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FINITE ELEMENT METHOD AS AN AID TO MACHINE DESIGN: A COMPUTATIONAL TOOL

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***Abstract*—The paper provides an overview of the state of art in computational electromagnetic. There are three major areas like Design, optimization and material selection for the electric machines. The computational tool based on finite elements is very useful and powerful field simulation techniques available to assist in the design and performance prediction of electric machines. But the complexity in the geometry and multi material composition often hampers widespread use of these techniques. Commercial software, based on finite element Comsol Multi physics is very advanced and provides a reliable tool for 2D and 3D analysis in particular for multi-physics and optimization problems. The present work emphasized on the Recent advances in design and simulation software improving the standards of research and development.**

I. INTRODUCTION

Designers of electrical machines need to satisfy the customer on a number of criteria and be competitive regarding low first and operating costs, high efficiency and reliability, minimum weight, close tolerances, etc. Moreover, new types of machines are being developed and applied. Thus it becomes increasingly essential to be able to analyse any proposed design in considerable detail, so that a near optimum may be obtained. Recent advances in Computational Electromagnetics, encouraged by continuing increase of power and speed of computers, make finite elements and related techniques an attractive alternative to well established semi-analytical and empirical design methods, as well as to the still popular 'trial and error' approach. There has been important progress in fundamental formulations providing more solid foundations for numerical field analysis. There are specialised conferences and symposia dedicated to development of methods and simulation techniques for magnetic, electric and electromagnetic fields. Although many devices are considered, with both low frequency and high frequency aspects featuring prominently, traditionally the electrical machines community is strongly represented and design issues a routine topic of discussions. There are several smaller, but more focused, regular meetings like CEM (Computation in Electromagnetics), organised by the Professional Network on Electromagnetics of the IEE (Institution of Electrical Engineers, London) with selected papers published as a special issue of IEE Proceedings [3,4]; IEEE Transactions on Magnetics; ICME, Paris, France (International Conference on Electrical Machines) ISEF (International Symposium on Electromagnetic Fields in Electrical Engineering) [5]; EPNC (Symposium on Electromagnetic Phenomena in Nonlinear Circuits) [6] and others. The International Conference on Electrical Machines (ICEM) – one of the main big meetings devoted entirely to electrical machines – has an appreciable proportion of papers reporting on field computation techniques and a section devoted specifically to finite element methods [7], with a selection of extended articles published in COMPEL journal [8]. The activities of the Computational Electromagnetics community are overseen and coordinated by the International Compumag Society [9], an independent organisation with around 700 members from over 40 countries, which has as its mission the advancement and dissemination of knowledge about the application of computer methods to field problems having significant electric, magnetic or electromagnetic components. The ICS Newsletter [10] regularly publishes review articles on hot topics in electromagnetics, often with direct relevance or application to electrical machines. Another form of networking is offered by the IEE through its Professional Network on Electromagnetics [11].

There are several books and monographs introducing the art of field computation to practicing engineers and designers at various levels, from fundamental [12] to advanced [13 – 15]; some are very specifically relating to electrical power engineering in general [16] or design methods for electrical machines in particular [17]. Books on FEM in Electromagnetic are also available. Finite Element Engineering in Electrical and Magnetic Field Problems by Charri and Silvester, Elementary Mathematical and Computational tools for electrical and computer engineers using MATLAB by Jamal T Mannassah, Numerical Computing with Matlab by Cleve Moter, Recent advances in Modeling and Simulation by Giuseppe Petrone and Giuliand Cammarata etc.Overall, there is a vast literature on the subject which covers various aspects of field simulations in the context of design and performance prediction of electrical machines.

II. DEVELOPMENTS IN FEM

A comprehensive survey of the key developments in FEM and their attribution has recently been published [27]. It appears appropriate to recall here some of the great achievements and milestone developments which have contributed to the art of field computation. In fact many of the ground rules can be traced back to the work of Southwell using finite differences in the 1940's [28]. The Finite Element method (FE) grew out of the structural mechanics community serving the aircraft industry [29], and its development was driven by the needs of the industries involved; it was only much later that the method was studied by mathematicians. An important milestone, as far as electromagnetic field problems are concerned, occurred in 1963 with Winslow [30] reporting on a discretisation scheme based on an irregular grid of plane triangles. He used a generalized finite difference scheme but also introduced a variational principle, both giving the same results. The latter approach can be considered equivalent to the FE method and is consequently the earliest example of this technique in electromagnetics. Silvester and co-workers at McGill University advanced the formulation more generally using unstructured meshes and generic higher order elements. The polynomials introduced by Silvester [31] using simplex coordinates allowed most formulations to be accomplished for a prototypal triangle. Then in 1970, came the first application of the method to rotational electrical machines by Chari and Silvester [32]. In the 1970's the FEM community started to come together by exchanging ideas between researchers in academia, national laboratories and industry. The year 1976 was especially significant as it saw the first Compumag Conference being held in Oxford. Several developments took place leading to significant advances in theory, formulations, numerical techniques and algorithms. The Incomplete Cholesky Conjugate Gradient method (ICCG) was introduced for solving large sparse systems of equations [33, 34] in which the operation count goes approximately $n\log n$ and is largely independent of bandwidth; the method still provides the basis for most contemporary codes. Another breakthrough was in the now widespread use of the 'Delaunay meshing', with the original idea dating back to 1934 and successful algorithms implemented more recently in 2D [35] and 3D (using tetrahedral elements) [36] including error analysis.

Finite element analysis is used in almost every engineering discipline. Earlier FEA packages were limited to linear, static stress analysis only. Now they have been extended to include nonlinear static stress, dynamic stress, fluid flow, heat transfer, electric, electrostatic, magnetic, etc. These capabilities are combined to perform coupled-field analysis that consider multiple physical phenomena and are tightly integrated within a CAD interface. The finite element method is very efficient since it can be applied to any geometry, any set of material properties, and loading conditions as long as the appropriate constitutive relationships and equilibrium conditions are met. One more advantage of this FEA tool is, it is not restricted by size, and one can use the so-called zoom feature in finite element meshing to describe a miniature MEMS device. Hence many researchers have used this finite element method for modeling MEMS devices.

Authors work on the analysis of EM forces on end winding for Electrical Rotating Machines has been published in IASTED, USA [37] and IEEE, PEDES Proceedings India [38].

III. THE INDUSTRIAL PERSPECTIVE

Finite Element Method (FEM), that is to say, the procedures for approximating electromagnetic fields by means of numerical algorithms, is now a mature subject – and an active research discipline in its own right practised by a large international community serving science and industry. Computer modelling is used at all stages in the design of electromechanical devices and it is clearly recognised that the use of analytical and experimental methods, followed by expensive and inflexible prototyping, is no longer cost-effective. However, it is perhaps true to say that many managers in industry – the very people who would benefit most from using electromagnetic software as an everyday tool to cut design times and costs – still perceive FEM as a kind of black magic". Moreover, since government funding available for fundamental work in this field is scarce, the industry increasingly needs to be involved more directly. But benefits need to be demonstrated to managers before they commit resources to support fundamental developments. All this may sound only too familiar to many scientists struggling to secure research funding, but there is a message to the community to be more proactive in promoting FEM as an efficient design tool. Closely linked with the industrial requirements are educational needs; these depend strongly on the type of users necessitated by industry to run the FEM based design systems efficiently. It may be argued that three categories of users are usually required:

1. Those able to run confidently dedicated electromagnetic software, understand field displays, interpret numerical results and incorporate them into design processes;
2. Design experts who understand the language of computational models using available commercial software;
3. Electromagnetic software developers – the ultimate FEM experts producing basic computational tools to be used in design offices. In the early days researchers tended to regard the creation of software as a cultural extension to their work and there was often a free exchange of programs between developers. It is obvious that this is no longer tenable as real costs are involved and software production is a commercial operation. There is no essential difference between hardware and software in this respect; both require development, maintenance and support.

IV. COMMERCIAL SOFTWARE

This section is not intended to provide a catalogue of all available software in electromagnetics. Nevertheless, it seems worthwhile to mention that there now exist quite a few commercially available systems offering integrated tools for computer Aided Designs in magnetics. A typical commercial package will have most of the following components:

Pre- and Post-Processor: fully interactive, advanced post-viewing facilities, comprehensive range of supported output devices, automatic and adaptive meshing;

Statics: magneto- and electrostatic analysis with nonlinear (and often anisotropic and hysteretic) materials, including permanent magnets, special versions for laminated materials;

Steady-state eddy currents: steady-state ac eddy current analysis, including complex permeabilities, approximate non-linear solutions (fundamental harmonic field), background dc fields, voltage-driven problems;

Transient eddy currents: full transient analysis, nonlinear materials, multiple drives and background dc fields;

Motional eddy currents: uniform motion induced eddy-current analysis (with constant or varying topology);

Stress and thermal: mechanical stress using forces, or thermal analysis using ohmic heating, calculated from electromagnetic solutions; 2D, 2D axi-symmetric and 3D formulations. The following is a non-exhaustive list, with relevant web links provided under References, of the most popular software packages already used extensively by designers:

- COMSOL Multi Physics[19];
- MagNet, Infolytica [20];
- Maxwell, Ansoft [21];
- Emag, ANSYS [22];
- FLUX, CEDRAT Software [23];
- MEGA, Bath University [24];
- Integrated Engineering Software [25];
- FEMM, [26].

In addition, there are many in-house systems developed in academic and research institutions, some of which are also commercially available. Finally, there exists software written specifically for designing electrical machines, which can link to some of the general purpose finite element packages listed above.

V. THE STATE OF THE ART

Significant progress in implementation of new techniques has lead to more efficient, faster, more accurate and numerically stable algorithms. Amongst the advances which have recently made the greatest impact on the CEM community, the following should be mentioned:

- a new Finite Element Difference (FED) method,
- higher order Finite Difference Time Domain (FDTD),
- Boundary Element Method (BEM)
- Integral Equation Method (IEM)
- the Multiple Multipole Technique (MMT),
- the use of Finite Integration Technique (FIT),

- a Subspace Projection Extrapolation (SPE) scheme,
- formulations in terms of differential geometry,
- the usage of total/reduced magnetic vector potential and electric scalar potential,
- implementation of edge and facet elements,
- improved anisotropy and hysteresis models,
- multi-objective optimisation.

The already cited conferences COMPUMAG [1], CEFC [2] and others [3]–[9] are a continuing source of information about most recent advances. As an example, two particular areas of development will be elaborated, with which the author has been closely involved, namely the computation of electromagnetic forces and application and modelling of superconducting materials. Knowledge of total forces and their distribution is one of the most important pieces of information required in the design of electrical machines. The most common methods for force prediction are based on either the Maxwell Stress Tensor (MST) or the Virtual Work Principle (VWP). MST is derived from the Lorentz force expression, whereas VWP relates forces to the change in stored energy. For a comprehensive treatment of the principles behind force formulations, and their implications, the reader is refereed to [39]. The major advantage in using MST is that only a single solution is required; unfortunately there are significant implementation problems when applied to practical numerical solutions (e.g. the need for a very fine mesh in the air-gap region). The VWP, on the other hand, computes forces by a virtual displacement of a body and the associated change in the co-energy of the system. However, the required gradient of the co-energy function is rarely available explicitly and thus at least two field solutions are needed, or more for better accuracy. Many researchers have addressed the problem of how to improve the accuracy and reduce the computational effort, and the reader is referred to the works of Coulomb [40], McFee [41] and Hameyer [42]. The most recent attempt is also worth highlighting of a force computation algorithm based on continuum design sensitivity analysis [43]. The formulation allows the computation of the sensitivity of any global quantity to a perturbation in a parameter to be computed without reference to the underlying numerical computation scheme. In effect, it allows a Virtual Work calculation to be performed without the need for a physical displacement. The resultant expressions are similar to the MST but have the important advantage of the integration taking place on the surface of material rather than in the air outside. The approach can generate global forces as well as force distributions over the surface of a body, including the case of zero air gap. Moreover, the force expressions clearly indicate the contributions to the global force from each source of magnetic field. The implementation is simple, independent of the numerical analysis approach taken and can be easily used in combination with commercial software. Discovery and development of new materials present a modelling challenge and often lead to reformulation of fundamental equations or design methods. We will focus here on recent advances in superconductivity, in particular due to their potential impact on electrical machines industry. Ceramic superconductors were discovered in 1986 and their main advantage is that they can operate at liquid nitrogen temperature (78K) – hence the name High Temperature Superconductors (HTS) – and thus offer relatively cheap and reliable technology. With practical current densities of up to 50 times larger than in conventional copper windings they have great potential in electric power applications (generators, motors, fault current limiters, transformers, flywheels, cables, etc.), as losses are significantly reduced and power output per volume increased. From the design point of view they offer a challenge because of very highly non-linear characteristics and anisotropic properties of materials, and due to unconventional design solutions. The ability to predict and reduce all 'cold' losses is of paramount importance. The behavior and characteristics of the highly non-linear and anisotropic HTS materials is markedly different to conventional conductors. One of the first devices designed, built and successfully tested was a demonstrator transformer [44]; a particularly satisfying result was the two-fold reduction of losses through the introduction of magnetic flux diverters, which reduce an unwanted component of magnetic field in the coil region. Some more general aspects of the design of large HTS power transformers may be found in [45]. Another completed successful design was of a small synchronous generator [46]; in terms of modelling the important issues were no-load tooth ripple losses due to the distortion of the fundamental flux density wave by the stator slotting, and full-load losses that include the effects of the MMF harmonics of the stator winding.

VI. THE FUTURE SCOPE

Looking into a crystal ball to predict the future is hardly appropriate for a scientist or an engineer, but it might be worth re-emphasizing that Computational Electromagnetics is a very active area of research, the achievements to date are considerable and the tremendous effort continues. General purpose and specialised software packages offer flexible approach to design and virtual prototyping increasingly becomes a norm rather than an exception. One of the challenges is to 'keep up' with the technology; this may be accomplished by regularly monitoring what is reported at relevant conferences and other events.

VII. CONCLUSIONS

This paper is an attempt to review the significant advances in the field of Computational Electromagnetics to demonstrate how finite element method could aid the design of electrical machines and devices. Based mostly on the versatile finite element approach, the available software, including general purpose commercial packages, offer a mature tool for performance prediction, optimization and general design. Tackling the multiphysics problems and multi-objective optimization are identified as the biggest current challenges.

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