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# Investigation of a Hybrid Winding Concept for Toroidal Inductors using 3D Finite Element Modeling

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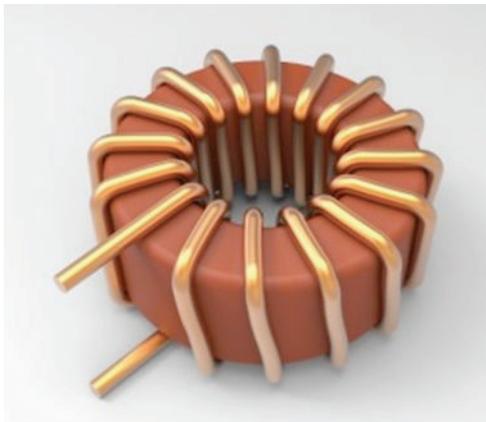
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**Abstract:** This paper investigates a hybrid winding concept for a toroidal inductor by simulating the winding resistance as a function of frequency. The problem of predicting the resistance of a non-uniform and complex winding shape is solved using 3D Finite Element Modeling. A prototype is built and tested experimentally to verify the simulation results. Finally COMSOL LiveLink to CAD is utilized to highlight a bottleneck for this kind of winding scheme.

**Keywords:** Inductor, Resistance, Mesh, Boundary layers, LiveLink.

## 1. Introduction

The conventional wire wound toroid shown in Figure 1 is used extensively in switch mode power supplies in EMC filters and as inductors and transformers. However the space between the windings increases gradually from the inner diameter towards the outer diameter of the core which limits the utilization of the available winding space. This effect can increase the resistance and thus the conduction loss of the component [1,2].



**Figure 1.** Conventional toroidal inductor

Furthermore, in the manufacturing process of a toroidal inductor with a large diameter wire and a small core a hook/pull type winding machine must be utilized. Under manufacturing a tool pass through the center of the toroidal core to grab and pull the wire which is manually feed to the hook for each turn.

To overcome these disadvantages a hybrid winding scheme may be used [3]. The basic idea of the hybrid winding scheme is to cut and bend copper foils into “U” shaped pieces that fit around the toroidal core as shown in Figure 2. To complete the winding the foil pieces are connected through the traces in a printed circuit board (PCB). In a final product the foil pieces would be pre-attached to a former for easy handling and alignment on the PCB.



**Figure 2.** Exploded view of the hybrid winding concept for a toroidal inductor.

The hybrid winding concept has the following benefits compared to the conventional single layer wire wound inductor:

- Large scale production and distributed stock of foil assemblies reduce cost and delivery time.
- Fully automated manufacturing process. Foil pieces are stamped, bended and attached to a plastic former. The core and the foil assembly can be placed by a pick and place machine.
- Better utilization of winding space. Constant resistance with increased number of turns or constant number of turns with decreased resistance for the same core size
- Low AC resistance due to increased surface area using foil.
- Configurable winding structure. The connections of the foil pieces through the PCB can be freely defined by the design engineer. The number of turns can be decreased by paralleling the foil pieces. It enables the same foil assembly to be used for inductors, common mode EMC chokes, transformers etc.
- Different core materials can be used with the same foil assembly.

The disadvantages may be as follows:

- Commercial available PCB layer thickness and interconnections between the foil cutouts and the PCB tracks is a bottleneck for high power applications.
- The assembly of the foil cutouts is limited to a specific core size.

## 2. Use of COMSOL Multiphysics

The challenge of predicting the resistance as a function of the frequency of such a complex 3D winding geometry is solved using the COMSOL AC/DC module[4]. The greatest challenge was to create the mesh since eddy currents need to be considered and the thickness of the foil to the PCB traces in this work vary from 0.5mm to 70 $\mu$ m. A boundary layer mesh with 4 layers and a stretch factor of 2.5 was used. The first layer fitness was set manually to 5 $\mu$ m. A free tetrahedral mesh was used for the DC resistance simulation.

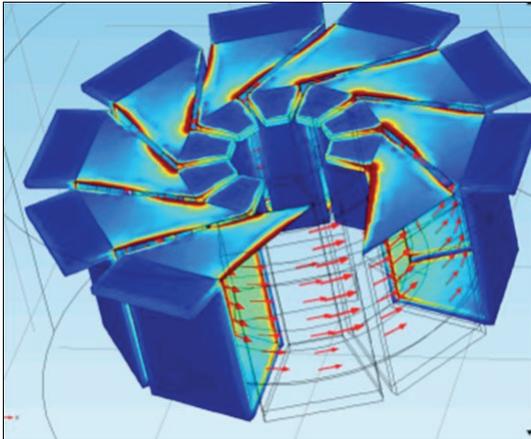
## 3. Results

In Figure 3 the current density at 100kHz in the foil cutouts and the PCB traces are shown. The 3D model of the hybrid inductor is shown from beneath in order to inspect the PCB traces. Some of the windings and the core are hidden in order to look at the inner part of the winding. From the colors it is easy to see that the current density is highest closest to the core where the current path is shortest and in the places where the width of the foil cutout is lowest. This suggests that the foil cutouts should be angled instead of the PCB traces in order to reduce the resistance.

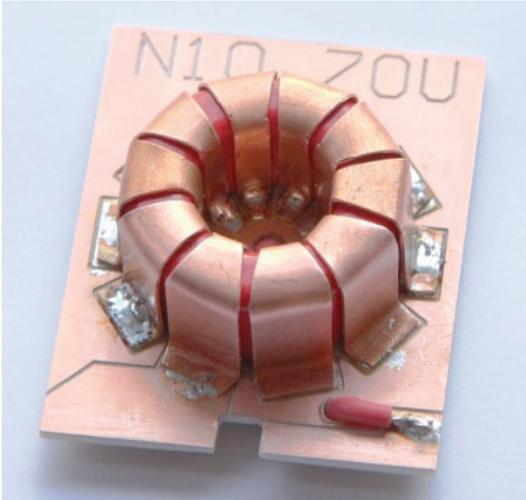
The implemented prototype is shown in figure 4. The PCB were milled with a router and the foil pieces were cut with a scissor and soldered manually. It is clear that the prototype has rounded corners and unequal spacing compared to the 3D drawing shown in figure 3.

In Figure 5 the simulated and measured resistance as a function of the frequency is shown. An offset is added to the simulation result to compensate for any static error sources such as imprecise cuts and clearance of the bent foils, all of which is not included in the 3D model. The simulation with offset fits the measured results from 10 Hz to 100 kHz which is the common operating frequency range. It is eddy currents in the core that causes the increase in the measured AC-resistance beyond the 100 kHz which is not accounted for in the simulation model.

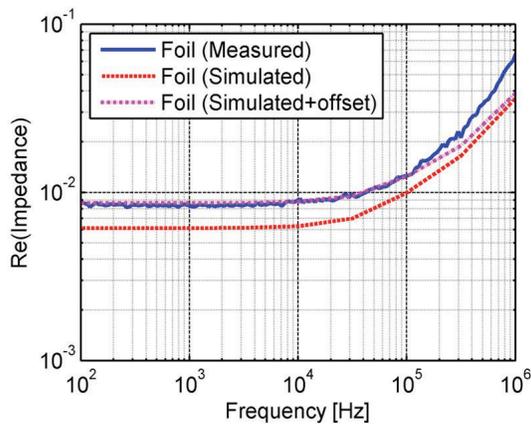
A LiveLink to a computer aided design (CAD) program [5] was also implemented and several simulations were performed in order to investigate the DC-resistance versus the PCB Thickness. The result shown in figure 6 indicates that the DC-resistance could be halved by using 220  $\mu$ m thick PCB traces compared to the common 70  $\mu$ m PCB trace thickness. The simulation prove that the PCB trace thickness is a bottleneck for high power applications.



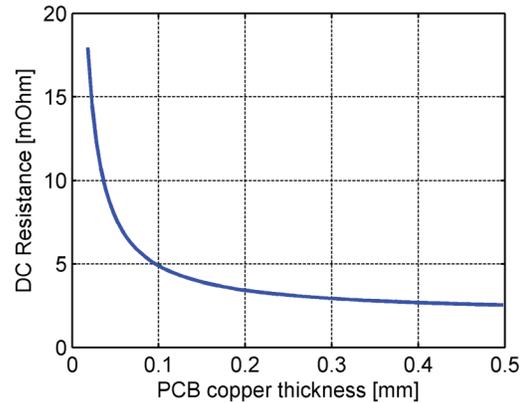
**Figure 3.** Simulated current density and magnetic flux density



**Figure 4.** Prototype used for validation of the simulation results



**Figure 5.** Resistance as a function of the frequency



**Figure 6.** Simulated DC-resistance as a function of PCB copper thickness. Foil thickness is fixed at 500  $\mu\text{m}$ .

#### 4. Conclusion

A hybrid winding concept for toroids using the traces in a printed circuit board to make connection to bent copper foil cutouts has been evaluated in terms of AC-resistance and the DC-resistance as a function of PCB trace thickness.

A FEM analyses have been carried out and the model have been experimentally validated.

It is found that the commercially available layer thickness in a PCB is a bottleneck for high power applications. Finally a plot of the simulated current density in the winding reveals that the winding configuration can be optimized which is crucial for performance.

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