Technical Article

Electric Field Modelling: Applications to High Voltage Power Apparatus

An Introductory Overview

This original, shorter, form of this paper was read at an IEE Colloquium, "Field modelling: applications to high voltage apparatus", 17th January, 1996, which included eight papers describing electrical field problems in high power applications. The main emphasis of the meeting was on electric field effects in HV, power applications. This paper was intended to set the scene for the colloquium, by outlining how CAD could assist the designer.

Introduction

Field modelling is an old and well established science; or should that be art? Algebraic analysis using Schwarz-Christoffel transformations were used by J.J. Thomson in 1883. Then in 1900, F.W. Carter published a paper on airgap induction, using conformal mapping. Many other papers followed. For the most part, these were all concerned with field solutions in parts of devices, not the whole device. Somewhere around the mid twenties, finite differences appeared applied to both electrical and magnetic field problems. The labour involved was considerable, and it was not until the introduction of digital computers in the early sixties that the technique became widely used. Within ten years finite differences gave way to finite elements. Possibly the first paper in which the technique was applied to electrical problems was by Silvester in 1969. Since that time, the method has become extremely popular for the solution for both magnetic and electric field problems. More recently, boundary element methods have appeared. These have their own loyal following. It has to be added, that much of the early development of all the above numerical methods owes much to structural engineering. That situation has now changed, and there is a healthy flow of new ideas in both directions.

Sources and Nature of Electric and Magnetic Field Problems

Society, as we know it, would cease to exist if all sources of electrical energy were removed. The bulk of energy conversion from mechanical to electrical and back again is via a magnetic field, i.e. most power generation and utilisation of electrical energy is electromagnetomechanical in nature. The devices are ubiquitous and tend to be magnetomechanical. The required analyses are largely magnetic. However, the energy has to be transformed in voltage level, switched and transmitted somewhere. It is here that the electrical problems loom large. I exaggerate for effect here, since we all know that energy conversion involves electric field problems and the other areas involve magnetics analysis.

Magnetic field analysis has developed and flourished commercially, whereas electric field analysis has not. It might simply be market forces. There is an enormous market for devices with a magnetic field as a core element. It is well known that to live and work comfortably, an average household requires about 200/300 such devices. It is only the engineers with the responsibility of getting the electrical energy to where it is required, who know about the electric field problems. The result is that money has been available for magnetic analysis on a larger scale than for electric analysis.

There is also the unavoidable fact that magnetic field problems are, for the most part, easier to analyse. The reason is straightforward, many magnetic field problems are not coupled. They stand on their own. No other area of engineering science is significantly involved. The problem reduces to solving the Poisson equation, perhaps for non-linear materials. This is now a relatively simple exercise, there are many text books to provide advice. Commercial CAD packages abound. By way of total contrast, many electric field problems include: non-linearities; new physics; time dependence; stochastic processes; and are also multidisciplinary. More on this below.

Recent Developments in CAD and Magnetic Field Modelling

Computers were used in magnetic and electric field modelling from their introduction in the early sixties. However, the use of CAD ideas did not take off until the mid to late seventies, when computer memory and power became large enough to tackle the computational problems entailed. Then the pace became very rapid. CAD packages became available with the aim of simplifying the whole process, from the input of the data, through to processing of results in the form required by the user.

Broadly, CAD package vendors could be divided into two schools. The first school comprised specialists in magnetic, and perhaps electric field analysis. The second school was made up of the large companies who specialised in CAD, or numerical modelling, of mechanical or structural problems. For them field modelling was an additional feature to be offered as an adjunct to their main package. The situation was not stable, and specialist magnetics vendors developed and offered multidiscipline add-ons to their magnetics CAD; while the structural and mechanical specialists took on offered add-ons in magnetics.

The aim of those concerned, was to provide as broad a CAD package as possible. This is a fearfully expensive exercise for the vendor. As an aside, producing computer code on any scale, properly designed, documented, tested, and supportable on a wide range of platforms, places heavy demands on resources. A typical, single discipline, package might contain 100,000 to 1,000,000 lines of code. A software engineer might only produce 2,000 lines per year. Many of the packages currently available, have required man-centuries of effort.

Fortunately, the vast labour of covering several disciplines has now been recognised, and as a result we see vendors collaborating to provide data exchange interfaces. Thus the overall cost can be kept down. In many instances, this process is driven by the users who take an eclectic view, and select the various modules they require from a variety of CAD packages.

As an example of the multidisciplinary CAD approach being taken by the more advanced magnetics groups, consider the car-alternator project at The Machines Institute, at the University of Aachen. The 3-D modelling and meshing is done in a structures package, the magnetics problem is solved in a specialist magnetics package, the mechanical stresses and forces are calculated and fed back to the structures package, the deflections are fed into an acoustics package to assess the noise level perceived by those in the car. The magnetics calculations are also linked into a circuit analysis package. A second project at Aachen concerns an induction furnace. This also includes MHD effects, the object, again, was to estimate the sound levels near the loading platform. Similar projects on induction motors have been running for some years at K.U. Leuven, Belgium.

The quoted figures above, contrast sharply with the statement about the ease of writing a program to solve the Poisson equation, even non-linear. The reasons are easy to see. Today's users are much more demanding than they were ten years ago. Since then fashions have changed. Users now demand much more. They expect, not unreasonably, to see a package available on their machine, running under their work-station operating system. Also, it has to run on a PC under all of the Microsoft operating systems. The look and feel have to be the same as they have for all their normal electronic office packages, with all the on-line help facilities one would expect. It must accept data in a variety of standard forms. It must have an easily expandable, comprehensive, materials library. Every feature known to CAD-man should be included. The range of solvers must cover statics, time-harmonic and transient. The post-processing must be fast and unobtrusive for all quantities. Interactive and batch operation are both expected.

In addition, there is an interesting move away from requiring users to have expert knowledge of computational methods. Up until recently, the prospective user of an advanced package was required to have such knowledge. Now one can start to find packages where all reference to computational techniques has been expunged. There is no longer a need to know about quantities that are outside the users normal range of engineering expertise. Indeed, why tell the user at all about finite elements? Let the user specify the accuracy required and leave the choice of solution method to the package designers. Similarly, automatically applied open boundaries are beginning to appear. Solvers are becoming much, much faster and there are some very nice error bounding techniques based on complementary methods, which can be used to reduce overall solution times.

There is also a shift towards providing artificial intelligence within packages. For example, using a neural network finite element mesh generator can significantly reduce the overall time needed to reach a solution when using automatic error detection and mesh adaption. This is only the start, we can expect to see far more in this area in the near future. This also ties in with the need to provide fast optimization techniques, as part of an CAD package. What we are seeing is a shift, at last, from simple analysis to real optimized computer aided design.

Electric Fields and Coupled Problems

Nearly all of the above relates to what has happened in magnetic field analysis. There are few, if any, commercial packages which attempt to tackle the sorts of problems described in the colloquium. Those problems which can be accommodated in currently available packages, are relatively simple. The solution of the Laplace, or Poisson equations, would commonly be the limit. Perhaps one or two packages accommodate the calculation of beam trajectories with space charge taken into account.

The main difficulty is that electric field problems appear to have a far greater variety than do magnetic field problems. Dimension ratios are far greater in electric devices, i.e. the dynamic range is larger. Many materials exhibit properties which might be extremely non-linear, stochastic and changing in time. It is difficult to see how they could all be brought under the CAD umbrella. However, many vendors now recognise the need for more open systems. More flexible data-structures and data exchange interfaces are becoming available. These make it possible, with relative ease, to select useful modules, including electric, from a number of sources. Others might be better left as specialist product, or device, specific, stand-alone packages making use of shareware modules, and/or inexpensive maths packages. The third category might be so local and specialised, that they never leave the laboratory of origin, mainly because the underlying science is still being discovered.

The first group includes those problems which are inherently coupled. Currently, there are many examples in magnetics of coupled problems. Commonly one finds two disciplines, but there can be many more, as in the Aachen and Leuven examples quoted above. These include: thermal; acoustic; mechanical; dynamic; electronic; chemical; and fluids. The coupling can be loose, in which case the problems are solved successively, until the values settle down. Alternatively, the coupling is tight, and the solution for all variables has to be obtained at the same time. Tightness or looseness can be established by considering the time constants involved. Electrical problems which are clearly coupled include: conducting particles in moving liquids; temperature sensitive behaviour of insulation, perhaps in a magnetic field; enhancement of boiler tube performance in an electric field; transient voltages, including lightning strikes, applied to machine or transformer windings; and arc/magnetic field dynamic interaction.

The second group includes what could be product specific software. Examples are: coil design to include resonance effects; transformer and coil transient response characteristics; substation grounding; EMC for equipment and people; and liquid or powder flow with charges distributed throughout the volume due to triboelectric effects. For this class of software, it is convenient and important to have close links between the university team and the industrial users. This is sometimes done through consortia. The SPEED group at Glasgow, under the direction of Professor T. Miller, is a good example.

The third group would include all those problems requiring long term research and high levels of expertise to solve. Included here are such problems as: electric arcs as a phenomenon in the airgaps of induction motors; any problem requiring fundamental measurements for the input data; corona discharge from HV lines in a steady wind; ionospheric source current modelling and geomagnetic induced currents.

Human Resources

There is one major snag. Where are these skilled users of multidisciplinary systems going to come from? Many university courses are nowadays so highly specialised within a single discipline, that the graduating products will, increasingly, find themselves inadequately equipped to expertly tackle problems in disciplines other than their own. Yet such expertise is essential for successful interdisciplinary design. There are two solutions in the short term. In the first, Users will have to obtain training, and thereby eventually expertise, by attending specialist courses. The second solution is to provide the Users with systems which make use of artificial intelligence in its manifold forms. The work of my colleague Professor Lowther, on Knowledge Based Design, comes to mind here, where among other techniques, use is made of neural networks for mesh generation; and case based reasoning to provide starting points for design optimisation. These are just two examples of the techniques being employed to reduce the level of expertise and training time of a CAD system User.

Conclusions

There are no simple answers here. However, there are things that can be done to ease the pain. There is now much more information available on the techniques and methods mentioned above. A good starting point is to join the International Compumag Society, contact Jan Sykulski at the University of Southampton. Internet, of course is a good source of information. CAD vendors are noted for their excessive generosity and helpfulness, talk to them. Rather obviously, a great deal more R & D funding is needed. If the power goes off, we all suffer.

Further Reading

A comprehensive list of references would be out of place here. The interested reader is invited to contact the author via any of the coordinates listed, for a start-up reading list. This includes references to the work directed by Lowther at Infolytica/McGill; Henneberger at Aachen; Belmans at Leuven; and the CAD books by Lowther and Silvester; and that by Sykulski at Southampton.

The author would be pleased to discuss further any of the topics discussed in this paper.

Ernie Freeman

The UK Magnetics Society

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A Puzzle:

Consider a current loop in which circulates a steady current of density j. In a region where resistivity ρ is not uniform, the conduction equations predict the presence of electric charge, the density of which is $\mathbf{q}=\mathrm{j}\,\mathit{grad}\,\rho$. Considering that $\mathbf{q}$ is exposed to the electric field $\mathbf{e}=\rho\mathbf{j}$, this charge is subject to a Coulomb force $\mathbf{qe}$. Still, it just sits there.

Why doesn't it move?

Can anyone provide an answer?

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