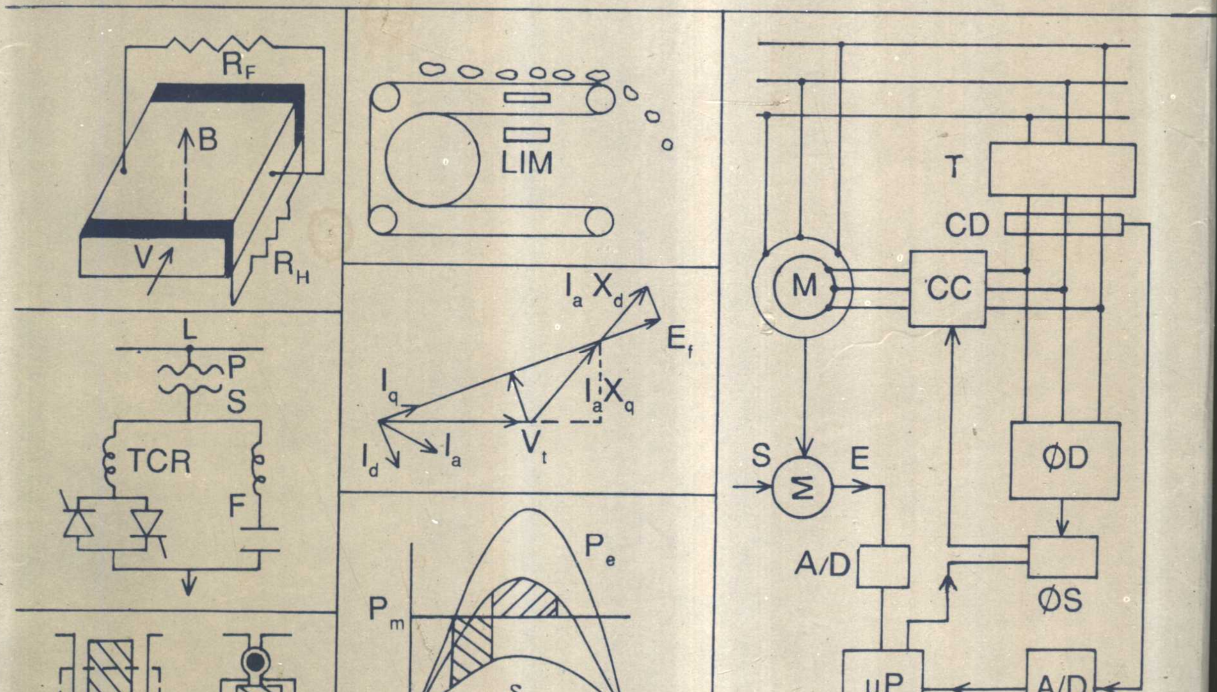
Rakosh Das Begamudre

Electro-Mechanical Energy Conversion With Dynamics of Machines



Electro-Mechanical Energy Conversion with Dynamics of Machines

RAKOSH DAS BEGAMUDRE
Visiting Professor in Electrical Engineering
Indian Institute of Technology, Kanpur
India

JOHN WILEY & SONS
New York Chichester Brisbane Toronto Singapore

First Published in 1988 by
WILEY EASTERN LIMITED
4835/24 Ansari Road, Daryaganj
New Delhi 110 002, India

Distributors:

Australia and New Zealand:
Jacaranda Wiley Ltd., Jacaranda Press
JOHN WILEY & SONS, INC.
GPO Box 859, Brisbane, Queensland 4001, Australia

Canada:
JOHN WILEY & SONS, CANADA LIMITED
22 Worcester Road, Rexdale, Ontario, Canada

Europe and Africa:
JOHN WILEY & SONS LIMITED
Baffins Lane, Chichester, West Sussex, England

South East Asia:
JOHN WILEY & SONS, INC.
05-05, Block B, Union Industrial Building
37 Jalan Pemimpin, Singapore 2057

Africa and South Asia:
WILEY EASTERN LIMITED
4835/24 Ansari Road, Daryaganj
New Delhi 110 002, India

North and South America and rest of the world:
JOHN WILEY & SONS, INC.
605 Third Avenue, New York, NY 10158, USA

Library of Congress Cataloging in Publication Data

Begamudre, Rakosh Das.
Electro-mechanical energy conversion with dynamics of machines.

1. Electromechanical devices. 2. Electric machinery.
I Title
TK145.B416 1988 621.31'042 87-23148

ISBN 0-470-20956-9 John Wiley & Sons, Inc.
ISBN 81-224-0070-1 Wiley Eastern Limited

Printed in India at Prabhat Press, Meerut.

To

my former classmates and life-long friends

Chintakindi Lalitamba Rao

Ajit Kumar Sharma

B.R. Rangaswamy Iyengar

and their fine wives

Sita, Anita and Sita

Preface

Introductory text books on EMC and Electric Machines are available in large numbers in technical literature so that a new book needs an explanation for its preparation*. As in every branch of Electrical Engineering, very rapid improvements are taking place so that students and teachers have to keep pace with the progress of knowledge. Fifteen years ago, the use of electronic devices for excellent speed-torque control of industrial drives and excitation systems of central-station generating units were introduced resulting in better utilization of equipment capabilities. Recently, mini- and micro-computers are being applied for control of performance of devices, machines, and interconnected systems. With increasing power demands and use of higher and higher voltages feeding very long transmission lines, series-capacitor compensated lines are coming into use. While resulting in increase of power-handling capacity and improvement in stability limits, certain dangerous electromechanical torques at sub-synchronous frequencies are generated which form a potentially hazardous condition for the long shafts of turbo-generator units with consequent shaft failures. The problem of sub-synchronous resonance has assumed great importance and the design of large alternators is now being carefully looked into for torque interactions at these frequencies.

Stability considerations also led to increasing use of shunt reactors for compensating line-charging currents. The reactors can be regulated in the production of reactive power or Vars very quickly by using high-power high-speed switching devices such as thyristors (SCR's) and are known as Thyristor-Controlled Reactors. Unfortunately, the resulting non-sinusoidal currents resulting from these switching operations give rise to harmonically-rich voltages in the system resulting in interference to communication.

New problems such as the ones described above have not yet found a prominent place in existing text books written for a first full course in EMC and Dynamics of Electric Machines. The author has bridged this gap. In many engineering curricula, a first one-semester course in this subject might form the only course devoted to the principles, operation, and

*Please see "General" in Bibliography at the end of text.

design of electro-mechanical devices and machines. Therefore, the student must be provided with a strong background leading to appreciation of advanced problems in elective courses or post-graduate programmes. The contents of this book commence with the elements of electric and magnetic fields which are the reservoirs of energy storage and lead the student through principles of EMC, torque characteristics, a detailed analysis of the operating principles of D.C. machines, A.C. induction motors, synchronous machines, transformers and reactors, and finally to application of solid-state devices, and some aspects of design. The description of material in each of the ten chapters follows.

Chapter 1 deals with the theory and calculation of electric and magnetic fields with particular reference to electro-magnetic devices and machines. The laws of Coulomb and Ampere for the electrostatic and electro-magnetic fields are the starting points for developing the equations of Laplace and Poisson through the theorems of Green and Stokes, and finally Gauss's Law. These are applied for calculating the properties of simple field geometries and mechanical forces. The important method of Conformal Transformations is discussed which is followed by the Schwartz-Christoffel Transformation for straight boundaries. Numerical methods of field plotting are then described which can be used with Digital Computers. Magnetic circuit calculations are given for devices and a d-c machine.

The laws of Faraday-Lenz for electro-magnetic induction and Ampere's circuital law and force for electro-magnetic fields are described in Chapter 2. These form the basic laws for evaluating the performance equations of e.m. transducers such as the loudspeaker, pick-up, meters, relays, rotating machines, eddy-current brakes, Hall-Effect devices, Magneto-hydrodynamic generation of power, etc. The problem of hysteresis loss, eddy-current loss, temperature rise in insulation of devices and copper losses are then described. The design principles of electro-magnetic devices are given a detailed treatment from the energy point of view. The significance of co-energy is pointed out. The chapter concludes with the application of Lagrange's equations for the e.m. devices treated earlier from the Faraday-Lenz and Ampere's Laws.

Chapter 3 analyzes the basic phenomena of induced voltages, armature reaction, and torque of rotating machines. These are dealt with in connection with D.C. machines, synchronous machines, and rotating fields. A very detailed and rigorous treatment is provided of harmonic torques produced in machines fed by thyristors (SCR's). Forward- and backward torques at sub-synchronous, synchronous and super-synchronous speeds generated by these devices are presented.

In Chapter 4 the first 'machine' is presented. The author considers the Transformer and Reactor as important static types of machines and gives them equal importance as rotating machines as controlling the *operating* performance of a power system. Equivalent circuits of transformers, testing methods, regulation, efficiency, polarity are all covered. But the more important problems pertain to representing the transformer as a network device. Equivalent circuits of 3-winding transformers, the 3-phase connections, and voltage distribution in the winding on the incidence of a surge are given detailed treatment so that the student appreciates that transformers are very important parts of a system. This is followed by static reactive elements with thyristor-control for system improvement, and the problem of harmonic-generation and schemes used for suppression are discussed.

Chaper 5 deals with the D.C. machine, both generator and motor, with their applications after describing their performance characteristics. Speed control using solid-state devices are covered in Chapters 8 and 9 under Machine Dynamics and Application of Solid-State Devices.

The next machine to be covered is the 1-phase, 2-phase, and 3-phase induction motor, Chapter 6. Following classical methods, equivalent circuits are derived and the parameters are determined from suitable tests. Both the exact and approximate equivalent circuits for one phase of a motor are compared as regards performance characteristics, which is novel to this book. Principles of modern methods of speed control are given although the details of hardware are reserved for Chapter 9. The second half of the chapter introduces the Generalized Machine Theory following the work of Gabriel Kron. The equations dervied in phase quantities are transformed to reciprocal- and non-reciprocal forms in the d, q, O axes. The inverse transform is made. This material also forms the basis for understanding the axes transformations dealt with in the next chapter on Synchronous Machines.

Chapter 7 is a very detailed treatment of the Synchronous Machine in both the steady state and transient state. Cylindrical rotor and salient pole alternators and motors are covered commencing with the e.m.f. equation, breadth coefficient, distribution factor, and reduction of harmonics. Regulation, field excitation, fluxes existing in the machine under lagging, leading and unity power factors are fully discussed which gives an insight into the inner workings of the machines One aspect which is rarely dealt with in introductory text books is the calculation of synchronous-machine constants under steady-state and transient conditions. The author allows the student to calculate these quantities from the flux and current interactions. Thus, synchronous reactance, (both direct and quadrature axes), transient and subtransient reactance, negative-sequence reactance, and the resulting time constants are calculated by exciting the windings suitably.

The second half of Chapter 7 deals with Generalized Machine Theory. The two-reaction theory of Park, that of Clarke, and Kron are presented. The (d, q, O) and (α, β, γ) axes transformations are made and the advantages of the latter for multi-machine analysis when they are connected on the stator side are indicated. An example of performance of a machine under short-circuit using the generalized equations is worked out. The chapter concludes with problems of harmonic and sub-harmonic torques generated with series-compensation, faults and faulty synchronizing.

Chapter 8 deals with dynamics of electric machines. Open- and closed-loop working of D.C. machines resulting in speed and torque changes under voltage and mechanical load variations are analyzed. Tachometer control and constant speed and position servo operation are analyzed and their applications described. The dynamic performance of synchronous machine takes up most of this chapter. Parallel operation, load sharing, synchronization, hunting and small oscillations are discussed, giving a full insight into the physical phenomena. Damper windings are described. Transient stability is then taken up. Commencing with Crary's Equal-Area Criterion, and the simple pendulum, the student is led step-by-step in formulation of phase-plane equations and the Liapunov Stability Criterion. This will help a student with interest in advanced concepts of stability to understand the vast amount of technical literature in the field. The aim of the author is to provide a discussion of many types of methods of analysis so that the growth of knowledge of the student is not stunted. If the instructor feels like it, he may omit this portion from class-room instruction.

Chapter 9 is devoted to description of modern speed and torque control methods of rotating machines using solid-state devices, and improvements in machine performance using solid-state excitation systems. Phase control, cycloconverters, PWM, and many types of control are discussed. They are grouped into D.C. machine control, A.C. induction motor control, and synchronous machine control. Applications in industrial drives, traction, cement mills, etc., are mentioned.

The last Chapter, Chapter 10, deals with principles of design of transformers, and synchronous machines. No pains are spared in dealing with concepts such as optimum use of copper, iron, and insulation since the availability of digital computers has vastly improved these concepts, resulting in the important field of Computer Aided Design. In order to keep the length of the chapter to a minimum only principles are given which should help the student to design machines on his or her own.

RAKOSH DAS BEGAMUDRE

Acknowledgements

This text book has been the outcome of the author's practical experience at Messrs. Hitachi Ltd. in Japan, and teaching of under-graduate and post-graduate classes at the Universities of Mysore, Roorkee, Banaras, Lehigh, and the Royal Military College of Canada. He has been influenced in his learning and teaching, as well as setting up post-graduate courses at Universities in electric machinery (theory, operation and design), by four of his teachers and guides: Principal Manoranjan Sengupta at the Banaras Hindu University, Professor Kenneth Aston at the Roorkee University, Professor Loyal Vivian Bewley and Professor Archie R. Miller, both at the Lehigh University, Bethlehem, Pennsylvania. U.S.A.. His work in variable-speed drives using Solid-State devices was done while Manager of R. and D. for Walden North Laboratories in Lillooet, B.C., Canada. The author acknowledges his gratitude to all his venerable professors and to Mr. Vernon Pick, owner of Walden, who gave him a free hand in all matters of Research and Development.

The author's thanks are due to the personnel who typed the manuscript and did the drafting in an excellent manner and for their pleasant cooperation. He acknowledges the constant encouragement received from Dr. S.S. Prabhu, former Head, and Dr. P.K. Chatterjee, present Head of the Department of Electrical Engineering, I.I.T. Kanpur, and to Sri. H.S. Poplai, Publishing Manager, Wiley Eastern Ltd., for his continued interest. The author owes a debt of gratitude to Dr. A. Ghosh, Coordinator, Quality Improvement Programme at I.I.T. Kanpur for sanctioning funds through the Curriculum Development Cell for defraying the expenses involved in preparation of the manuscript. Finally, the author's heartfelt thanks are due to the Board of Governors of the I.I.T. Kanpur and the past Director, Professor S. Sampath, for having given him a Visiting Professorship which enabled completion of the present work.

"Ananda", 21, Ist Cross,
Kumarcot Layout, High Grounds,
Bangalore – 560 001

RAKOSH DAS BEGAMUDRE

Contents

Chapter 1

Electric and Magnetic Field Calculations

1.1 MAGNETIC CIRCUIT CALCULATIONS FOR DEVICES AND MACHINES

Electromechanical energy-conversion devices, of which electric machines form a major portion, depend on magnetic fields through which the energy conversion from electrical to mechanical and vice versa takes place. The magnetic fields are produced by electromagnets and permanent magnets. Where one part of the system has a translatory or rotary motion with respect to another, an airgap is necessary. This has very poor magnetic qualities as compared to other portions of the magnetic circuit which are usually made from good magnetic steels. The latter may work and usually do in the non-linear part of their B-H characteristic. Consequently, graphical methods are necessary for determination of excitation current in the coil of an electromagnet in order to set up a desired or prescribed flux density or flux in one part of the magnetic circuit. This section will deal with methods of calculation used for determining the excitation current when a magnetic circuit may comprise of magnetic materials with linear and non-linear magnetization characteristics.

Even though this chapter is entitled 'Electric and Magnetic Field Calculations', it is assumed that the reader has done a previous course or is familiar with all the methods of electric-circuit calculations. Therefore only magnetic circuit calculations will be discussed here, and in almost all cases, a parallel between the magnetic circuit and the electric circuit will be indicated. The idea is that the student will not find magnetic-circuit calculations any more difficult than electric-circuit calculations, with suitable and simple modifications to account for non-linearities.

1.1.1 Similarities Between Magnetic- and Electric-Circuit Quantities

Consider Fig. 1.1 which shows simple cases of a series electric circuit and

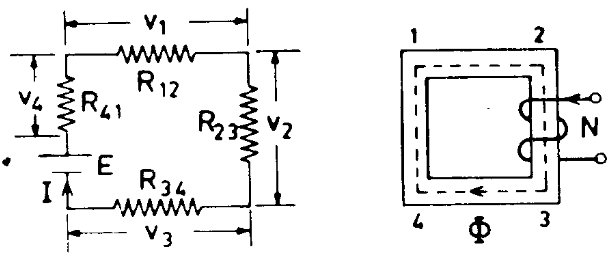


Fig. 1.1 Electric and magnetic circuit analogies

a magnetic circuit. The source of EMF in the electric circuit, shown as a dc source E, drives a current I through four resistances in series whose voltage drops are v_1, v_2, v_3, v_4. Evidently, $E = v_1 + v_2 + v_3 + v_4 = I(R_1 + R_2 + R_3 + R_4)$. Now, assuming for simplicity that the resistances are wire-wound, then $R = \rho l/a$, where ρ = specific resistance of the material (at a certain temperature), l = length of wire along the direction of current flow, and a = area of cross-section of wire at right angles to I. We will further assume that ρ is current-independent but only temperature-dependent. Further, since any voltage drop is $v = RI = \rho . l\ I/a$, we can write this as $(v/l) = \rho . (I/a)$, or, voltage drop per unit length = specific resistance × current density. If the areas of wire in the different resistances are unequal, the current densities will also be different for the same current. The above ideas can be directly transferred to a corresponding magnetic circuit.

The source of flux Φ in the magnetic circuit of Fig. 1.1 is the magnetomotive force (mmf) $M = NI_e$ in the coil, where N = number of turns and I_e is the excitation current in the coil. The magnetic circuit is also shown as having four parts in series so that the flux flowing in every part is the same. Each portion has a reluctance $R = l/(a\mu_0\mu_r)$, where l and a are obviously the length along Φ and the cross-section at right angles to the flux Φ. Also, for each part, there is a drop of MMF whose value is

$$m = R . \Phi = l . (\Phi/a) . (1/\mu_0\mu_r) \tag{1.1}$$

giving

$$m/l = H = (1/\mu_0\mu_r) . (\Phi/a) \tag{1.2}$$

where μ_0 = permeability of non-magnetic substance = $4\pi . 10^{-7}$ H/m, and
μ_r = relative permeability of the magnetic substance.

For all non-magnetic substances, $\mu_r = 1$, but for magnetic materials, $\mu_r (= B/H\mu_0)$ is a constant in the linear portion while in the non-linear portion μ_r depends on the induction B, the flux density.

We can now construct a short table showing similarities between electric-circuit and magnetic-circuit quantities.

Note that for iron and its compounds, the B-H relation, called the magnetization characteristic, is usually non-linear at high values of B. Some examples are shown in Fig. 1.2, which will be used for magnetic-circuit calculations in this chapter.

Table 1.1 Parallel Between Electric- and Magnetic-Circuit Quantities

No.	*Quantity*	*Symbol*	*Unit*
		Electric Circuit	
1	Electromotive force	E	Volt
2	Voltage drop	$v = RI$	Volt
3	Voltage gradient	$\mathcal{E} = v/l$	Volt/m
4	Current	$I = E/\Sigma R$	Amp.
5	Current Density	$J = I/a = \mathcal{E}/\rho$	Amp/m^2
6	Resistance	$R = \rho l/a = l/ag$	Ohm
7	Specific Conductance	$g = l/\rho$	Mho/m
8	Conductance	$G = 1/R = a/l\rho = ag/l$	Mho
9	$\mathcal{E}-J$ Relation (usually linear)	$\mathcal{E}/J = \rho$	Ohm-m
		Magnetic Circuit	
10	Magnetomotive Force	$M = NI$	Amp-Turn or Amp.
11	MMF drop	$m = R\Phi$	A-T or Amp.
12	Magnetizing Force or MMF per unit length or H-Field	$H = NI/$	A-T/m or, A/m
13	Flux	$\Phi = NI/\Sigma R$	Weber
14	Flux Density	$B = \Phi/a = \mu_0\mu_r H$	Tesla or Wb/m^2
15	Reluctance	$R = l/\mu_0\mu_r a$	AT/Wb or (Henry)$^{-1}$
16	Permeability	$\mu_0\mu_r$	Henry/m
17	Permeance	$P = 1/R = \mu_0\mu_r a/l$	Wb/AT
18	B-H Relation Linear for non-magnetic substances. Non-linear for ferro-magnetic materials at high values of B	$B/H = \mu_0\mu_r$	Henry/m

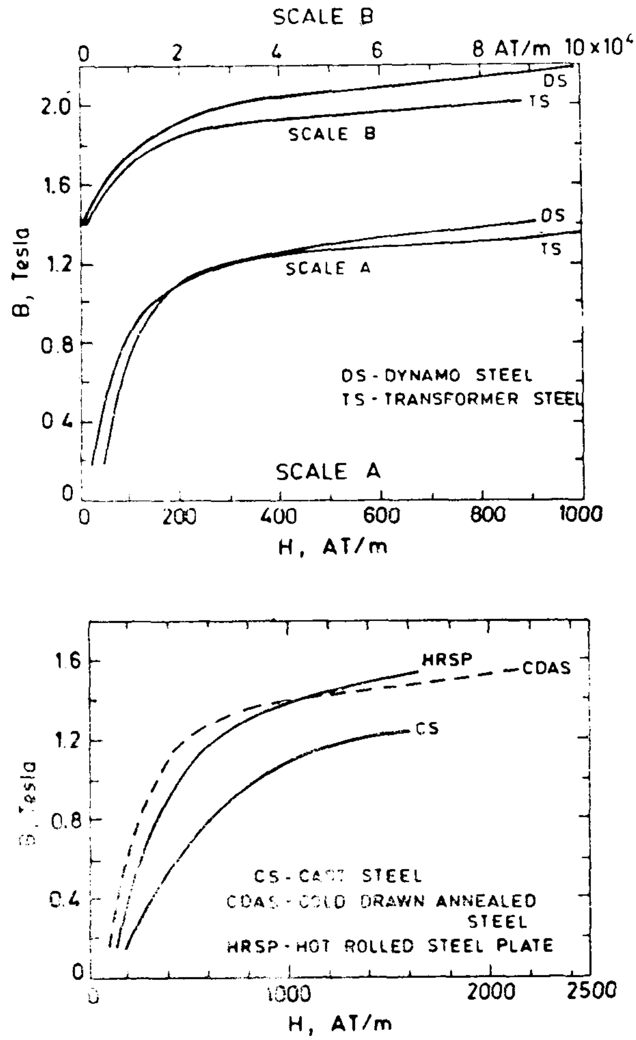


Fig. 1.2 Magnetization characteristics (B-H curves) for normally-encountered magnetic steels

1.1.2 Examples of Calculation of Series and Parallel Magnetic Circuits

EXAMPLE 1.1 Calculate the mmf required in the coil in Fig. 1.3 to set up a flux density of 1 Tesla between the pole faces through the airgap. The areas of pole faces and the rest of the magnetic circuit are 1 cm × 1 cm for calculation.

Solution The electrical equivalent circuit is shown on the right of the magnetic circuit which is a simple series circuit consisting of two resistances and a source of EMF. We assume that the area for flux flow through the