CHAPTER 3
APPLICATION OF FINITE ELEMENT METHOD IN THE EVALUATION OF ELECTROMAGNETIC FIELDS

3.1. INTRODUCTION

Electromagnetic field patterns govern the behaviour of all electromagnetic devices such as electrical machines, wave-guides and antennas. Since these fields obey Maxwell’s equations, in order to be able to predict the performance characteristics of these devices, it is necessary to solve these equations, in the course of their design. Differential or, alternatively, integral form of the Maxwell equations has made electromagnetic field computations a heavily mathematically oriented discipline. Before the advent of the computer, the electromagnetic equations had to be solved, using solution concepts such as series expansions, separation of variables, Bessel and Legendre polynomials, Laplace transformations and conformal mapping. However, the solution of electromagnetic field in even trivial cases employing these methods is a rather lengthy and cumbersome procedure. Moreover, it happens frequently that no solution is possible without resorting to rather drastic simplifying assumptions concerning device geometry, current or charge distributions, and so on. Fortunately, with the developments in computerised numerical techniques, it is now possible to use simple numerical approximation schemes to solve large-scale problems within reasonable time limits. Although these schemes are known as approximation methods, the term is in a sense misleading. Indeed it is possible to increase the accuracy of the results to a desired level, if one is willing to tolerate increased computing costs. In the real world involving
complex geometries and numerous electromagnetic configurations, numerical schemes yield far more accurate solutions than their classical analysis counterparts. Nowadays, modern trends in electromagnetic field computations are almost entirely based on these numerical schemes.

One of the most important and widely employed numerical computation methods today is the finite element method (FEM). It was originally developed as a tool for structural analysis, but the theory and formulation have been progressively so refined and generalized that the method was applied successfully to other fields like heat flow, seepage, hydrodynamics and rock mechanics. Silvester and Ferrari [35] have elaborated the applications of FEM in problems related to electrical engineering. As a result of this broad applicability and systematic generality of the associated computer codes, the method has gained wide acceptance by designers and research engineers. The fundamental idea of the FEM is to replace a given continuous function by piecewise approximations, usually polynomials. With this method, the solution region is subdivided into finite number of sub-domains, called elements, and a trial function is postulated over each of the elements. It is commonly found to be plausible to have interpolation nodes on the element and to define the trial function in terms of the unknown values of the unknown variable of the differential equation at the node itself. As a result, the nodal values become the free parameters, i.e., the degrees of freedom. The finite element method essentially relies on finding the values of the free parameters with respect to certain constraints, usually given in the form of boundary conditions and a chosen criterion for optimizing such as minimum error, energy extreme,
functional orthogonality etc. This method is widely regarded as one of the most powerful numerical schemes available in Engineering. The following sections present a brief explanation of the method, the current trends in finite element analysis, its application in the evaluation of electromagnetic fields of electrical machines and address the main problems and limitations of certain modern finite element based software packages.

3.2 OVERVIEW OF FINITE ELEMENT METHOD

The basic concept of traditional FEM is to divide the domain under investigation, either two-dimensional (2-D) or three-dimensional (3-D), into finite number of simple sub-domains or elements and then to approximate the unknown variable in each sub-domain by low order piecewise functions usually polynomials. These elements may be triangular in 2-D or tetrahedral in 3-D domain. The values of the unknown variable at each node of such an established network of elements, usually called finite element mesh, are the objective of the analysis. In the next step, by using the node values of each element, and the previously established piecewise approximation functions, the values of the unknown function at each point inside the domain of analysis can be easily computed.

Analysis of electric and magnetic fields in electromagnetic devices is usually performed by solving differential equations, for the potential quantities obtained from Maxwell’s equations. Once the differential equations are formed, for a particular problem, the potential quantities that determine the field are solved by FEM. In finite element analysis, Maxwell’s equations in the differential form are used. It is well known that satisfying differential equations
in any region having Neumann and Dirichlet boundary conditions is equivalent to extremizing a functional, which gives the total energy of the region of interest.

3.3 Application of FEM in Electrical Machine Design

Currently, computer modelling is used at all stages in the design of Electrical Machines. It is now clearly recognised that the use of analytical and experimental methods followed by expensive and inflexible prototyping is no longer cost effective. Preston and Sturgess [36] have described two FEM integrated design procedures for Electrical Machines. According to this, the method allows the designer to obtain a clearer understanding of the flux distribution in the machine and so indicates directly the corrective action to be taken, if necessary. Chao et al [37] have explored a hybrid method, which combines finite element with analytical solutions for solving electromagnetic field problems in rotating electrical machines.

Many researches have attempted to incorporate FEM into the design and analysis of induction motors. Parkin and Preston [38] have developed a design procedure using a 2-D time stepping finite element method, to investigate the performance and reliability of induction motors. Two methods for predicting the performance of cage induction motors using finite elements have been discussed by Williamson et al [39]. The first method, which is suitable for steady state analysis, employs a phase band model for the stator together with a single slot model for the rotor. The second one, suitable for transient analysis, uses a time stepped coupled circuit model for the machine, together with finite element field solutions that are used to update the circuit
parameters. Williamson and Robinson [40] have described a means by which FEM can be used in conjunction with the conventional equivalent model to determine the equivalent circuit components for a three-phase cage induction motor. However in this method, the effects of stator slotting on the fundamental air gap field has been included in an approximate way only, by using Carter’s coefficient. Mukhodhyay et al [41] also have described a technique for interfacing the conventional equivalent circuit model with FEM, to predict the performance of a cage rotor induction motor. The application of complex analysis and FEM for predicting the performance of a three-phase squirrel cage induction motor under sinusoidal voltage forced operation has been discussed by Hong and Hwang [42]. A comparison between the analytical and numerical (FEM) methods has been made by Ionel and Cistelecan [43], for the investigation of the no load performance of induction motors. They have also commented that finite element method offers some interesting results related to slot and tooth leakage flux, pulsation of air gap flux density and other local properties of main or leakage field. Cannistra and Sylos [44] have utilised FEM to conduct a thermal analysis in an induction machine. A time stepping FEM was used by Ho and Fu [45], while analysing the temperature rise in induction machines.

FEM has been widely used for the design and analysis of various other Electrical Machines also. A finite element model capable of analysing the behaviour of single-phase induction generator, operating at constant speed, has been developed by Rajanathan et al [46]. Finite element analysis of magnetically saturated DC machines was carried out by Chari and Silvester
[47] with the help of an automatic plotting program, which they developed for the graphical plotting of flux distributions. Predictions based on this type of analysis have been compared with experimental results also. A method to simulate non-linear magnetic field problems utilising the capability of FEM has been proposed by Righi et al [48]. Non-linear magnetic field of a permanent magnet DC tachogenerator has been analysed by Stoia and Raulescu [49], by applying FEM. Application of FEM in a linear variable differential transformer (LVDT) has been demonstrated by Sykulski et al [50]. The finite element aided design of a particular LVDT, has been used to illustrate the practical aspects of such modelling.

One of the major applications of FEM in Electrical Engineering is in the optimisation of the Electrical Machine design parameters. Jornet et al [51] have utilized FEM for optimizing the design of high frequency induction motors, since conventional tools could not easily take into account the phenomenon of high frequencies. A novel method, utilising neural networks in conjunction with FEM, for the optimisation of electromagnetic devices has been proposed by Seguin et al [52]. Modelling and optimization of a permanent magnet machine in a flywheel, has been developed by Holm [53], with the help of finite elements. Andersson [54] has also utilised the capability of FEM to optimise a servomotor, used for industrial robot application.

Attempts have been made by many investigators to further improve the accuracy of the results obtained from finite element analysis, by refining the models. An efficient technique of combining finite element and hysteresis models, which shows good convergence with short calculation time was
presented by Kim et al [55]. Stumberger et al [56] analysed iron loss in a synchronous generator, using finite elements.

Three dimensional finite element models were seldom used, though they provided more accurate results. Canova et al [57] have presented a method to use 3D finite element procedure for the analysis and design of two different induction machine structures: a radial and an axial machine. In this study, eddy current problems have been solved to evaluate machine performances. Engstrom [58] has examined the effect of axial leakage in Electrical Machines with special attention to the torque production in slot-less machines. The analysis has been carried out by means of 3D finite element calculations.

3.4 Finite Element Packages

The I-DEAS and PATRAN program packages are very powerful general-purpose finite element packages, widely used for defining the domain of the functional equation and generating FEM meshes. However it is not very easy to provide boundary conditions, in most of these softwares. FLUX is a software package for electromagnetic design, developed by Maxsoft, which utilizes finite element analysis. FLUX includes full geometry parameterization capabilities, static and dynamic excitation capabilities, connection to internal or external electrical circuits, and linear and rotating motion capabilities. FLUX can be used in the research, design, and production of every type of electric device and process, from small appliances to large machinery, from audio speakers, to medical MRI. Coupled with other programs, FLUX solutions expand into drive technology, fluid power, mechanics, acoustics, and thermal analysis. FLUX offers a direct link to Simulink, enabling one to develop a
control strategy directly in Simulink with the FEM model described in FLUX. During the computation, FLUX and Simulink are run in transient co-simulation.

MAXWELL is a multi-purpose simulation software tool of Ansoft Corporation that delivers numerical power and ease of use. With Maxwell, we can quickly and accurately develop virtual prototypes of electric machines, actuators, transformers, sensors and other electromagnetic devices. It is capable of handling frequency and time domain electromagnetic fields and steady state thermal fields. TABLE 3.1 lists some important commonly available FEM packages for low frequency application.

### TABLE 3.1: LIST OF FEM PACKAGES

<table>
<thead>
<tr>
<th>SI No:</th>
<th>Vendor &amp; Web</th>
<th>Package</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ansoft Corporation, Pittsburgh <a href="http://www.ansoft.com">www.ansoft.com</a></td>
<td>Maxwell 3-D</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<tr>
<td>2</td>
<td>Ansys Inc, Canonsburg, Pa <a href="http://www.ansys.com">www.ansys.com</a></td>
<td>EMAG</td>
</tr>
<tr>
<td>3</td>
<td>Field Precision, Albuquerque, N M <a href="http://www.rt66.com">www.rt66.com</a></td>
<td>Tri comp</td>
</tr>
<tr>
<td>4</td>
<td>Infolytica Corp, Montreal <a href="http://www.infolytica.com">www.infolytica.com</a></td>
<td>Mag Net</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Elec Net</td>
</tr>
<tr>
<td>5</td>
<td>Magsoft Corp, Troy, N.Y <a href="http://www.magsot.flux.com">www.magsot.flux.com</a></td>
<td>Flux</td>
</tr>
<tr>
<td>6</td>
<td>Tera Analysis Co, Tarzana, California <a href="http://www.tera-analysis.com">www.tera-analysis.com</a></td>
<td>Quick Field</td>
</tr>
<tr>
<td>7</td>
<td>Vector Fields Inc Aurora, IL, USA <a href="http://www.vectorfields.com">www.vectorfields.com</a></td>
<td>OPERA, Elektra, Tosca</td>
</tr>
</tbody>
</table>
In the present work, NISA/EMAG, an integral part of the NISA family of programs, of M/s Engineering Mechanics Research Corporation (EMRC), was used for the analysis. It uses finite element method to analyse the electric, magnetic and thermal behavior of electromagnetic devices. Coupled with the geometric modeling program NISA/DISPLAY, NISA/EMAG offers the designer an efficient tool for fast simulation of the device by allowing various changes to the model parameter, thereby reducing design time and cutting testing costs. It has the feature that it directly interfaces with the Pre-and Post Processor, NISA/DISPLAY to create and modify the physical and material properties of the model and view the various analysis results. This software can handle two-dimensional, three-dimensional and axi-symmetric electromagnetic problems and includes provision for feeding linear, nonlinear, anisotropic and permanent magnet material properties. It also allows steady state or time varying excitations and wide range of boundary condition including Neumann, Dirichelet, and infinite elements. For the design and analysis of inductor type alternator, the MFIELD section of EMAG is to be used. The procedure for this is shown as a flow chart in figure 3.2.
Physical Problem
Input Geometry
Patch the surface
Meshing
Input Material ID & Material Data
Select Analysis Type
Input Boundary conditions
Specify sub analysis type & Set Tolerance
Run EMAG
Read post files
Select type of result
Output the result
END

Fig 3.2. Flow Chart for Analysis with EMAG
3.5 CONCLUSION

Finite element method permits great freedom in respect of the geometric disposition, size and material properties of elements and hence can be concluded that finite element method of Electrical Machine analysis is thoroughly practical as a design tool, even when different magnetic characteristics occur and when different and asymmetric current distributions exist in the same machine. The investigations made in this field and the softwares dealing with finite element analysis of electromagnetic fields have been discussed in detail, in this Chapter.