Technical article

Implementation of the Finite Element method into an industrial design environment

Introduction

It was the middle sixties when events necessitated the development of advanced solution methods to enable designers to build with confidence. Such an event was the increasing demand in electrical energy at that time. To meet the demand the power per unit volume of large turbine generators had to be increased. Up to this time analytic design methods prevailed but were becoming limited due to the need to model the non-linearity of magnetic materials, irregular geometric components and many other features.

To meet the shortcomings in analysis tools, numerical techniques based on the finite difference method (FDM), the boundary element method (BEM) and the finite element method (FEM) were developed. The finite difference method was the technique used initially probably because of the limited computational power available at the time; a memory allocation of 32 Kbytes being the norm and speeds of less than 0.1 MIPS (Millions of Instructions/sec) considered supersonic. However, as the power of computers increased the FEM came more into its own and was by the early seventies the preferred choice, by some industries albeit only as a research tool. The BEM still had its place in design, especially in electrostatics, but the need to solve a large unsymmetrical and full matrix was and still is its major drawback.

From the early seventies the FEM has been progressively developed into an analysis technique which is used consistently in today's design of electrical equipment either as part of a design procedure or to support design.

Although the method is now taken for granted as the preferred design tool it has been a long and tortuous road to achieve its implementation into the design office. This paper attempts to show where obstructions have arisen to its implementation in industry and where it may be going in the future.

The comments made concerning the implementation of the FEM into design relate mainly to the large Power Company ALSTOM, formerly GEC-ALSTOM and GEC. However I believe the views represent most industrial companies who have been or are involved in improving their design calculations through the use of the FEM.

Early days - research tool

Although in the late sixties/early seventies computer power was small, the FEM made a significant contribution in the design of large electrical machines. It enabled the designer, for the first time, to assess the effect that magnetic non-linear materials and geometric irregularities had on the design. Figure 1 shows an early example of the FEM used to obtain the correct balance between copper and iron in the rotor of a large generator.

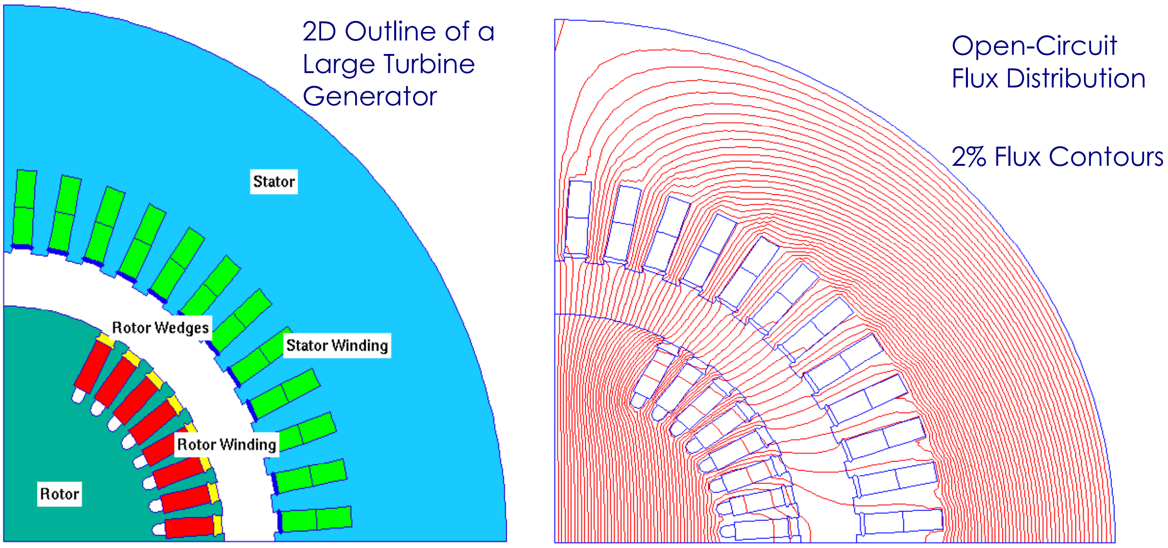

Figure 1: Outline of a the Rotor of a Large Turbine Generator

It has only to be realised that the I^2R loss of the field winding of a 660MW generator is of the order of 4MW to show how optimising this component could lead to a considerable financial saving with capitalised losses costing £2000/kW. However this investigation would have been done by the research department and probably taken several weeks to obtain a fully optimised solution. The optimisation method would be trial and error based on experience.

There are many more examples where different formulations of the FEM proved extremely useful to the designer. One such formulation worth mentioning is the quasi-3D approach which one can consider being a "half way house" between 2D and 3D. The formulation is 2D numerically but the variation of potential in the third direction is represented as an analytical function. The method was used extensively in the seventies to aid in the design of the end winding bracing system of large generators – figure 2. This had become necessary since the forces on the winding under both steady state and short-circuit conditions where considerably higher than previously experienced since they were approximately proportional to the square of the stator current.

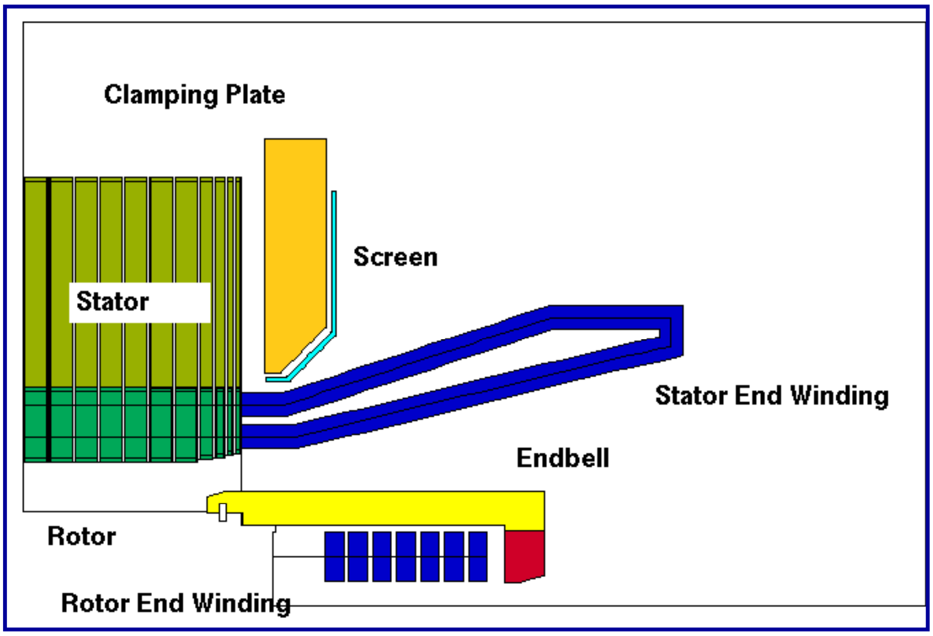

Figure 2: End Region

Initially the method was restricted to the end-air region but later extended to include the stator core region by "engineering" the finite element equations. The method models the laminated structure, magnetic non-linearity, induced currents in the plane of the lamination and the inclusion of design features such as Pistoye slits in the end lamination. The technique is still used today to obtain information on losses, forces, etc in the end region. Such a method does show how the FEM can be 'manipulated' by engineering know-how to give an analysis technique readily adaptable to the design office.

Early implementation in the design office

It was probably the early eighties before some of the formulations based on the FEM where used as a regular analysis tool in the design office. Even then the method was treated with scepticism and mis-trust. The major drawback was that designers/managers expected difficult problems to be solved on a small multi-user computer, minimum storage, minimum human intervention and in a nano second. This was at a time when the aircraft industry was using 'Cray' type machines for solving similar complex problems, backed by a department of engineers. In the electrical industry it was not unusual for a trainee fresh out of University with no experience in the method to be expected to operate the FE program. Thus it is no wonder the technique did not make serious in-roads into aiding the design of electrical equipment, as one would have expected.

Thus a prolific amount of research was done at this time in order to speed up the overall solution time of the method to meet the demands of an industrial design office. In the eighties many types of alternative formulation were developed, 2D became the norm with 3D starting to be developed and as computer power increased, transient solvers started to appear. Hand in hand with the formulation development, special engineering adaptation were implemented into the FE model in order to reduce the solution time and memory requirements, thereby increasing the range of problem that could be solved. Such an implementation was the surface impedance modelling of induced currents in materials in which the skin depth was small e.g. the tank wall of transformers. Using conventional modelling by 3D elements requires the discretisation of the skin depth that is of the order of millimetres, in a component that is metres wide and metres long. The number of elements required could thus be considerable (in excess of 100,000) whereas modelling by surface impedance elements require the discretisation of the surface only and so a much reduced number of elements are needed.

There have been several such engineering implementations, which have aided in obtaining results in electrical equipment design more quickly and with a greater degree of accuracy. Some examples are the representation of laminated structures, allowance for eddy current losses in stator cores where laminations overlap each other, representation of foils in bushing design, modelling of the characterisation of High Temperature Superconducting (HTS) material, hysteresis etc. All these developments give the designer a wider range of problems to solve.

Present design use of the fem

It was not until the early 1990's, that is about 20 years after the FEM was first used in anger to solve electromagnetic problems, that it became accepted in the design environment. The main reason for its acceptance was the introduction of semi-or fully automatic meshing routines and most of all high-speed computers with lots of memory that could be purchased at low cost.

There were several ways the FEM is being utilised today:

a) By having a department specifically set up to solve, electromagnetic problems. This approach could only be adopted in larger companies due to the costs. However, such a department would have one or two engineers who are familiar with the art of finite element modelling.

b) By building the FEM into a specific design procedure to evaluate a certain task. For instance in the heavy electrical industry, design procedures have been written for evaluating:
  i) no-load and load excitation
  ii) end-region design
  iii) determination of reactances
  iv) starting performance (Figure 3) of a large solid pole motor
  v) loss evaluation due to the currents induced in the solid pole rotor of large motors.

c) By performing the complete electromagnetic design in which FEM forms the central analysis tool. An example would be the design of an induction motor in which the design procedure would call up a CAD package to obtain the rotor and stator lamination dimensions. These would be discretised and adapted to meet the needs of the excitation required and then solved. The design would then return all relevant results such as torque, losses, force etc. available to the designer. All with very little designer intervention.

d) By purchasing one of the many packages now available and training a member of staff to use the FEM for all of the designers within the department.

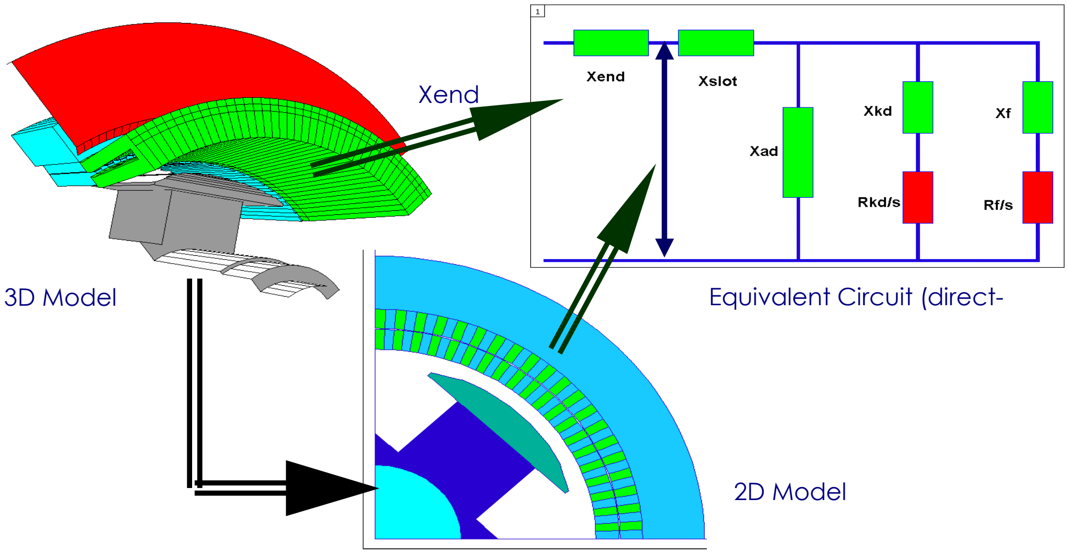

Figure 3: Outline design procedure for evaluating the starting performance of large solid salient pole motors.

All of these approaches have advantages and disadvantages. Method (a) is costly but probably makes best use of the FEM to advance design. It is normally associated with the large industries. Method (b) relies on having the expertise to implement the FEM into the design procedure. This approach is the most flexible since it could make possible the interface with external CAD systems. This system can then be added to as required. It also has the advantage that a designer with no finite element experience can operate it. However there are dangers doing this if the limitations of the method are not clear to the user.

Procedure (c) is ideal if there is one product to be designed for but can prove expensive if a new integrated design procedure, in which the FEM is embedded, is required for each product.

Finally, method (d) is a general approach that is probably the way forward for most small companies who can call upon the support team of the vendors of the package. The approach however can be restrictive since the user has no control over modelling the unusual.

Future use of the fem in industry

Construction of Models

- Full automatic 3D adaptive schemes to discretise the problem will be the norm. As long as an adaptive procedure is set to realistic values then reasonable meshes can be produced.

- Another approach is to discretise individual components, such as the winding, stator core, rotor end-bell etc. and store into memory. The mesh is then constructed by placing the discretised components into space and ‘stitching’ them together with a suitable algorithm.

- Similar to the first suggestion but with the geometric details being obtained directly from a CAD system.

However, whichever method is used the main criterion will be its robustness in handling all the complex geometries and electromagnetic peculiarities that will be present in industrial applications.

Solvers

The ICCG matrix solver has been a good servant to the FE modeller since its introduction in the late seventies. With preconditioning the speed of solution with minimum memory has been excellent and today we are able to solve in excess of one million unknowns in a reasonable time with middle of the range computers.

The speed of solution is problem dependent and an “ill-conditioned” matrix can still take an extremely long time to converge and in some cases fails to converge. “Ill-conditioning” can arise in many structures but one example is solving for induced currents in components in which the skin depth is large in comparison to its thickness (opposite to surface impedance elements). Understanding the reason for “ill-conditioning” and rearranging the matrix structure accordingly can overcome the problem.
Another way, of course, to speed up the solution time is to increase processor speed, which historically is doubling every year. Also parallel processing can be advantageous especially as more integrated solutions are developed to solve engineering problems.

Post Processing

Again the speed of graphics has enabled results from large problems whether 2D or 3D or time stepping to be efficiently extracted from the solution and translated into a form the designer understands.

Future use of the fem

I believe the main thrust for the future will be associated with integrated design whereby all aspects of the engineering problem are considered in one solution and not as at present by several single solutions linked in series.

Most electrical equipment is being driven by electronics and accordingly it is essential the electronics be integrated directly with the electromagnetic design, mechanical design, thermal design etc. as shown in Figure 4.

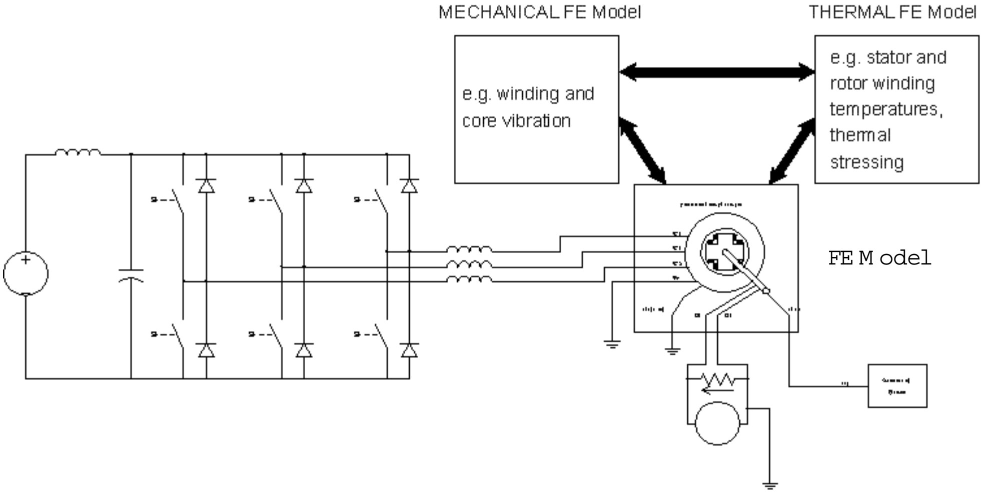

Figure 4: Integrated design procedure

Already there are some packages that offer this type of solution but early experience suggest that, for simple input/output, connection to the electronic driver is fine, but once the number of inputs and outputs increases convergence problems occur. There is certainly a lot of investigative work required before designers can be guaranteed a stable solution.

Finally, it seems like fantasy, but with current technology it is possible to model in 3D, for example, an induction motor and, with time-stepping techniques and other mechanical facets of engineering, “listen” to the motor starting up. Also, with virtual graphics, it is possible to “walk” into the motor to measure temperature, or sit on the end winding and measure vibration and forces. All the technology is there as shown in the oil industry when designing the structure of oilrigs, but the cost is far too high at present for the electrical designer. But who knows? In 10-15 years time when computer costs have been reduced even more, it may be possible for the designer to design the equipment, optimise the design to the customer’s specification and test it under all fault conditions. This could all be done in the designer’s own virtual world and without having to cut metal.

T W Preston