

# Optimizing Inductor Winding Geometry for Lowest DC-Resistance using LiveLink between COMSOL and MATLAB

H. Schneider\*, T. Andersen, J. D. Mønster, M. P. Madsen, A. Knott and M. A. E. Andersen  
Department of Electrical Engineering, Technical University of Denmark - DTU

\*Corresponding author: Oersteds Plads 349, Kgs. Lyngby, 2800, Denmark, hensc@elektro.dtu.dk

**Abstract:** An optimization routine is presented to optimize a hybrid winding geometry for a toroid inductor in terms of the DC resistance. The hybrid winding geometry consists of bended foil pieces connected through traces in a printed circuit board. MATLAB is used to create a graphical user interface that visually plots the winding using input parameters such as core dimensions, number of turns, clearance between windings, and the winding angle of each segment of the winding. COMSOL LiveLink is used to import the winding geometry from MATLAB and create a 2D finite element model to simulate the DC resistance. Finally the winding configuration with the lowest DC resistance is found by sweeping the parameters of the winding geometry and simulate and save the result in each step. An improvement of more than 30% compared to previous work is achieved in this way

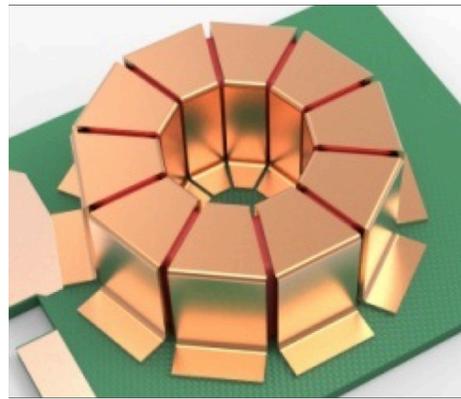
**Keywords:** Inductor, Resistance, Boundary layers, LiveLink to MATLAB, Periodic Condition.

## 1. Introduction

The conventional wire wound toroid is used in many power electronic applications such as EMC filters, power inductors, transformers and so on. However it has the following disadvantages regarding the winding scheme and the manufacturing/production process [1, 2]:

- The spacing between the windings increases gradually from the inner diameter towards the outer diameter of the core limiting the utilization of the winding area.
- For large wire diameters a hook/pull type manufacturing machine is used. The space required for the hook and the wire being pulled through the center of the core further decrease the utilized winding area.
- For large wire diameters manual work is required for feeding the hook with the wire leading to increased cost.

- Complex manufacturing machines are needed for winding due to non-separable core.
- Manufacturer lead time and price strongly depends on the purchase history and number of ordered magnetic components.
- The leaded toroid may be placed and soldered manually in a production increasing time to market and cost.



**Figure 1.** Surface mounted hybrid toroidal inductor.

This work focuses on a hybrid foil combined with printed circuit board (PCB) trace winding scheme in an attempt to improve both the utilized winding space and improve the time to market by creating more freedom in the manufacturing and production process.

The basic idea is to cut and bend copper foils into “U” shaped pieces that fit around the toroidal core. The number of bended foil pieces determines the number of turns and in a final product all the foil pieces would be pre-attached to a plastic former for easy handling and alignment on the PCB.

In previous work [3] a hybrid inductor with 15 turns, a foil thickness of 500µm and a single layer PCB with a layer thickness of 70µm was implemented as a prototype. The measurements were used to evaluate a 3D Finite element model (FEM) created in COMSOL with good agreement. The results showed that typical available PCB layer thicknesses (18µm – 210µm)

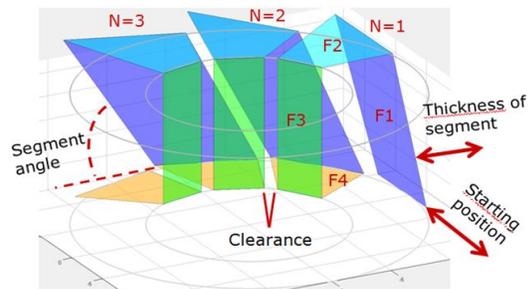
are a bottle neck for the DC resistance in a hybrid inductor.

In the implemented model the bended copper pieces went straight over the core and the traces in the PCB was angled to complete the winding. It is easy to imagine how the DC resistance would be improved if the thin traces in the PCB were straight and short and the thicker copper pieces were angled over the core connecting the winding. It is however hard to predict the optimum angles of each segment in a turn and to predict the impact on the DC resistance. It is necessary to find an answer to these questions in order to take full advantage of the hybrid inductor.

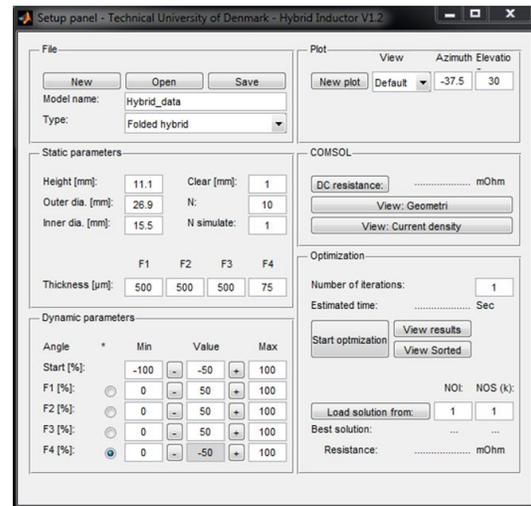
## 2. Use of COMSOL Multiphysics

COMSOL is used to simulate and find the DC resistance of the windings in the inductor. The system is set up as a 2D simulation to improve simulation time, which is needed for the optimization algorithm solution time not to get extremely long.

The 3D model is based on four segments per turn, labeled F1-F4 as shown in Figure 2. The optimization algorithm's input parameters are the coil dimensions, number of turns, minimum clearance between turns, the starting position of the winding following the tangent of the core, the angle of each segment and the thickness of each segment.



**Figure 2.** Geometry of the winding and the related parameters.



**Figure 3.** The designed MATLAB GUI with LiveLink to COMSOL.

To control the optimization routine a MATLAB program was developed, that can take all the inputs, and set the different constraints, and in general control the optimization. For setting up the 2D structure in COMSOL the LiveLink for MATLAB [5] was used. The following steps were implemented in the MATLAB code in order to automate the calculation of the DC resistance with changing winding geometry:

- Creating a MATLAB GUI – See Figure 3
- Creating the winding geometry
  - The geometry of a single turn is created based on the parameters set by the GUI for the winding such as size of the core, clearance, thickness of the foil and the angle of each segment in a turn. The coordinates positions are translated from 3D to 2D by unfolding each turn.
  - A for loop creates the desired turns by copying the coordinates of the single turn by rotating them in a polar coordinate system. Every section of a turn is created as a polygon and the coordinates is saved for later selection of domains and boundaries. Each segment is shifted so they lay in layers. This is done to ensure that the windings will not cross each other, as shown in Figure 3.

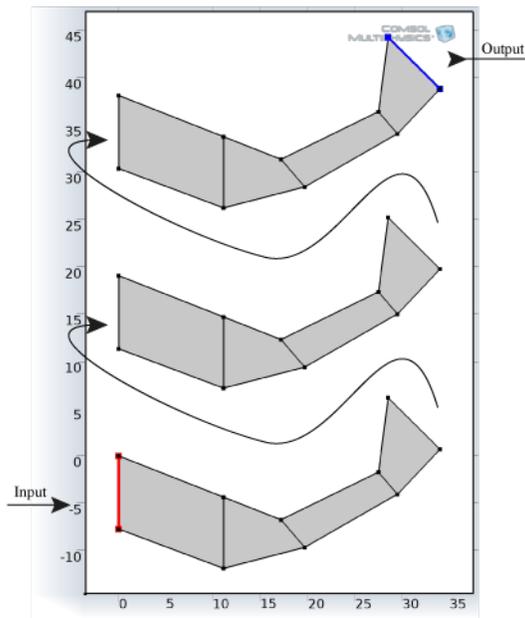
- Selecting the boundaries. As the specific boundaries are not numbered as they are generated, it is necessary to find them in order to set up the rest of the simulation. This is done using the LiveLink method “mphselectbox”. The saved positions used to generate the turns are used and the boundary are stored for later use.
- The material setup is defined for each segment in the simulation, instead of using the standard Copper material, this is done since the different segments can have (and usually has) different thickness of the copper. The difference is used to define an electrical conductivity for each segment modelling the thickness.
- The physics is set up as an “Electrical Currents” model, with a stationary study, and the discretisation of the electric potential to (the standard) quadratic. To enforce a voltage over the entire structure a Terminal is added on the first structure (bottom structure with red boundary in figure 3). Here a voltage of 1V is set. On the last (top) structure a Ground node is added. To ensure the connection between each turn structure the Periodic

Condition is used, between the boundaries of the end of one structure and the input of the next, as indicated by the arrows in Figure 3.

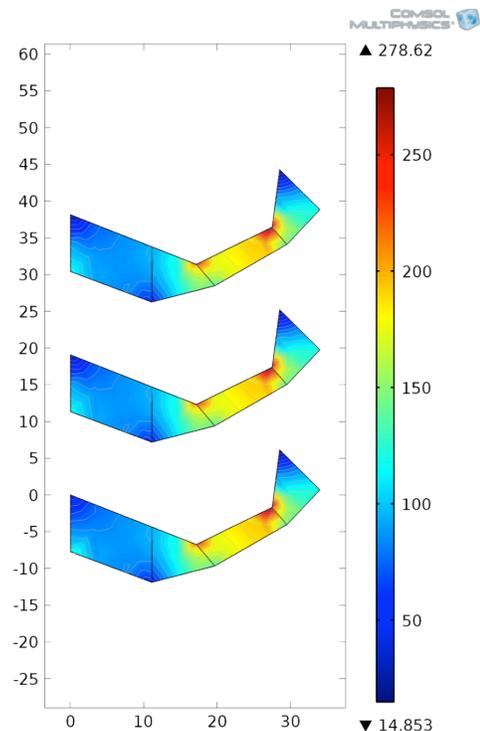
- The geometry is meshed using the standard mesh Free Triangular, with the size set to “Normal”. This gives a simple, yet accurate approximation.
- The study is set as a stationary standard study, with direct solving.
- The results are taken in two parts
  - A global variable is used to calculate the DC resistance seen from the terminals. The conductance  $G$  is available directly from the solution and the DC resistance is then calculated.

$$R_{DC} = \frac{1}{G}$$

- The current density is evaluated in the same way but as a surface maximum and minimum, as well as plotted using COMSOL, see Figure 4 and shown in a MATLAB figure using the function “mplot”.



**Figure 3.** Illustration of an unfold winding which is copied and connected in series via “Periodic Condition”



**Figure 1.** Current density plot of each of the turns structures.

### 3. Results

The result of the optimization routine is shown in Figure 5. The plot shows the simulated resistance for a given number of solutions where the previously mentioned parameters of the winding were altered. In this specific case the resistance don't change as much as a function of the winding parameters as in other cases. In this work the following 3 cases were examined:

- **Case 1:** Few turns, PCB layer thickness  $\ll$  Foil thickness
- **Case 2:** Many turns, PCB layer thickness  $\ll$  Foil thickness
- **Case 3:** Few turns, PCB layer thickness = Foil thickness

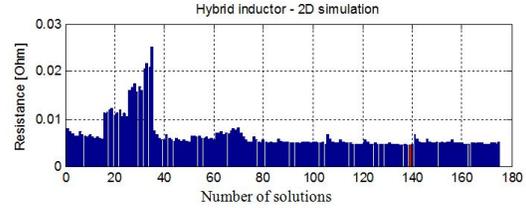
In table 1-3 the parameters and result for each of the 3 cases are summarized. In each case 3 winding configurations are compared. One where only the PCB trace is angled called "Bottom", one where the lowest DC-resistance were found called "Opt." for optimized and one where only the top segment of the bended foil was angled called "Top".

In Case 1 the optimized solution resulted in an improvement of 32 % compared with only angling the PCB trace. However an 31 % improvement was achieved by only angling the top segment of the bonded foil piece. If few turns and a big difference in foil and PCB trace is utilized the "Top" solution may be sufficient since it will result in a low DC-resistance and may be easier to fabricate.

In Case 2 a very small improvement of 0.8 % for both the "Opt." and the "Top" compared to the "Bottom" is achieved. The limited space due to many turns reduce the influence of angling the segments in the winding and obviate the optimization.

In Case 3 the "Opt." configuration resulted in 11 % improvement. The "Top" resulted not surprisingly in the same efficiency as the "Bottom" as the copper thickness is the same. For few turns and equal winding thickness the optimized solution is therefore attractive. This could be an important conclusion since this configuration is highly suitable for high frequency operation which is in high demand. However this must be confirmed in a 3D

simulation of the AC-resistance which is out of the scope in this work.



**Figure 5.** Illustration of optimizing routine for a single integration. The x-axis is the combination number for the given angle span and the y-axis is corresponded DC resistance.

**Table 1:** Case 1 (Few turns, PCB layer thickness  $\ll$  Foil thickness)

Number of turns: 10, Segment thickness: F1, F2, F3 = 500 $\mu$ m, F4 = 70um, Clearance = 1mm			
Winding angle configuration	Bottom	Opt.	Top
Starting point SP [%]	0	20	0
Outer Foil Segment F1 [%]	0	63	0
Top Foil Segment F2 [%]	0	37	100
Inner Segment F3 [%]	0	0	0
Bottom Segment F4 [%]	100	0	0
DC resistance [m $\Omega$ ]	6.78	4.64	4.71
Improvement [%]	Ref.	32	31

**Table 2:** Case 2 (Many turns, PCB layer thickness  $\ll$  Foil thickness)

Number of turns: 100, Segment thickness: F1, F2, F3 = 500 $\mu$ m, F4 = 70um, Clearance = 1mm			
Winding angle configuration	Bottom	Opt.	Top
Starting point SP [%]	0	0	0
Outer Foil Segment F1 [%]	0	75	0
Top Foil Segment F2 [%]	0	25	100
Inner Segment F3 [%]	0	0	0
Bottom Segment F4 [%]	100	0	0
DC resistance [m $\Omega$ ]	435	432	432
Improvement [%]	Ref.	0.8	0.8

**Table 3:** Case 3 (Few turns, PCB layer thickness = Foil thickness)

Number of turns: 10, Segment thickness: F1, F2, F3, F4 = 500 $\mu\text{m}$ , Clearance = 1mm			
Winding angle configuration	Bottom	Opt.	Top
Starting point SP [%]	0	100	0
Outer Foil Segment F1 [%]	0	38	0
Top Foil Segment F2 [%]	0	21	100
Inner Segment F3 [%]	0	0.5	0
Bottom Segment F4 [%]	100	40.5	0
DC resistance [ $\text{m}\Omega$ ]	2.6	2.3	2.6
Improvement [%]	Ref.	11	0

#### 4. Conclusion

A MATLAB program for optimizing the structure of an inductor in order to minimize the DC resistance have been created. The program sets up the 2D simulation of the structure dividide into turns, again dividede into 4 segments, each with different thickness. The system is simlated and the numerical as well as grapical results are extracted. The program shows that it is capaceble of finding the optimum winding geometry, leading to an improved DC-resistance. The findings are in general:

- Few turns and large difference in foil and PCB trace thickness
  - Angeling the top segment (F2) is a suitable solution
- Many turns
  - Less degree of freedom to alter the shape of the winding
- Same thickness of all the segments in a turn
  - An optimized solution is preferred

#### 5. References

1. M. Seitz and M. Roeber, Squeeze more performance out of toroidal inductors, *Power Electronics Technology*, vol. 31, p. 30 (2005)
2. M. Nigam and C. R. Sullivan, Multi-layer folded high-frequency toroidal inductor windings, *Applied Power Electronics Conference and Exposition – APEC*, Twenty-Third Annual IEEE,, pp. 682-688 (2008)

3. H. Schneider, T. Andersen, A. Knott and M. A. E. Andersen, “Hybrid winding concept for toroids”, ECCE Asia (2013)

4. Introduction to AC/DC Module, COMSOL, Application note, [www.comsol.com](http://www.comsol.com).

5. "LiveLink™ for MATLAB", COMSOL, Presentation, [www.comsol.com](http://www.comsol.com).