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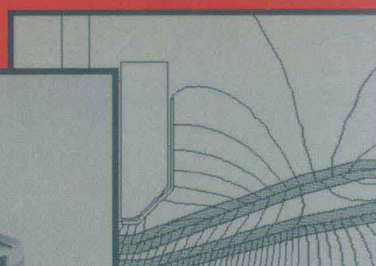
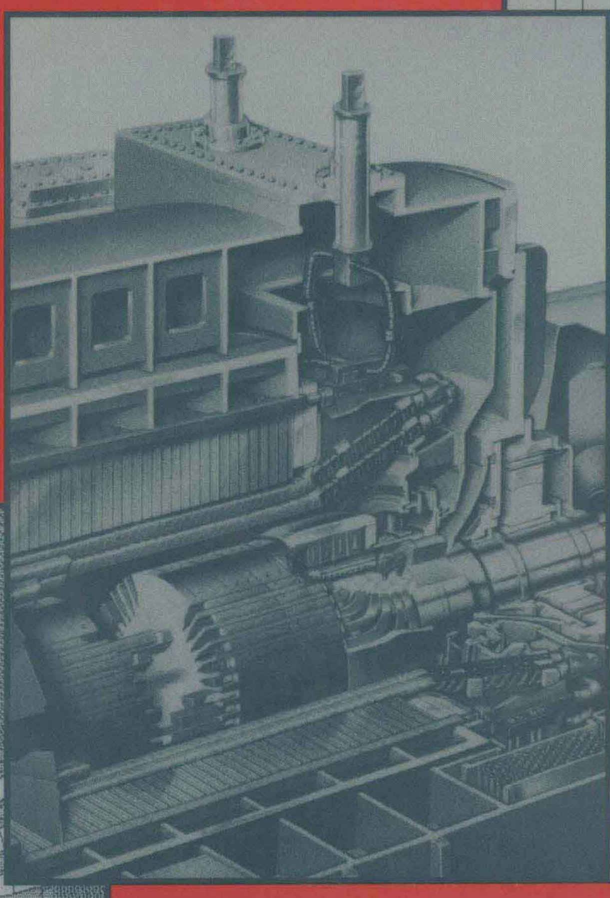
FINITE ELEMENT METHODS IN ELECTRICAL POWER ENGINEERING

A.B.J. REECE
and T.W. PRESTON





Finite Element Methods in Electrical Power Engineering

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To Gwen and Pat
for their patience and encouragement
and to our colleagues past and present
whose contributions over the years have made this book possible

Preface

The appearance of yet another book on finite element computation of electromagnetic fields needs some explanation.

As developers and users of the finite element method in electrical engineering and advocates of the value of the method in design and development work, we have become aware of the difficulties experienced by new users when introduced to the subject. The difficulties appear to arise in two areas, viz., (i) an inadequate understanding of relevant electromagnetics and (ii) an inability to appreciate the tricks and traps of modelling. Whilst there are excellent books which deal with electromagnetics, numerical computation and some aspects of modelling, we believe there is no single comprehensive volume which gives the new user or the interested inquirer the foundation needed. This book is therefore aimed at aiding this group: it is *not* intended to help the reader write finite element software.

We have chosen to divide the book into three parts, believing this will facilitate its use. Part I covers 'Relevant Theory', avoiding the use of mathematics as far as possible and aiming to emphasise the physical significance of the subjects discussed. This means that it may not be sufficiently rigorous to satisfy the purist, but it should provide the background needed to understand the later sections. Although three-dimensional situations are briefly considered, the emphasis is on two-dimensional cases, which are both easier to appreciate physically and, with care, adequate for many practical cases. It also shows how the governing potential differential equations for two-dimensional cases may be represented in finite element terms.

Part II discusses the 'Principles of Modelling'. After describing data generation and post-processing possibilities, it outlines basic hardware and software requirements. It concludes by considering representation of saturation and permanent magnet effects and the determination of derived quantities such as inductances and forces. It also describes additions to basic software to deal with excitation prediction, voltage-fed circuits, machine end fields and time stepping. It concludes with a chapter on the importance of engineering judgement when setting up models.

Part III is entitled 'Case Studies'. The examples described here are either taken from, or based on, investigations carried out by the Electromagnetics Group of ALSTOM Research and Technology Centre. They cover a wide range of studies made on electrical machines, transformers and auxiliary equipment. Some of the examples given date back an appreciable time, but have been included either because they make an important point and/or because test data is available to illustrate accuracy. The aim is to show what is possible, to outline the steps necessary and, in some cases, to indicate what can go wrong. The authors' experience is, in the main, with the ALSTOM package SLIM and the examples given used this package. However, the comments throughout are intended, as far as possible, to be of general applicability.

The cases described and the programs used are the result of work carried out in the Electromagnetics Group at ALSTOM Research and Technology Centre at

Stafford over a period of more than 30 years. The work has been a team effort and we are grateful to past and present colleagues for all their contributions in developing and applying finite element software to aid designers in many product companies. A mark of the team's success is that most of these companies are now regularly using finite element methods as part of the design process.

We wish to thank Lucas Varity (formally Lucas Electrical Industries) for permission to use data relating to their products and ALSTOM product companies (particularly ALSTOM Energy Ltd and ALSTOM T&D Transformers Ltd) for allowing us to publish work carried out on their behalf. Thanks are due to the Institution of Electrical Engineers and the Institute of Electrical and Electronic Engineers for permission to reproduce tables and illustrations from papers published in their proceedings. We also wish to thank the management of ALSTOM Research and Technology Centre, Stafford for encouragement to publish. Finally, we thank Helen Johnson for her efforts in producing the final manuscript from our drafts.

Stafford A.B.J.R.
January 1999 T.W.P.

Symbols

Many symbols are defined as they occur, but frequently used ones are given below:

$\boldsymbol{A}$	vector magnetic potential	Wb/m
$\boldsymbol{B}$	magnetic flux density	T
B_R	remanent flux density	T
C	capacitance	F
C_e	coenergy	J
$\boldsymbol{D}$	electric flux density	C/m^2
$\boldsymbol{E}$	electric field	V/m
F	'energy' functional	J
f	force	N
$\boldsymbol{H}$	magnetising force (field strength)	A/m
H_C	coercive force	A/m
$\boldsymbol{J}$	current density	A/m^2
L	self inductance	H
M	mutual inductance	H
$\boldsymbol{T}$	vector electric potential	A/m
V	electric potential	V
W_e	stored magnetic energy	J
W_{elec}	stored electric energy	J
δ	depth of penetration $= (2\rho/(\mu_0\mu_r\omega))^{1/2}$ (penetration constant)	m
ε	absolute permittivity $= \varepsilon_0\varepsilon_r$	F/m
ε_0	permittivity of free space	8.854×10^{-12} F/m
ε_r	relative permittivity	—
μ	absolute permeability $= \mu_0\mu_r$	H/m
μ_0	permeability of free space	$4\pi \times 10^{-7}$ H/m
μ_r	relative permeability	—
ν	reluctivity $= 1/\mu$	m/H
σ	electrical conductivity	S/m
Φ	flux linkage	Wb
ρ	electrical resistivity	ohm-m
Ω	scalar magnetic potential (mmf)	A
ω	angular frequency	rads/s

Suffices

d	direct axis
e	eddy (or induced)

q	quadrature axis
s	source (or applied)

Bold letters indicate vector quantities. However, in two-dimensional problems, ***A***, ***E*** and ***J*** will have one component only, and in this case they are represented by normal characters A, E and J.

Contents

Part III: Case Studies