

## Magnetic component design

### New generation of 3D electromagnetic finite element analysis software with breakthrough simplicity facilitates magnetic component design

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**Table of contents summary** Multiple layers of conductors in high frequency transformers can increase copper losses many times due to the proximity effects. Traditionally used Dowell's curves are accurate only in some geometrical arrangements. New generation of Finite Element Analysis software like EMS simulates high frequency phenomenon with much higher accuracy and is easy to use.

#### Abstract

High frequency currents stacked in multiple layers in the transformer winding can increase copper losses manyfold. Traditional method of optimizing copper thickness based on Dowell's curves is accurate only for typical a winding geometry. Many high frequency designs deviate from assumptions beyond Dowell's solution, which leads to suboptimal design. Finite Element Analysis software allows accurate modelling of high frequency phenomenon but is still considered too tedious to use and requiring expert operators for accurate results. New generation products like EMS from EMWorks combine powerful simulation capabilities with easy to use interface appropriate for hands on engineers in every day use

**Keywords:** FEA, high frequency transformer, proximity effect, copper losses

#### 1. Introduction

Finite Element Analysis software has been used by electrical engineers for several decades. It is a great tool for simulating electromagnetic fields in chokes and transformers allowing accurate computation of spatial distribution of the current, flux density, associated losses and resulting temperature rise as well as the impact on efficiency of the whole converter. By manipulating dimensions and geometrical arrangements we can arrive at most compact, efficient and lowest cost structure.

Unfortunately commercial 3D FEA software gained reputation as expensive, tedious and requiring highly skilled and specialized operator to yield sufficiently accurate and reliable results. In this situation practicing power supply designers were forced to resort to simplified methods, with results left to chances.

FEA vendors has been busy for years trying to improve the ease of use, accuracy, stability and versatility of their tools with slow but systematic progress. Some of them become truly practical design tools not only for Ph.D working on science project but also for hands-on power supply designers with general knowledge of magnetic components. In my consulting practice I use EMS from EMWorks which was also used to generate the examples for this article.

#### 2. High frequency copper losses due to proximity effect

The nature of high frequency challenge in the power supply magnetic design is well known. High frequency currents in the windings induce eddy currents creating uneven current distribution in the wire they flow in as

well as in the adjacent ones. This increases copper losses leading to the thermal problems and necessity to redesign the magnetic or even the whole power supply. In general, currents tend to alter their paths in a way which minimizes the overall amount of energy extracted from the source. Reduction of the energy stored in the magnetic field is accompanied by the increase of the copper losses. Resulting current crowding in a single conductor can be characterized by the skin depth but with more elements things become complex very fast.

While the current distribution and resulting effective AC resistance in a single, round conductor can be derived analytically the solution for two several round wires becomes very complex and anything more becomes completely impractical – see strange patterns induced by the presence of the core in Fig.1. (For interested in an analytical approach I recommend an excellent book [2]).

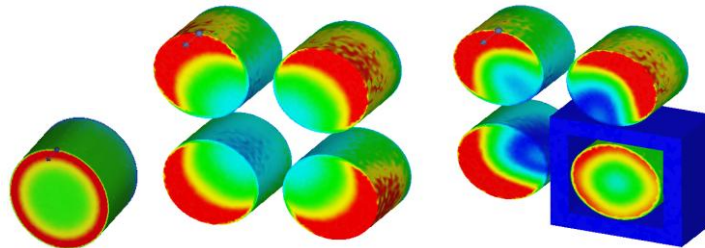


Figure 1. Current density in a single conductor (left) group of conductors (center), and the impact of the core (right)

### 2.1 Dowell's curves – estimating high frequency copper losses

In 1966 P. Dowell made few simplifying assumptions corresponding to the typical geometry of the transformer and solved Maxwell equations with very insightful results. Converting analytical solution to a graphical form created ubiquitous Dowell's curves shown in Fig. 2. Horizontal axis is scaled as the ratio of the thickness of the copper to the skin depth, individual curves correspond to the position of the layer in a stack conducting the current in the same direction. Left graph shows the increase of the copper loss versus DC, the right one the variation of the copper loss depending on the layer thickness.

As intuitively obvious, if the layers are thin enough, all eddy currents become suppressed and there is no difference between the DC and AC resistance. But what is less obvious is how quickly AC resistance rises with the copper thickness when the number of layers is high, leading to the situation where the thicker foil may actually increase copper losses many times. This important result can be more directly appreciated from the second form of the Dowell curves on the right where the optimal thickness corresponds to the function minimum.

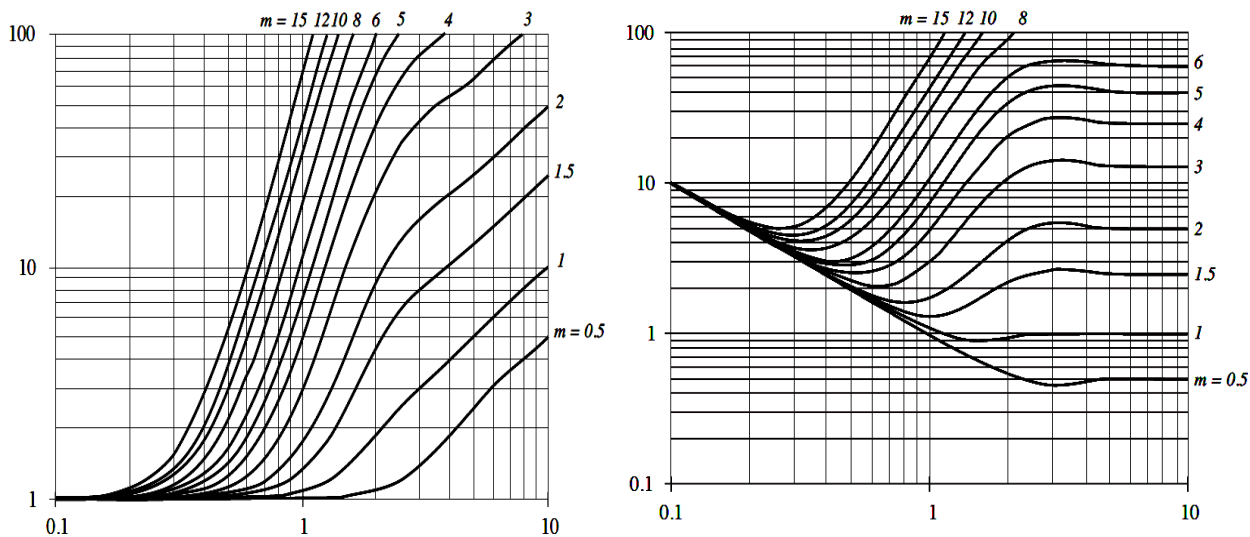


Figure 2. Dowell's curves showing the ratio between AC and DC resistance pictures [1]

## 2.2 Finite element simulation – obtaining actual distribution of the current

Typical distribution of the current from proximity effect leading to increased losses can be seen in Fig.3

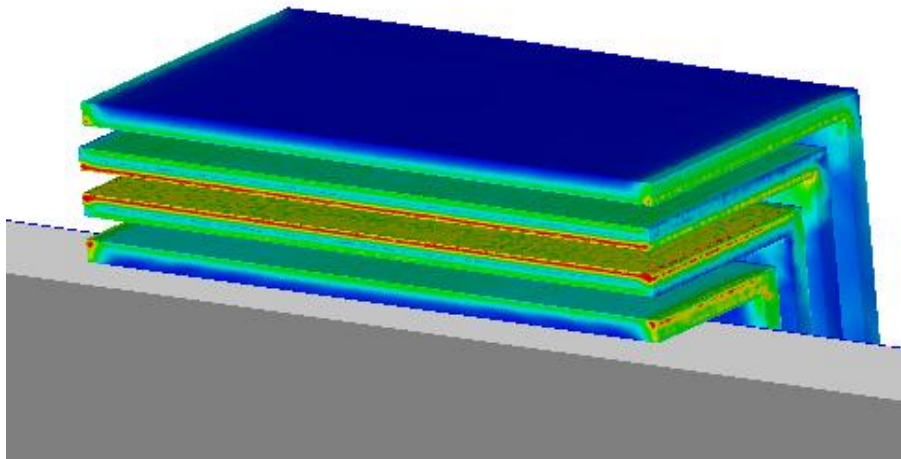


Figure 3. Current density distribution in 2primary-2secondary configuration (layers 1-2-2-1 from the Dowell's curves)

The current in the first layer crowds on the side opposite to the core. This induces a mirror image current in the directly facing surface of layer 2 flowing in the opposite direction. This eddy current “returns” on other side of the second layer, where it is summed with the net winding current. This doubles the effective current density in this region (and quadruples losses density). Adding losses: x4 on the top side plus x1 on the bottom side gives us factor 5 (which is what we can read on right side of the second Dowell's curve. Plotting the same simulation using current density  $J$  vectors gives us a nice illustration of this phenomenon – see Fig. 4.

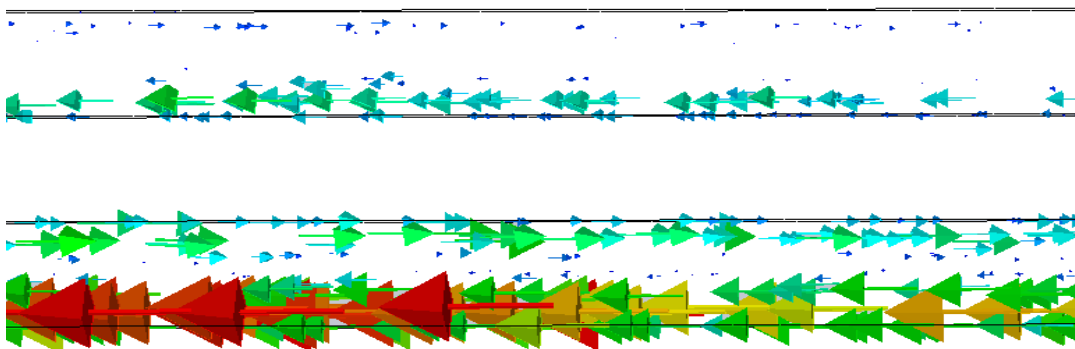


Figure 4. Current density vectors showing circulating eddy currents in two top layers of Figure. 3, looking from the right side. Visible current flowing “backwards” on the top of layer 2 and doubling current density on the bottom

3D pictures like those in Fig.3 and Fig.4 not only help to design a transformer but are also immensely helpful in developing much better understanding of high frequency phenomenon leading to completely new design ideas.

## 3. Finite element analysis assets

Armed with Dowell curves we can design a transformer, but practical application is more complicated than it might seem at first. For example different number of primary and secondary turns lead to the fractional number of layers in the Dowell scheme. Also what we should really do is to vary the thickness of individual layers depending on their proximity situation such that we hit the minimum from Fig. 2. Most windings carry both AC and DC current requiring weighting one against another.

In addition, in practical transformer geometry, assumptions behind the Dowell's model are significantly violated leading to large errors. The most important are:

1. Non-negligible and varying distance from the external layers to the core
2. Non-negligible ratio of the thickness to the width with current crowding on the edges
3. Current crowding around the vias and winding terminations
4. Current crowding on the inner side of the corner or round path of the planar windings
5. Flux fringing from the core gap
6. Rectangular current pulses with significant higher harmonics producing more severe proximity losses

The impact of these discrepancies on the current distribution can be seen in Fig. 5.

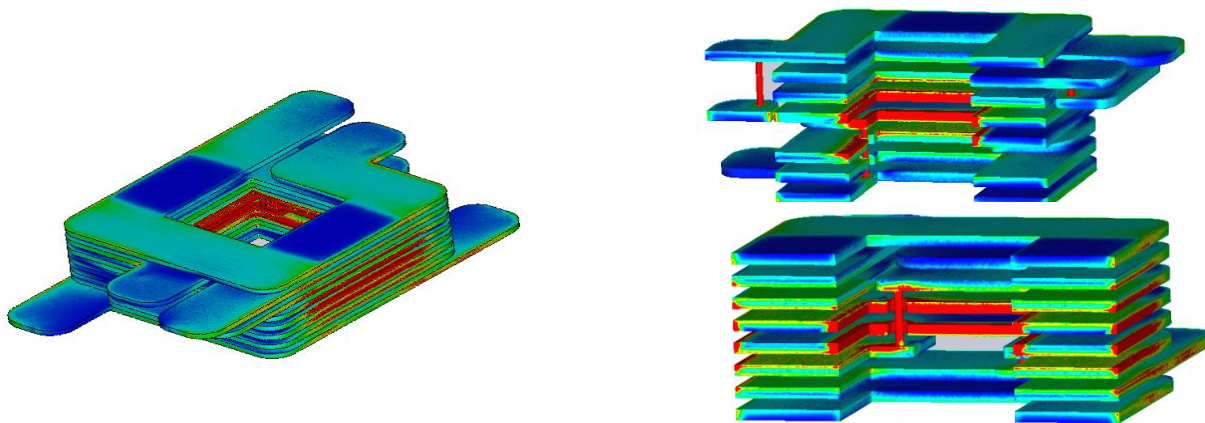


Figure 5. Practical arrangement of the planar transformer showing various deviations from Dowell model and their impact on the current distribution.

Notice in Fig. 5 completely different proximity effects in cross section in plane X and plane Y, visible also on the surface picture on the left.

Contrary to sometimes voiced opinion planar magnetics, in principle, follow Dowell's curves equally well, if we take into account current crowding mentioned in points 4 and 5. Windings themselves are exposed to very similar arrangement of electromagnetic fields, planar or standard, no difference.

Considering above, the Dowell's curves are very useful tool but mostly in keeping us from committing very bad design with severe AC losses like on the right side of Fig.2. But even with the most careful and detail oriented application of the Dowell's model it is easy to design a transformer with AC losses exceeding optimum by the factor of 2 or 3. Using new generation of FEA software, like EMS, results can be much better while the time spent on the design optimization shorter. Created models can be easily reused in the future.

With FEA package fully integrated with Solidworks, like EMS, we get one, nearly seamless environment – no file transfers, no compatibility issues. Any change in the geometry in the Solidworks is automatically reflected in the FEA model. Solidworks is the most popular mechanical CAD design package and efficient operators can be found in most companies or freelancers hired at reasonable rates. EMS pre and post-processing nicely leverages the quality and geometry manipulation capability of Solidworks.

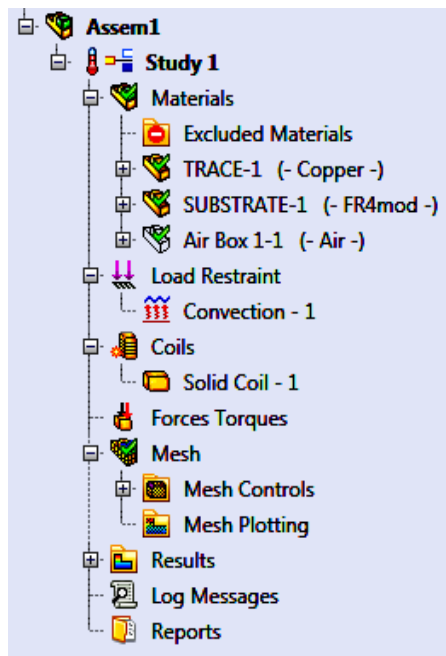


Figure 6. Pull down menu for setting simulation conditions

Experienced power electronics designers can learn the whole process in matter of hours providing they understand electromagnetic circuits. After building the 3D structure, exactly like any assembly in Solidworks, all we need to do is to input from pull down menu:

- type of the analysis and frequency (AC magnetic for HF transformers but also transient magnetic, magnetostatic, electrostatic and electric conduction are available)
- assign materials to all bodies (copper, ferrite, air, dielectric)
- define current paths (coils) and their excitations (voltage, current sources)
- define areas with fine mesh where you want more accurate results and Run

You get all important physical quantities in 3D plots, losses in all conductors, self inductance, coupling, etc. A very convenient option is the possibility of running thermal analysis in one step with the electromagnetic one. Core and copper losses are automatically used to generate temperature distribution, giving us immediate insight into the hot spots inside the structure (please note that with planar PCB windings our ability to measure internal temperatures are very limited).

The thermal simulator here is not a CFD (Computational Fluid Dynamics) type of software, so we cannot check the impact of the actual airflow. Most practical approach is to assume a uniform thermal flux density on the object surface corresponding to the natural convection cooling.  $10W/K*m^2$  is a good number for a case with still air and relatively free space around.

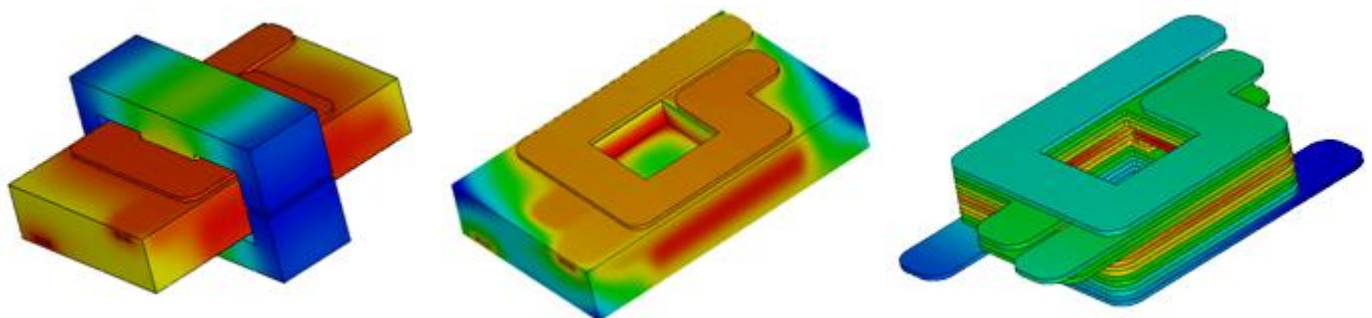


Figure 7. Thermal simulations performed in one step with electromagnetic simulation

Thermal simulation allow to pinpoint trouble spots. See high temperature of the central windings caused by the flux fringing from the core gap. Temperature rise needed to remove the heat through the PCB or ferrite core is also simulated.

To verify the accuracy of this rather crude simplification I run the simulation of the temperature rise of a single trace on FR4 board and compared with commonly used IPC guidelines for the current density allowed for specified temperature rise. The results were spot on. Naturally, inside the real power supply the adjacent components producing heat and restricting natural airflow may create higher temperature but it is still an excellent reference.

Fig. 6 was generated with fine mesh across whole structure to observe all details of proximity effects in planar windings. Model with 18 million elements was simulated overnight on a single processor portable BOX workstation. This should be enough even for very complex structures with strong proximity effects. Such complex models are necessary only for final verification and “global” results. Optimization of the details is usually done defining fine mesh only in selected areas. “Selective” simulations with several hundred thousands of elements zap through in few minutes.

## Conclusion

New generation 3D electromagnetic simulation software is a practical tool for improving performance and economics of the magnetic components in switching power supplies. You may also take advantage of the consulting services of Envelope Power LLC. EMS project with parameterized model of the planar transformer similar to the one used for this article is available for download from [www.envelopepower.com](http://www.envelopepower.com).

## Bibliography

- [1] *R.W. Erickson and D. Maksimovic, Fundamentals of Power Electronics, Kluwer Academic Publishers 2001*
- [2] Marian Kazimierczuk from Wright State University, *High-Frequency Magnetic Components, Willey 2014*

## Author



Peter Markowski has been involved with power supply design since graduating in 1990 with an advanced degree in power electronics. Most of his career he worked for Emerson, formerly Artesyn and Computer Products as a product designer and advanced technology engineer. Recently, Peter has been involved in high-performance FPGA digital controllers and very high bandwidth, purely switched-mode envelope tracking voltage modulators as well as advanced magnetic design. This year he started the consulting business Envelope Power LLC offering complete power supply design and 3D electromagnetic simulation. Peter is the author of 16 U.S. patents and several applications encompassing various aspects of the power conversion engineering.