

Latest Generation Of 3D Electromagnetic Finite Element Analysis Software With Breakthrough Simplicity Facilitates Magnetic Component Design

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Finite element analysis (FEA) 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 the spatial distribution of the current, flux density, associated losses and resulting temperature rise as well as the impact of the magnetic component on the efficiency of the whole converter. By manipulating dimensions and geometrical arrangements we can arrive at the most compact, efficient and lowest-cost structure.

Unfortunately, commercial 3D FEA software gained the reputation of being expensive, tedious and requiring a highly skilled and specialized operator to obtain sufficiently accurate and reliable results. As a result of these drawbacks, practicing power supply designers were forced to resort to simpler methods, with results left to chances.

FEA vendors have 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 have become truly practical design tools not only for Ph.Ds working on science projects 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.

The nature of the high-frequency challenge in power supply magnetics 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 thermal problems and the necessity to redesign the magnetics or even the whole power supply.

In general, currents tend to alter their paths in a way that minimizes the overall amount of energy extracted from the source. Reduction of the energy stored in the magnetic field is accompanied by an increase in the copper losses. The resulting current crowding in a single conductor can be characterized by the skin depth but with more elements, things become complex very quickly.

While the current distribution and resulting effective ac resistance in a single, round conductor can be derived analytically, the solution for several round wires becomes very complex and anything more becomes completely impractical—see the strange patterns induced by the presence of the core in Fig. 1. (For those interested in an analytical approach I recommend an excellent book by Marian Kazimierzczuk from Wright State University, “High-Frequency Magnetic Components,” Willey 2014.)

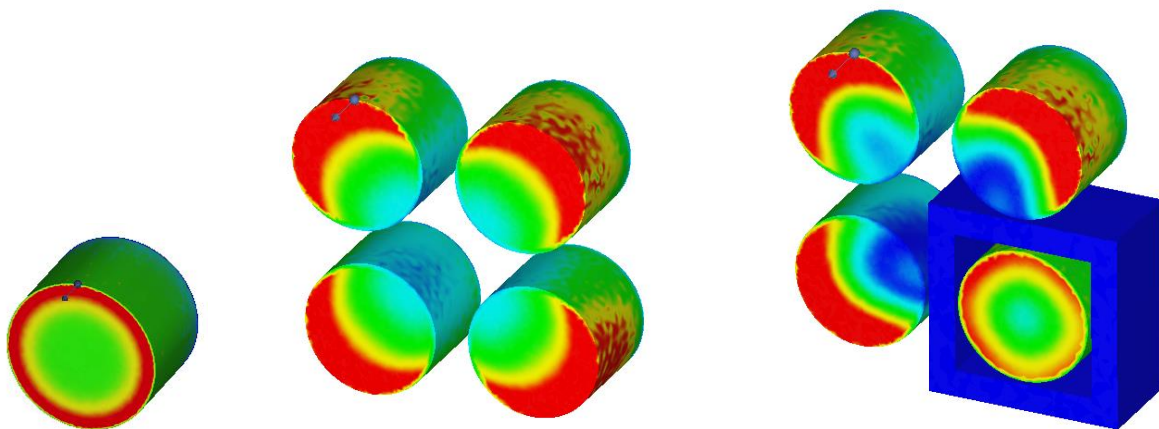


Fig. 1. Current density in a single conductor (left), group of conductors (center), and the impact on the core (right).

However, in 1966 P. Dowell made a few simplifying assumptions corresponding to the typical geometry of a transformer and solved Maxwell's equations with very insightful results. Converting an analytical solution to a graphical form created the ubiquitous Dowell's curves shown in Fig. 2.

In these curves, the 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. The left graph shows the increase in the copper loss versus dc, the right one the variation in the copper loss as a function of the layer thickness.

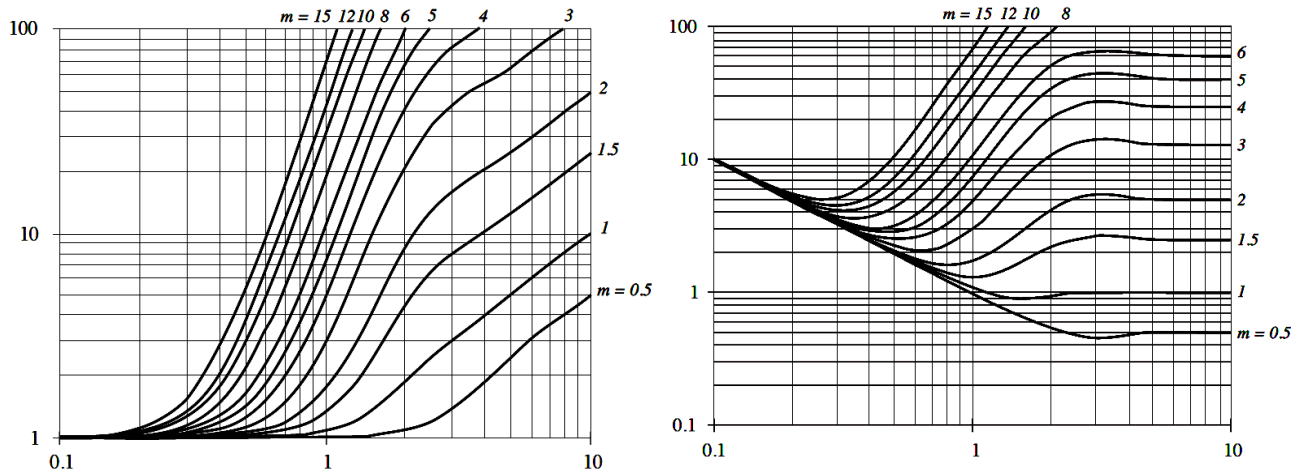


Fig. 2. Dowell's curves showing the ratio between ac and dc resistance, pictures from R. W. Erickson and D. Maksimovic's "Fundamentals of Power Electronics," Kluwer.

As is 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.

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

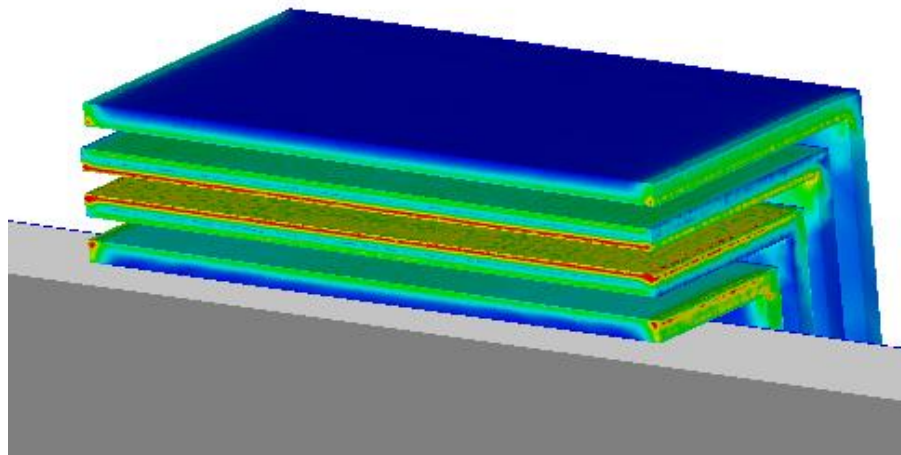


Fig 3. Current density distribution in a 2-primary-2-secondary configuration (layers 1-2-2-1 from the Dowell's curves.)

The current in the first layer crowds on the side opposite of 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 the 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 the loss density.) Adding losses: x4 on the top side plus x1 on the bottom side gives us a factor of five (which is what we can read on the 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 (Fig. 4.)

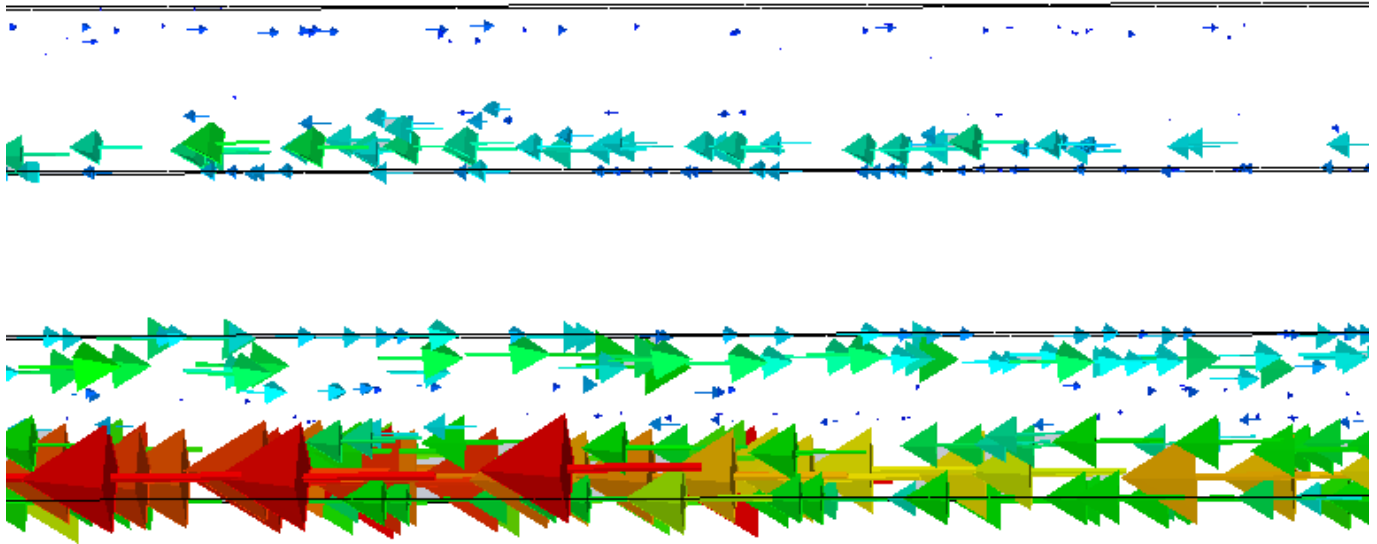


Fig. 4. J vectors showing circulating eddy currents in the two top layers of Fig. 3, looking from the right side. There is a visible current flowing "backwards" on the top of layer 2 and a doubling of current density on the bottom.

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

Armed with Dowell's curves we can design a transformer but a practical application is more complicated than it might seem at first. For example, a different number of primary and secondary turns leads to a fractional number of layers in the Dowell scheme. Also, what we should really do is 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 a 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 and
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.

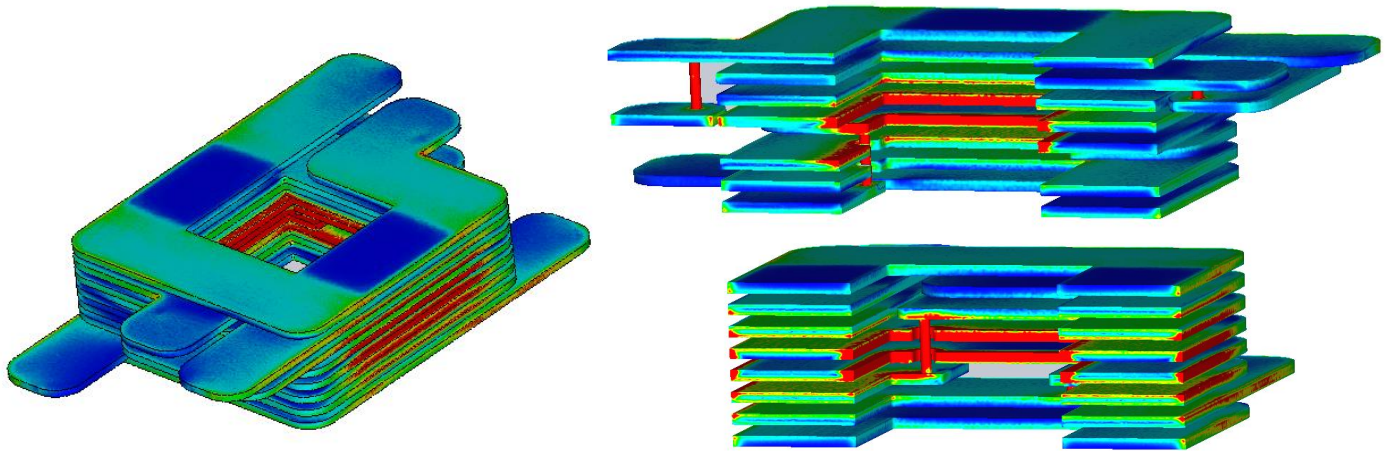


Fig. 5. Practical arrangement of the planar transformer showing various deviations from the Dowell model and their impact on the current distribution. Notice completely different proximity effects in cross section in plane X and plane Y, visible also on the surface picture on the left.

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

Given the considerations mentioned above, the Dowell's curves are a 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 Dowell's model, it is easy to design a transformer with ac losses exceeding the optimum by a factor of two or three. However, using the new generation of FEA software, like EMS, results can be much better while the time spent on the design optimization can be shorter. Moreover, the created models can be easily reused in the future.

With an FEA package (like EMS) that is fully integrated with SolidWorks, we get one, nearly seamless environment—in other words, no file transfers and no compatibility issues. Any change in the geometry in 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.

Experienced power electronics designers can learn the whole process in a matter of hours, providing they understand electromagnetic circuits. Those who also know SolidWorks can start a simulation practically right away. After building the 3D structure, exactly like any assembly in SolidWorks, all we need to do is to input the following from a pull-down menu (also see Fig. 6):

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

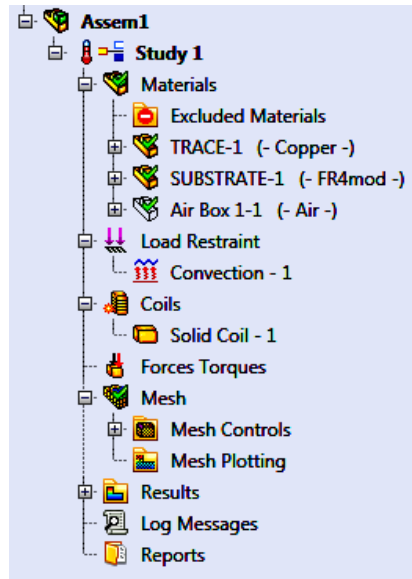


Fig 6. Pull down menu for setting simulation conditions.

You get all the 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 the same step as the electromagnetic analysis (Fig. 7.) 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 is very limited.)

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

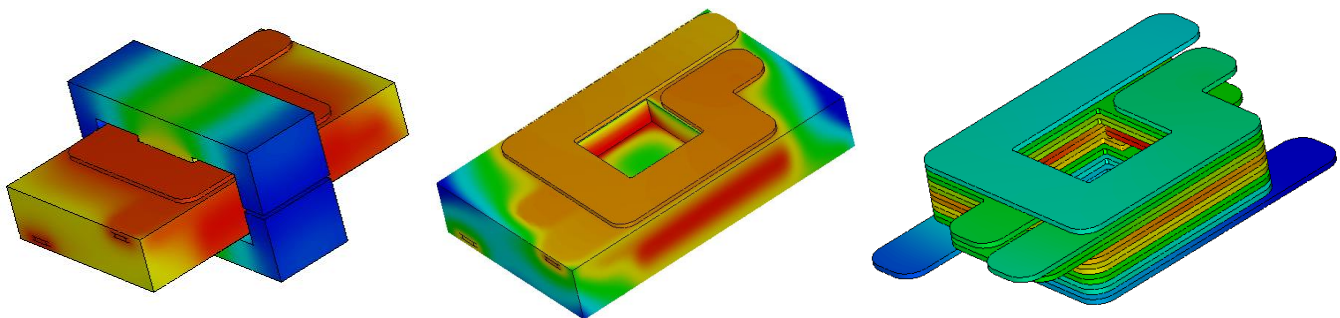


Fig. 7. Thermal simulations performed in one step with electromagnetic simulation allow us to pinpoint trouble spots. Notice the high temperature of the central windings caused by the flux fringing from the core gap. Temperature rise needed to remove the heat through the PCB or ferrite core is also simulated.

To verify the accuracy of this rather crude simplification I ran a simulation of the temperature rise of a single trace on FR4 board and compared it with commonly used IPC guidelines for the current density allowed for a 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 a higher temperature but even such a simplified thermal simulation is still an excellent reference.

Fig. 5 was generated with fine mesh across the whole structure to observe all details of proximity effects in planar windings. A 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 a few minutes.

New-generation 3D electromagnetic simulation software is a practical tool for improving the performance and economics of the magnetic components in switching power supplies. I encourage readers to take a fresh look at this valuable tool.

About The 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.

For more on magnetics design, see the How2Power Design Guide, select the [Advanced Search](#) option, go to Search by Design Guide Category, and select "Magnetics" in the Design Area category.