FINITE ELEMENT ANALYSIS IN POWER CONVERTER DESIGN

Rudy Severns
PO Box 589
Cottage Grove, OR 97424

ABSTRACT

Finite element modeling (FEM) software, capable of solving 2 and 3 dimensional electromagnetic problems is now widely available. This software, while very powerful, is relatively expensive and can require a substantial investment of time to become proficient in its use. Questions have been raised as to what kinds of problems FEM is appropriate and beneficial.

This paper identifies problems for which FEM is useful or even necessary. The paper also points out problems for which FEM is not needed.

INTRODUCTION

Computer simulation is becoming accepted as a normal tool in the design of power electronics equipment. The various forms of SPICE simulation software are an example of this. While the use of simulation software is recognized as a practical necessity, the negative aspects of this software are also coming to the fore. In addition to the acquisition cost of the software and hardware to run it, there can be a substantial cost associated with learning to use the software in a productive way. With circuit simulation software there can also be a hidden cost when designers tend to use the software for cut and try design without taking the time to learn the more difficult analytical basics. This is particularly common for newcomers to the field. This kind of design approach can extend rather than reduce the engineering effort required for a given project. For these and other reasons, managers tend to be a bit skeptical when asked to fund a new simulation tool.

When asked to authorize the purchase of this software, managers tend to ask a number of questions. For example:

1) Is this new tool worth the time and expense in the context of practical design?
2) Can we solve the problem without it?
3) Will we be able to create more competitive designs with this tool than would be possible using more conventional approaches?
4) Will there be a net savings in engineering effort and/or schedule?

These are reasonable questions. In many cases the expense of FEM software will be justified but in others it will not.

A number of companies [1,2,3] have developed FEM software for use in solving electromagnetic problems which commonly arise in power electronics. This software, which is available for both PCs and workstations, can solve 2 and 3 dimensional geometries. While the software is versatile and potentially very useful, it is also relatively expensive. A typical 2D package will cost in the range of \$4000 to \$10000 per year. 3D packages are much more expensive, costing up to \$50,000. In all fairness it should be pointed out that much of this cost is due to the relatively low usage of this kind of software. Were it as widely used as circuit simulation software, the cost would be lower. In addition to the direct expense of the software there is the cost associated with learning to use the software and acquiring fluency with it. This can represent an additional cost equal or greater than software acquisition. This cost varies greatly from one software package to another. In general however, the 3D software is more difficult and time consuming to use than 2D. Whenever possible it is wise to recast the

0-7803-1456-5/94 \$4.00 © 1994 IEEE

problem into a form which allows the analysis to be performed using 2D FEM.

FEM software can perform several functions:

1) Analysis. It can be used to determine the characteristics of a given design.

2) Synthesis. Most design problems involve creation of new designs, which are different from previous work in at least some details. This means that the designer must synthesize to some degree. FEM can be used to chose between different approaches and, by allowing the designer to visualize the actual fields and currents, may allow conceptually new approaches to be created.

3) Intuition and understanding. Electrical engineers are required to take at least some courses in electromagnetics in school. Very few however, make extensive use of this background once they are in industry even if they are solving electromagnetic problems. In transformer design for example, a number of simplifying assumptions are usually made which reduce the computations to simple arithmetic and rules of thumb. For most engineers, a good understanding of fields quickly fades into the background. Given the recent trends towards very high switching frequencies designers are discovering that the previous simplifying assumptions are no longer valid. They must view their magnetic components and circuit layouts as RF components where the field and current distributions are first order effects. Perhaps one of the most important uses for FEM is to retrain the designers intuition by allowing the fields and current distributions to be visualized. It is this intuition which allows new and better designs to be synthesized.

There are many problems for FEM is either useful or even necessary. There are also many problems for which the conventional techniques are more than adequate and the use of FEM could actually slow down the design process. The following examples serve to illustrate this.

GAPPED LAMINATED CORES

It has long been recognized that when an air gap is introduced into a laminated core there will be flux leakage out of the core orthogonal to the laminations. The orthogonal flux induces eddy currents which result in additional power loss over and above the normal core and winding losses. The traditional method for calculating the increase in loss due to the gap is to estimate it from an expression developed by Lee and Stephens[1,2]:

$$W_g = G\, l_g\, d\, f\, B_m^2 \quad (1)$$

Where:

W_g = the power loss in the core due to the gap

G = a numerical constant related to core material and geometry

l_g = the gap length

f = the line frequency

B_m = the peak flux density in the core

The constant G must be determined experimentally for each core material, lamination thickness, frequency range and geometry.

Experimental work by Lee and Stephens [2] indicated that equation 1 gave a estimate of the gap loss of ± 25% when compared to experimental measurements. The range of utility appeared to be limited with the error increasing as f was increased. The problem with this approach for calculating gap loss is that it is restricted to those designs where an experimentally determined values for G are available. The extension of this expression for high frequency filter inductors using thin strip cut C-cores, for example, would require careful measurement. For some users this perfectly acceptable and in many cases the estimated gap loss will be small enough that greater accuracy is not required. FEM is of no advantage in such cases.

In some designs however, the gap loss is much larger than the core loss and is a major concern. These losses can be determined using FEM. FEM allows the particular materials and geometry to be modeled directly. The computed loss will be much closer to reality. A simple example for a cut C-core with the gap outside of the winding is given in figure 1. This is a relatively large gap (.15") on a core with dimensions of .15" x 2.15" x 2.15". The following conditions were assumed:

f = 60 Hz
B_m= 1.2 T
laminations are .014", 3% Silicon-Iron

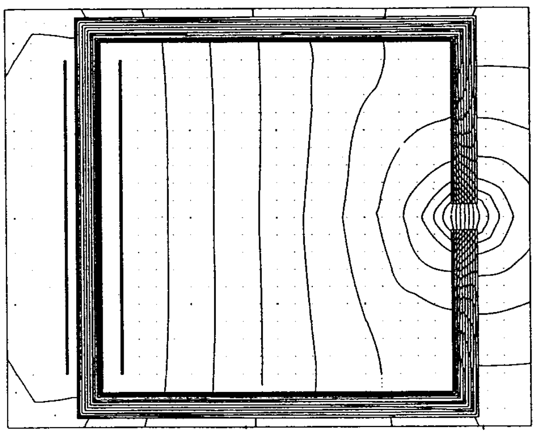

Figure 1, Gapped cut C-core AC reactor

The computed and FEM losses are:

FEM.................................. W_g = 10.3 W
Computed from equation 1.... W_g = 25.9 W

This is a difference of more than 2:1 which illustrates the need for caution in applying equation 1. In this example the core loss is estimated to be 320 mW so that even though the actual gap loss is lower than estimated, the gap loss is still quite large and must be taken into account.

This example makes two important points:

1) The gap losses can be large compared to the core losses and must be taken into account in laminated cores with large gaps.
2) The traditional computation using experimentally determined constants must be used with caution.

In general if there is any question concerning gap losses it would be wise to use FEM to compute the gap loss. FEM provides additional information as part of the modeling process. Referring again to figure 1, it can be seen that there is some flux crowding in the inner laminations. This means that the actual core loss will be higher than that predicted from a uniform flux assumption. Other useful information can be derived from FEM:

1) Gap length for a given inductance and number of turns.
2) The effect of banding materials when they cross the gap region.
3) Winding losses due to gap fields.
4) Losses due to adjacent conductors.
5) Magnetic field shielding.

Traditional formulas for computing the effective gap length, taking into account fringing, are only approximate, especially for large gaps. FEM allows accurate gap determination in advance of building the magnetic component.

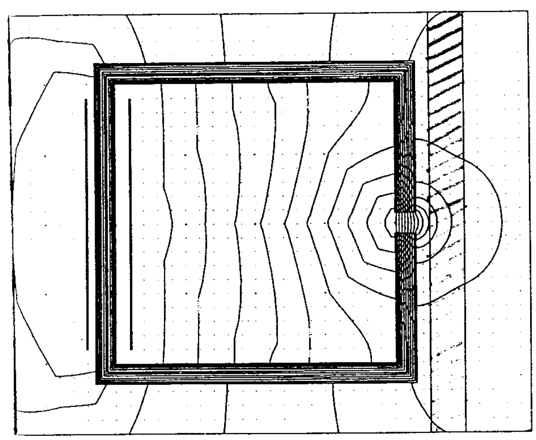

Figure 2, Gapped AC reactor with the gap near a conductor.

Sometimes the results of modeling hold surprises. Normally every effort would be made to keep the gap away from adjacent conductors such as a chassis because of the eddy current losses induced in the conductor by the gap field. Figure 2 shows an example where the gap is near a .25" aluminum plate which could be part of the support structure. FEM results show a power loss of 3.1 W due to eddy currents in the aluminum. Modeling also shows that the loss in the laminations has been reduced from 10.3 W to 7.1 W! The total loss for the system is actually reduced slightly. The reduction in lamination loss is due to the partial cancellation of the orthogonal field components in the gap by the eddy current in the adjacent conductor. Depending on the conductor material, thickness and spacing from the gap, the total loss may be reduced or increased. In any case a manual calculation is not practical for this problem.

INVERTER BUS DESIGN

A very common problem in power electronics is high current bus connections between components in high power polyphase inverters. Similar problems are encountered in low voltage, high current power supplies. Frequently the bus conductors are required to provide a minimum of loss without adding unnecessary weight.

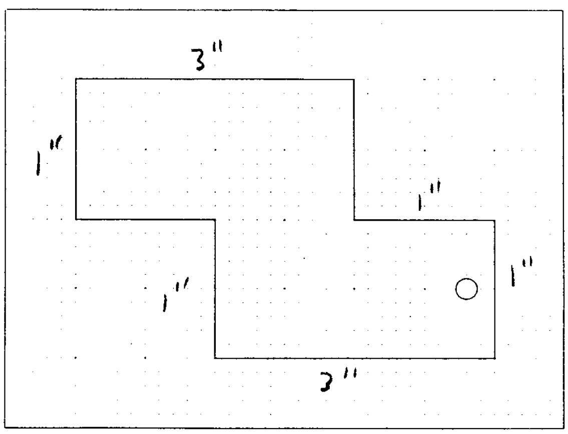

Figure 3, High current bus section

An example of a section of bus which connects a switch back to a DC rail is given in figure 3. Because of weight limitations in this particular application the thickness of the conductor is limited to .010". The normal way to estimate the resistance of this conductor would be to use the mean length (4") and the cross sectional area (.01 in^2). For this example Rc =.271 mΩ. If the loss due to that amount of resistance is acceptable then there is no reason to go further. In this case however, both the loss and the weight are critical. One of the problems with the simple estimate given above is that it does not take into account the current crowding which will occur around the bolt hole for the switch connection and the corners of the conductor. FEM can be used to examine this as shown in figure 4 which is a plot of the current density in the conductor.

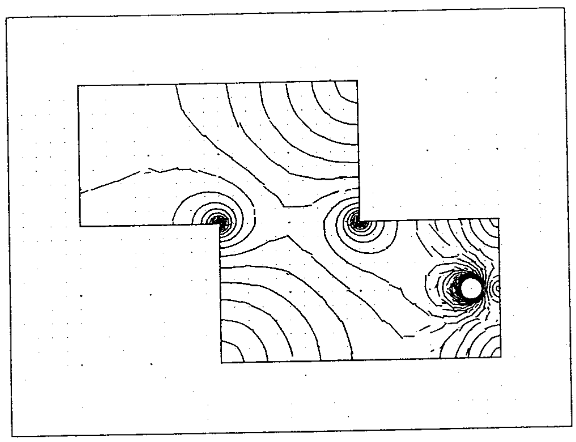

Figure 4, Bus current density (J) plot.

There is clearly current crowding at the two inside corners and around the bolt hole. The plot also shows that there are regions of low current density which contribute little to lowering Rc but which do add weight. From FEM, Rc =.214 mΩ which is actually over 20% lower than predicted by the simple computation. The question now arises can we reduce the weight without increasing Rc? The most obvious approach would be to add small radiuses to the two inside corners to reduce dissipation in these areas and to remove conductor in areas of low current density.

One possible example of this is shown in figure 5.

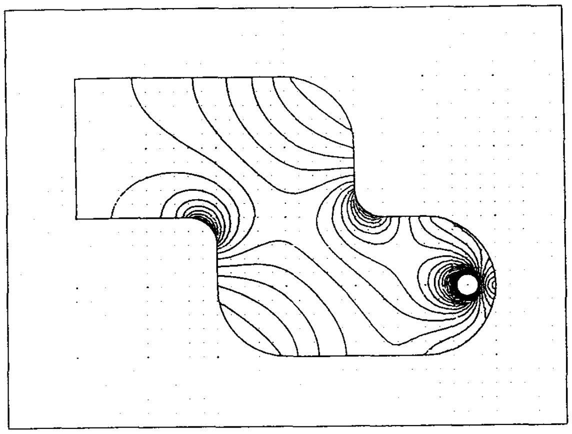

Figure 5, Modified bus section

In this case a substantial amount of the conductor has been eliminated but Rc =.209 mΩ which is a small decrease. Even more conductor could be removed with only a small increase in Rc.

It would be impractical to make these improvements analytically. It would be possible to use a milliohm meter, a sheet of thin conductor and a pair of scissors to arrive a more optimum conductor but you would still not have the benefit of the current density plot to show what areas to cut away. A good deal of cut and try would be needed. In this example FEM is not essential but it is very helpful and in the hands of an experienced user would probably be quicker and lead to a more optimum solution.

HIGH VOLTAGE PACKAGING

Much higher power densities are being required for new power converters than has been the case in the past. For many applications, both military and commercial, power densities of 50 to 100 W/in^3 are needed. Such power densities are very difficult to reach in high voltage power converters especially if multiple outputs of several kV are required. The problem is controlling the voltage gradients in the high voltage portions of the converter. Traditionally the voltage gradients have been estimated from field calculations for simple geometries such as a sphere over a plane, parallel round wires, etc. From experience rules of thumb have been developed but in most cases large safety factors are added to make up for the lack of detailed knowledge of the field in complex structures. An old but very effective technique for complex geometries is to use resistance paper with conductors drawn on it with conducting paint. The equipotential lines are then drawn point by point from measurements with a voltage probe. Quite complex geometries have successfully been designed using this technique but it is time consuming and strictly limited to 2 dimensions.

3D FEM can used for 3 dimension problems but in many cases 2D is adequate. In most 2D FEM programs objects are actually modeled as 3 dimensional objects, although only two dimensions can be varied. In the case of an X-Y plot for example, the object is assumed to extend into the screen for 1 meter. Objects which have radial symmetry are modeled in 3 dimensions where the cross section drawn on the screen is rotated through 360°. This greatly extends the utility of nominally 2D software.

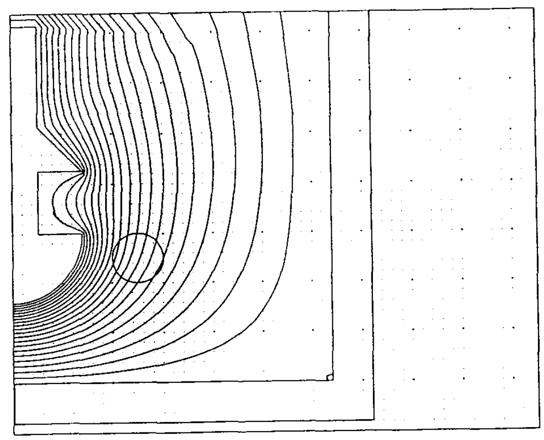

Figure 6, Equipotential plot without a guard ring

Figure 6 shows a example of a lead which is terminated in a PCB. The lead has a solder fillet on the top and a solder ball on the bottom. For simplicity the PCB is not modeled since it does not affect the field associated with the lead and its solder attachments. The small circle in the figure is an equipotential ring which is not activated during the first part of the analysis so that the fields in the absence of the ring can be examined. The lead has a potential of 10 kV relative to the nearby metallic can in which the assembly is installed. The equipotential lines are spaced at 500 V per division. The potential at the tip of solder ball can easily be computed from the known expressions for a sphere over a plane. The points where the solder ball and fillet join the PCB are not so easy to calculate, particularly because the relative sharpness of the corners is neither well defined nor easy to control. It can be seen from the crowding of the equipotential lines that the fields near the two corners may be relatively high. FEM gives electric field intensities (**E**) of about 250 V per mil for these regions. If the edges are very sharp **E** could easily be much higher. Note that this example is modeled using radial symmetry so that the true values for **E** are obtained.

This is a case where some type of equipotential ring is needed to control **E** independent of how the solder behaves in the region of the lead attachment.

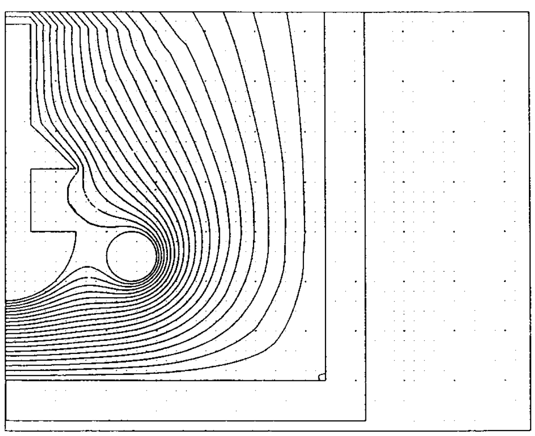

Figure 7, Equipotential plot with guard ring

Figure 7 shows the effect of adding an equipotential ring below the PCB. **E** at the lower corner has dropped dramatically ($\cong$ 35 V/mil) and **E** is also lower ($\cong$120 V/mil) at the upper corner. If further reduction in **E** is required another ring on the top of the PCB could be added. Circular rings are not the only possibility for this purpose. In fact it would be better is the rings could be etched directly onto the board instead of being added later. This would save cost and assembly labor. Various equipotential ring geometries can be modeled directly using FEM and results obtained quickly.

The ability to obtain accurate field intensities for complex high voltage geometries is a very powerful tool when the power density must be increased. The weight associated with potted modules is often a concern also. Increasing the power density in the high voltage portion of the converter will almost certainly reduce weight. On the other hand if the design permits lower power densities and the size and weight penalty associated with arbitrary safety factors is acceptable, there is no real need to go to FEM. Many successful high voltage power supplies have been built without using FEM. There have also been many failures where the designer guessed wrong. High voltage supplies are a perennial problem for systems engineers. More extensive use of FEM would reduce these problems. It would also reduce (but not eliminate!) the need for expensive and time consuming corona and breakdown testing. Such testing should be a tool for confirming a design and not used on a cut and try basis to achieve acceptable performance.

CONCLUSION

Finite element modeling is powerful and very useful tool for a wide variety of design problems in power electronics. It does not however, replace the more traditional approaches for most problems. It is an additional tool which is particularly helpful in new designs where the state of the art must be advanced and the costs, both monetary and time, are justified by the results. One of the unique advantages of

FEM is the insight it gives into the physical operation of devices and assemblies.

Is the software worth the cost? That will depend on the project. If it is a relatively low budget project that requires little innovation the chances are FEM will not be that helpful. On the other hand if it is a large project or a series of projects where considerable innovation or improvement in the state of the art is needed then FEM might just be a bargain.

The key to success is allowing sufficient time for the users of the software to become fluent with it.

ACKNOWLEDGMENT

The author would like to express his appreciation to Ansoft Corporation and Mr. Paul Pyzowski for making available the Maxwell software to create the examples given in the paper.

REFERENCES

[1] Maxwell 6.0, Ansoft Corp., Four Station Square, Suite 660, Pittsburgh, PA, 15219-1119, (412) 261-3200

[2] Magnet5, Infolytica Corp., 1140 de Maisonneuve, suite 1160, Montreal, Canada H3A 1M8

[3] EMAS, MacNeal-Schwendler Corp., 815 Colorado Blvd., Los Angeles, CA 90041-1777