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Electrical Machines and Drives

An Introduction to Principles and Characteristics

J.D. Edwards

*Senior Lecturer
School of Engineering and Applied Sciences
The University of Sussex*

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Preface

This is an extensive revision of the second edition of *Electrical Machines* (Macmillan, 1986), incorporating the latest developments in electrical machines and drive systems. It retains the original aim of its predecessor: to give a short modern account of the principles of electrical machines and drives in a form accessible to the non-specialist, yet with sufficient rigour to provide a basis for more advanced studies. The first six chapters are unchanged in scope; they cover fundamental principles and the 'classical' electrical machines: DC commutator machines, AC synchronous machines and AC induction machines. The introduction to generalised machine theory has been removed, since it no longer seems appropriate in a text at this level. In its place are four new chapters on DC and AC drive systems.

Many applications of electrical machines require an adjustable speed. In the past this has been achieved with ingenious machines such as the AC commutator motors, or with constant-speed motors and mechanical variable-speed transmissions. These machines have been superseded by combinations of power electronic controllers and electrical machines which form the modern drive system. Chapters 7 and 8 cover the principles of power electronic controllers as applied to the classical AC and DC machines. Chapters 9 and 10 cover the newer non-classical machines which work in conjunction with special-purpose electronic controllers: stepper motors, electronically commutated (or brushless) DC machines, and switched reluctance motors.

A distinctive feature of the earlier book has been retained: a unified treatment of AC and DC machines based on the interaction of currents and magnetic fields, which gives a clear physical picture of the operating principles. The treatment is fully quantitative, and meets the requirements of rigour and simplicity by taking the simplest model of a machine which will demonstrate the essential features of its operation. Departures from the ideal are mentioned only briefly, since these form the subject of specialised study.

AC machines generally give students the most difficulty; a feature of this book is a novel approach to AC machines, introduced in chapter 4 and developed in chapters 5 and 6. Traditionally, the concepts of MMF and flux dominate the theory; these are useful concepts, but they make the action of the machine difficult to visualise because they are one step removed from the fundamental current and field. I have therefore based the theory on the concepts of current density and flux density. These concepts give an immediate picture of the electromagnetic action; they also lead directly to the rotating field principle, the torque equation and the equivalent circuit.

The reader is assumed to have an elementary knowledge of electromagnetism, circuit theory, and vectors. Background material is listed in the Bibliography at the end of the book. Space has limited the number of worked examples and problems for solution. In general the problems at the ends of the chapters are not straightforward, and they extend the material of the chapter. Readers who require more problems and worked examples will find them in the books listed in the Bibliography.

I wish to thank the Controller of Her Majesty's Stationery Office and the Longman Group for permission to reproduce figures 1.36 and 2.12 respectively, and several manufacturers, acknowledged in the text, for photographs of machines. I am grateful to reviewers and my university colleagues for suggestions; to second-year engineering students for encouraging me to find better ways of presenting machine theory; and to my wife for many hours of work with the computer in preparing both text and drawings.

J. D. Edwards

Notation, Units and Symbols

SI units are used throughout the book, and the recommendations of the British Standards Institution [1] are followed for unit names and symbols. With electrical quantities, the usual convention is followed in denoting time-varying values by lower-case symbols and steady values or magnitudes by upper-case symbols. Three kinds of vector quantity occur in the book: space phasors, time phasors and three-dimensional vectors. Bold-face type is used for all these quantities, in line with normal practice, for example ***I***, ***B***. In some cases the same symbol may be used for a field vector or a space phasor; the context will always show which meaning is intended.

In general the recommendations of the Institution of Electrical Engineers [2] and the British Standards Institution [3] have been followed for symbols, abbreviations and subscripts. One exception is the symbol for linear current density; the recommended symbol ***A*** seems a poor choice because it is the established symbol for magnetic vector potential, and distinct symbols for both quantities are needed in advanced work. The symbol chosen is ***K***, which follows Stratton [4] and some current practice.

There is one area of notation in which no uniformity exists: the choice of symbols for the infinitesimal elements in line, surface and volume integrals. After careful consideration the notation adopted is that of Stratton [4], in which ds , da and dv denote the elements of path length, area and volume respectively. This is a consistent and convenient notation; it justifies the use of the subscript *s* for the tangential component of a vector; it releases capital letters for designating finite regions or quantities; and there is no confusion in advanced work between the symbols for length or area and the Poynting vector ***S*** or the vector potential ***A***.

The following lists refer only to the usage in this book. Further information will be found in the references already cited and in Massey [5].

List of principal symbols

<i>Symbol</i>	<i>Quantity</i>	<i>Unit</i>	<i>Unit symbol</i>
A	area	square metre	m^2
a	radius	metre	m
B, B	magnetic flux density	tesla	T
B	flux density phasor	tesla	T
C	capacitance	farad	F
da, da	element of area	square metre	m^2
ds, ds	element of path length	metre	m
dv	element of volume	cubic metre	m^3
E, E	electric field strength	volt/metre	V/m
$E; E$	excitation voltage phasor; RMS magnitude	volt	V
$E; E$	induced EMF phasor; RMS magnitude	volt	V
E, e	electromotive force	volt	V
F, F	mechanical force	newton	N
F	magnetomotive force	ampere	A
F_x	x component of force	newton	N
f, f	force per unit volume	newton/metre ³	N/m^3
f	frequency	hertz	Hz
g	airgap length	metre	m
H, H	magnetising force	ampere/metre	A/m
$I; I$	current phasor; RMS magnitude	ampere	A
I_0	no-load current	ampere	A
I_{01}	loss component of I_0	ampere	A

I_{0m}	magnetising component of I_0	ampere	A
I, i	current	ampere	A
J, J	current density	ampere/metre ²	A/m ²
J	moment of inertia	kilogram metre ²	kg m ²
j	$\pi/2$ operator, $\sqrt{(-1)}$	—	—
K, K	linear current density	ampere/metre	A/m
K	current density phasor	ampere/metre	A/m
K	DC machine constant	{ volt second/weber radian newton metre/ampere ²	{ V s/Wb rad N m/A ²
K_a	armature constant	{ volt second/ampere radian newton metre/weber ampere	{ V s/A rad N m/Wb A
K_f	field constant	weber/ampere	Wb/A
k	torque constant	newton metre/tesla ²	N m/T ²
L	self-inductance	henry	H
L_m	magnetising inductance	henry	H
l	leakage inductance	henry	H
l	length	metre	m
M	mutual inductance	henry	H
m	number of phases	—	—
N	number of turns	—	—
n	Steinmetz index	—	—
n	turns ratio	—	—
P	power	watt	W
P_e	electrical power	watt	W
P_m	mechanical power	watt	W
p	d/dt operator	1/second	1/s
p	number of pole pairs	—	—

<i>Symbol</i>	<i>Quantity</i>	<i>Unit</i>	<i>Unit symbol</i>
p_e	eddy current power loss per unit volume	watt/metre ³	W/m ³
p_h	hysteresis power loss per unit volume	watt/metre ³	W/m ³
q	electric charge	coulomb	C
R	resistance	ohm	Ω
R_e	equivalent total resistance	ohm	Ω
R_c	core loss resistance	ohm	Ω
r	radius	metre	m
S	reluctance	ampere/weber	A/Wb
s	fractional slip	—	—
T	torque	newton metre	N m
T_m	mechanical output torque	newton metre	N m
T_θ	torque associated with angle θ	newton metre	N m
t, t	stress	newton/metre ²	N/m ²
t	time	second	s
U	magnetic potential difference	ampere	A
u, u	linear velocity	metre/second	m/s
$V; V$	voltage phasor; RMS magnitude	volt	V
V, v	terminal voltage, electric potential difference	volt	V
W	energy, work done	joule	J
W_e	electrical energy	joule	J
w_h	hysteresis energy loss per unit volume	joule/metre ³	J/m ³

W_m	magnetic stored energy	joule	J
X	reactance	ohm	Ω
X_e	equivalent total reactance	ohm	Ω
X_m	mutual or magnetising reactance	ohm	Ω
X_s	synchronous reactance	ohm	Ω
x	leakage reactance	ohm	Ω
Z, Z	impedance	ohm	Ω
Z	maximum linear conductor density	1/metre	1/m
α, β, γ	general angles	radian	rad
δ	load angle, angle between magnetic field axes	radian	rad
δ	depth of penetration	metre	m
ϵ	voltage regulation	—	—
η	efficiency	—	—
θ	angular displacement, rotor angle	radian	rad
Λ	permeance	weber/ampere	Wb/A
λ_h	Steinmetz coefficient	—	—
μ	absolute permeability = $\mu_0 \mu_r$	henry/metre	H/m
μ_0	magnetic constant = $4\pi \times 10^{-7}$	henry/metre	H/m
μ_r	relative permeability	—	—
ρ	charge per unit volume	coulomb/metre ³	C/m ³
ρ	resistivity = $1/\sigma$	ohm metre	Ω m
σ	conductivity = $1/\rho$	siemens/metre	S/m
τ	time constant	second	s
τ_{em}	electromechanical time constant	second	s

<i>Symbol</i>	<i>Quantity</i>	<i>Unit</i>	<i>Unit symbol</i>
Φ	magnetic flux phasor	weber	Wb
Φ	magnetic flux, flux per pole	weber	Wb
Φ_l	leakage flux	weber	Wb
ϕ	phase angle, angular displacement	radian	rad
ψ	angular displacement	radian	rad
Ω, ω	angular velocity	radian/second	rad/s
ω	angular frequency = $2\pi f$	radian/second	rad/s
ω_r	rotor angular velocity	radian/second	rad/s
ω_s	synchronous angular velocity	radian/second	rad/s

General subscripts

a	armature
av	average
f	field
m, max	maximum value
n	normal component
r	radial component
s	tangential component
1, 2	primary, secondary; stator, rotor
α, β	two-phase quantities
a, b, c	three-phase quantities

Decimal prefixes

10^6	mega	M
10^3	kilo	k
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ

Abbreviations

AC	alternating current
DC	direct current
EMF	electromotive force
MMF	magnetomotive force
rev/min	revolutions per minute
rev/s	revolutions per second
RMS	root-mean-square

References

- 1 BS 3763, *The International System of Units (SI)* (London: British Standards Institution, 1976).
- 2 IEE, *Symbols and Abbreviations for Electrical and Electronic Engineering*, 3rd ed. (London: Institution of Electrical Engineers, 1980).
- 3 BS 5775, *Specification for Quantities, Units and Symbols* (London: British Standards Institution, 1982).
- 4 J. A. Stratton, *Electromagnetic Theory* (New York: McGraw-Hill, 1941).
- 5 B. S. Massey, *Units, Dimensional Analysis and Physical Similarity* (London: Van Nostrand Reinhold, 1971).