance among them, etc for the inductance of the component.

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