FIELD SIMULATIONS FOR HIGH VOLTAGE APPLICATIONS

K. Hameyer[2], R. Belmans[2], J. Driesen[2], P. Berghmans[2], U. Pahner[2] and E.M. Freeman[1]

[1] Electrical Engineering Dept., ICST&M, London, UK
[2] Katholieke Universiteit Leuven, Div. ESAT/ELEN, Leuven, Belgium
www.esat.kuleuven.ac.be/elen/elen.html
www.esat.kuleuven.ac.be/elen/BelgaF.html

Introduction and brief history of high voltage field computations

The modern technical disciplines, such as information technology, micro-system technology, hard- and software developments and electronics have without doubt made major steps in this century. Next to these results, the merits of research that is done in the field of power engineering are sometimes underestimated or just recognised as being unspectacular. This paper is not intended to be a theoretical firework, but a contribution to state the manifold and successful ongoing development and research activities in the framework of numerical field simulations in high voltage applications. It is shown how modern and novel techniques are applied to simulate physical phenomena out of the as classically regarded world of power engineering. Carefully selected examples of technical importance demonstrate the strength of the computation methods chosen. Nowadays, specialised software packages to tackle realistic problems are not exclusively used by highly skilled university researchers; there are various commercial software products on the market.

Field modelling is an old and well-established science. J.J.Thomson used algebraic analysis using Schwarz-Christoffel transformations in 1883 [1]. Then in 1900, F.W. Carter [2] published a paper on airgap induction, using conformal mapping. Many others 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 [3]. Since that time, the method has become extremely popular for the solution for both magnetic and electric field problems. More recently, in the 80th, boundary integrals have appeared. Combinations of finite elements and boundary integrals are also presented nowadays [4, 5 and 10] but are still under further development. In the late 80th a trend to numerical optimisations of details of technical devices can be stated. The beginning 90's the first automated optimisations of entire devices was performed [11]. Recent interest of research is directed to the topics of the computation of coupled fields. In this problem class, interdependencies of various types such as magnetic, thermal and structure dynamic fields are considered in weak or strong-coupled computer simulation [12].

Sources and Nature of Electric and Magnetic Field Problems

Society, as known now, would cease to exist if all sources of electrical energy were removed. The bulk of energy conversion from mechanical to electrical and back is via a magnetic field, i.e. most power generation and utilisation of electrical energy is electromagnetomechanical in nature. The devices tend to be ubiquitous and 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.

Magnetic field analysis has developed and flourished commercially. Due to its larger energy when compared to the electric field, 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.

Many electric and magnetic field problems include non-linearities, new physics, advanced materials, time dependence and stochastic processes. They are multidisciplinary. Due to the temperature dependence of the material parameters often the thermal field has to be firmly coupled with the electric and magnetic field computation (Figure 1). When motion effects and acoustic noise are studied, mechanical aspects have to be considered. External electric circuits have to be linked to the field problem to simulate a realistic technical device.

High Voltage Engineering Symposium, 22-27 August 1999
Conference Publication No. 467, © IEE, 1999

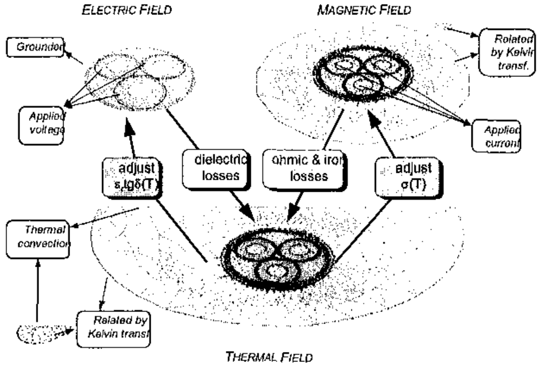

Figure 1. Coupling in electric and magnetic field analysis.

Developments in CAD and Field Modelling Software

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.

CAD package could be divided into two schools. The first school comprised specialists in magnetic and electric field analysis. The second school was made up of the large companies 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 experts in magnetics. However, only a full treatment, within the same software environment, can provide correct results.

In order to obtain an accurate simulation of electric machines (e.g. transformers), both magnetic and thermal fields have to be validated in a coupled field simulation approach. These systems encounter heat flow patterns with different thermal conductivities and often are thermally anisotropic. The methods combine a magnetic and a thermal finite element model. By using an appropriate projection method, the different field types are coupled by an iteration scheme. Therefore, the discretisations of the single sub-field problems must not be identical. Numerical strong and weak coupling schemes are possible.

Field Problem Types

A. Magnetic Fields: A wide range of field-solvers is required to cover all practical problems static, time-harmonic and transient. The post-processing must be fast and unobtrusive for all quantities. In a static problem, time-constant boundary conditions and time-constant current densities or permanent magnets drive a magnetic field. In time-harmonic, transient and motion problems, induced currents and induced voltages have to be considered (Faraday-Lenz). In general, current-carrying conductors excites electromagnetic fields. Therefore, there is a strong physical interaction between electric current flow-field and resulting magnetic system behaviour. This phenomenon can be modelled by describing external electric circuits consisting of voltage and current driven sources. Standard circuit elements, such as external resistances, capacitances and inductivities can be modelled in such circuit equations to form a realistic numerical model.

Applying such external circuit equations to the FEM model, distinction is made between solid and stranded conductors. A filament models a stranded conductor. Eddy currents are not considered in this case. If all solid conductors with a known voltage gradient and all stranded conductors carrying a known current are given, the electric behaviour of the entire system can completely be described. If in systems solid and stranded conductors, voltage and current sources and impedances are present and freely connected, appropriate electric unknowns have to be chosen and the system has to be described by both, magnetic vector potentials and circuit unknowns. An example of such a system is a transformer with foil windings. The accurate modelling of the current redistribution is required if e.g. the influence of harmonic loads of the transformer is required with respect to the resulting extra losses.

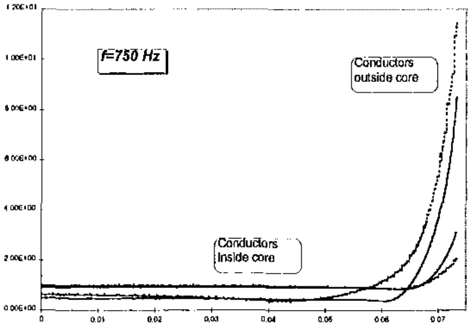

Figure 2. Current redistribution in the foil winding of a transformer

B. Electric Fields: The governing equation to describe electric fields is in principle very similar to the equation of the magnetic field. Using appropriate boundary conditions, voltages or charges can be applied as source terms. A typical result is seen in figure 3, where the electric field under a high voltage line, calculated using finite elements, is shown. The extra model at the top right corner is the Kelvin transformation to approximate the field at infinity [6].

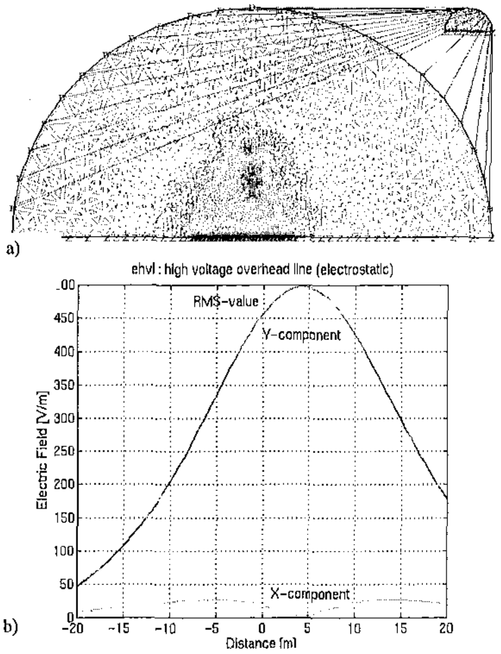

Figure 3. Electric field under a high voltage transmission line. a) Finite element discretisation and b) electric field in one metre above ground.

C. Coupled Fields: An important coupling are the losses and their thermal impact in electrical devices. The transformer discussed above is a first example. A second example in which the electric, the magnetic and the thermal fields are coupled as well, are the losses and the resulting temperature in a three-phase power cable. The three loss-sources, current in the conductors with respect to the current redistribution due to eddy currents, induced currents in the shields and dielectric losses in the insulation material, are considered.

1) Electrical field, described by means of the scalar potential V, is only of interest in the insulation of the cable. Therefore, a mesh covering this region is required to solve the static electric field equation.

2) Magnetic field, computed by means of a vector potential formulation A, has a sinusoidal time-variation, requiring a time-harmonic magnetic field solution on a further to this field type adapted mesh. Since this field is only shielded partially by the mechanical protection a leakage field can exist outside the model. The region surrounding the cable geometry considers this leakage flux; the far field is approximated by a Kelvin transformation. Losses consist of joule losses in the conductors, such as the lead, steel and copper and eventual iron losses inside the steel.

3) Thermal field, represented by the temperature potential T, is a static field covering the cable and the surrounding soil. For the ground surface model, cooling by convection is assumed [7].

The losses are calculated element-wise in the previous meshes and projected onto the thermal discretisation. The computed temperatures are used to update the material properties in the other fields. Basically, the dielectric permittivity and the thermal conductivity depend on temperature, but this is an effect of minor influence. The largest change is encountered in the conductivity of the copper. This gives rise to a three-domain mesh, represented in figure 4. The mesh for the electric field contains 9943 first order triangular elements, for the magnetic field 15378 elements and for the thermal field 15560 elements. The coupled calculation is executed for a rated balanced current and voltage load on the model of an individually lead sheathed three-core cable. Starting the iteration from an initial thermal field of 20°C, a solution for the overall coupled problem is found. The temperature in the centre of a conductor amounts 84°C, corresponding to reported measurements. Table 1 shows the value of the heat sources and their location. At full current load, the copper losses are dominant. For a minor current loading, the dielectric losses become relatively important.

TABLE 1
RESULTS OF THE LOSS CALCULATIONS.

Location	*Loss mechanism*	*Value [W/m³]*
Copper conductors	Ohms	$5,97.10^{4}$
Conductor insulation	Dielectric	$1,17.10^{2}$
Inter-conductor filling material	Dielectric	$2,55.10^{2}$
Mechanical protection	Ohms + iron	$1,23.10^{-3}$

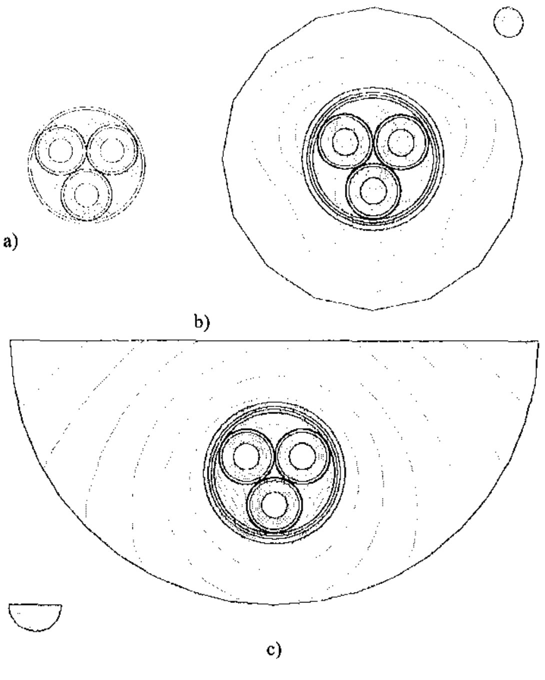

Figure 4. a) Lines of equal rms value of the electric field potential; b) lines of equal rms value of the magnetic field in and around the cable and c) isothermal lines in the cable modelled as buried in the soil.

Modelling of Large Structures

A well-suited method to approximate the far-field excited by high voltage transmission, is a semi-numerical approximation allowing computations of both electric and magnetic field. Due to the large wavelength, the problem can be determined by electrostatic calculation techniques. The electric field is computed by mirroring single line charges approximating the slag of the transmission line. The superposition of partial fields, calculated by the BIOT-SAVART law, yields the overall three-dimensional magnetic field distribution. A good agreement between computed and measured data can be stated.

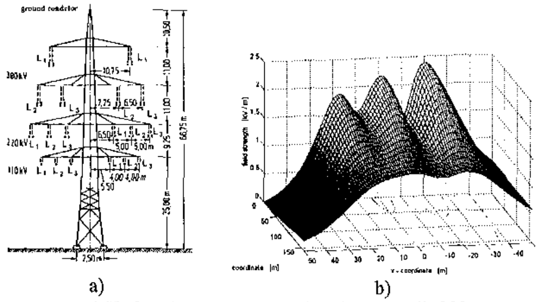

Figure 5. a) High-voltage tower carrying 6 systems (2x380 kV, 2x220 kV, 2x110 kV) and b) the electric field distribution.

Another issue of the research of fields excited by high-voltage devices is extended to the computation of the magnetic field in a substation (Fig.6). To model this situation a three-dimensional approach is required. Here, the finite element method is applied.

Conclusions

By using novel and modern numerical techniques, it is possible to compute the interesting field quantities inside and outside high voltage devices accurately. With the results of such field computations the behaviour of products and its technical value can be estimated realistically. The solution of coupled problems extends the accuracy of the entire simulation. Commercial software is able to tackle the basis types of problems. However, commercial software can give solutions as a first approach. The research and university community supports specific software for particular simulations, such as numerical optimisation or couplings to other field types. A trend can be noticed for the application of specialised numerical techniques. University spin-off companies maintain this industrial market with their scientific expertise. However, the future will lie in a combination of commercial software and high technology field-knowledge, available in such specialised spin-off companies [13], solving the real problems with advanced ad-on's and even totally new techniques.

Acknowledgements

The authors are grateful to the Belgian "FWO-V" for its financial support of this work and the Belgian Ministry of Scientific Research for granting the IUAP No. P4/20 on Coupled Problems in Electromagnetic Systems. The research Council of the K.U.Leuven supports the basic numerical research.

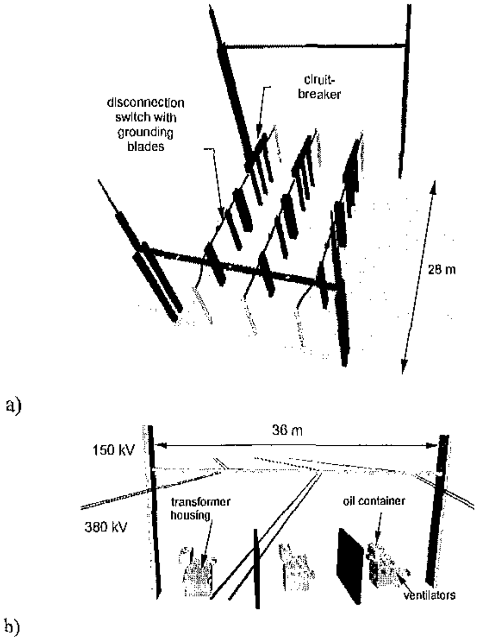

Figure 6. Three-dimensional model to compute the field a) inside a substation and b) close to a transformer.

References

[1] J.J.Thomson, *Recent Researches in Electricity and Magnetism*, OUP, 1893, Chapter 3.

[2] F.W.Carter, "A note on Airgap and Interpolar Induction," *JIEE*, 29 (1900).

[3] P.Silvester, "Finite Element Solution of Homogeneous Waveguide Problems", *Alta Frequenza*, 1969, 38, pp.313-317.

[4] D.A.Lowther, P.Silvester, *Computer Aided Design in Magnetics*, Springer Verlag, Berlin-Heidelberg, 1985.

[5] K.J.Binns, P.J.Lawrenson, C.W.Trowbridge, *The Analytical and Numerical Solution of Electric and Magnetic Fields*. John Wiley & Sons, Chichester, Reprint 1994.

[6] D.A.Lowther, E.M.Freeman,, "Further aspects of the Kelvin transformation method for dealing with open boundaries," *IEEE Transactions Vol.Magn.* (1992).

[7] K.Hameyer, U.Pahner, R.Belmans, H.Hedia, "Thermal computation of electrical machines," 3rd int. workshop on electric & magnetic fields, Liège, Belgium, 1996, pp.61-66.

[8] K.Hameyer, R.Mertens, R.Belmans: "Computation and measurement of electromagnetic fields of AC-high-voltage transmission lines," 6th int. conf. on AC & DC transmission, London, UK, 1996, nr.423, pp.52-57.

[9] K.Hameyer, R.Hanitsch, R.Belmans: "Optimisation of the electro-static field below high-tension lines" 6th int. IGTE Symposium on Numerical field calculation in electrical engineering, Graz, Austria, 1994, pp.264-269.

[10] A.Kost, *Numerische Methoden in der Berechnung elektromagnetischer Felder*, Springer-Verlag, 1994.

[11] K.Hameyer, "Optimisation strategies for the design of permanent magnet excited DC-motors," 13th Int. workshop on RE-magnets and their applications, Birmingham, UK, 1994, pp.217-226.

[12] K.Hameyer, J.Driesen, H.DeGersem, R.Belmans,: "The classification of coupled field problems," 8th IEEE Conf. on Electromagnetic Field Computation, Tuscon-Arizona, USA, 1998, pp.156.

[13] K.Hameyer, R.Belmans, "BELGAFIELDS, a preliminary university Spin-Off for electrical energy consultancy," *Le triangle*, no.3. www.esat.kuleuven.ac.be/elen/BelgaF.html