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Brushless Permanent-Magnet and Reluctance Motor Drives

T. J. E. MILLER



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Preface

The impulse to write this book was most recently inspired by the publication of Professor Kenjo's books in the same series, the idea being to extend the coverage and provide more detail on synchronous brushless motors and the switched reluctance motor. However, the basic idea of a book in this area goes back several years to a period of particularly interesting developments under the Motor Technology Program at the Corporate Research and Development Center of General Electric in Schenectady, New York. This programme was coupled with exciting developments in semiconductors and power electronics (Baliga 1987), as well as with rapid changes in the technology of motor drives originating in all parts of the developed world. While I was privileged to participate in this programme I also had the benefit of having worked under Professor Peter Lawrenson at Leeds University. The pressures of business prevented any writing until I accepted my present post at Glasgow University, which is supported by GEC, UK. The Scottish Power Electronics and Electric Drives Consortium (SPEED), established in 1986 and modelled on the Wisconsin Electric Machines and Power Electronics Consortium, has provided an environment for further analysis and experimentation, as well as new results and perspectives, and an appreciation of the need for a text in this area. In writing it, I claim no credit for the original inventions or for anything more than a small part in their subsequent development; the book is merely intended as a reasonably organized account of the fundamental principles.

It is hoped that this presentation of the theory of operation of brushless d.c. drives will help engineers to appreciate their potential and apply them more widely, taking advantage of remarkable recent developments in permanent-magnet materials, power semiconductors, electronic control, and motor design (including CAD). The objective is not to 'sell' particular technologies or teach design, but to lay out the basic principles, and it is hoped that this will raise the general credibility and acceptance of new technology that many engineers have striven to establish. It is also hoped that the sections on permanent magnets and magnetic circuits will assist in the exploitation of new PM materials with outstanding properties greatly improved from those of only a few years ago.

It is humbling to realize how much scope for innovation remains in the field of motors and drives, even a century and a half after Faraday. Yet in the academic world the subject of motor design and power engineering more generally has fallen into such decline that the demand for power engineers exceeds the supply, and motor designers are scarce. Some of the present material was developed for courses at Drives, Motors, and Controls Conference and at the University of Wisconsin, and this book is addressed to

some of industry's educational needs. Examples and problems are included, many of which were developed as tutorial material for (and by!) students at Glasgow University.

The approach taken is essentially academic: theory and calculation predominate, and the really difficult questions of comparisons between different drives, and the design of particular ones, are treated only lightly. It is hoped, however, that most of the basic theory of modern brushless drives will be found here. The treatment of magnetic saturation is given less attention than in classical works on electric motors: in the design of brushless motors, it is important to grasp the first principles, which can be understood, in the main, from linear theory. The widespread availability of finite-element analysis, and its ever-improving capability, make the problems of saturation much more tractable and relieve the need for a more complex analytical approach, which would be exceedingly complex before it could be really useful.

If nothing else, a study of brushless motor drives will lead to a further appreciation of the extraordinary properties of conventional motors, particularly the d.c. commutator motor and the a.c. induction motor, and will throw a little light on the achievements of our forebears. The arrival of silicon power electronics has reopened all the fundamental questions, and added a new dimension to the equation that has for so long been dominated by copper and iron.

Glasgow
April 1988

T. J. E. M.

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To my family and friends

Glossary of symbols

a	no. of parallel paths in winding		d	duty-cycle (of p.w.m.)	
A	area	m^2	D	stator bore diameter	m
A	electric loading	A/m			
A_m	magnet pole area	m^2	δ	phase angle defined on p. 136	deg or rad
α	angular acceleration	rad/s ²			
α	phase angle	deg or rad	e	instantaneous e.m.f.	V
α	overlap angle	deg or rad	e_0	per-unit value of E_0	p.u.
α	pole arc/pole-pitch ratio		E	r.m.s. e.m.f.	p.u.
			E_{dw}	e.m.f. ascribed to web flux	$V_{r.m.s.}$
β	torque angle	deg or rad	E_q	open-circuit e.m.f. due to magnet	$V_{r.m.s.}$
β	pole arc	deg or rad	E_0	value of E or E_q at corner-point or base frequency	$V_{r.m.s.}$
B	flux density	T			
B	magnetic loading (p. 22)	T	ϵ	chording angle	deg or rad
B_g	airgap flux-density (radial)	T	ϵ	step angle	deg or rad
B_r	remanent flux-density	T	f	frequency	Hz
B_s	saturation flux-density	T	F	magnetomotive force (m.m.f.)	A t
			F	mechanical force	N
C	commutation flux		F_m	m.m.f. across magnet	A t
C_Φ	concentration factor				
γ	slot pitch	elec deg or rad	ϕ	flux	Wb
γ	phase angle defined on p. 102	deg or rad	ϕ	power factor angle	deg or rad
γ	phase angle defined on p. 136	deg or rad	Φ	flux	Wb
γ	fraction defined on p. 113		Φ_g	airgap flux (per pole)	Wb

Φ_{M1}	fundamental magnet flux per pole	Wb	k	armature constant (p. 66)	
Φ_r	remanent flux of magnet	Wb	k	frequency ratio defined on p. 107	
Φ_y	flux in one link	Wb	k	coupling coefficient	
g	airgap length	m	k_{w1}	fundamental harmonic	
g'	effective airgap length $K_c g$	m	k_{d1}	winding factor fundamental distribution factor	
g''	effective airgap length allowing for magnet	m	k_{p1}	fundamental pitch (chording) factor	
g_d''	effective airgap length in direct-axis, allowing for magnet	m	k_{s1}	fundamental skew factor	
g_q''	effective airgap length in quadrature-axis	m	k_w	winding factor for inductance	
H	magnetizing force or magnetic field strength	A t/m	k_{ad}	defined on p. 129	
H_c	coercive force	A t/m	k_{1ad}	defined on p. 130	
H_{ci}	intrinsic coercivity	A t/m	K_c	Carter's coefficient (p. 60)	
i	current (instantaneous)	A	l_k	effective length of core or keeper	m
I	r.m.s. current or d.c. current	$A_{r.m.s.}$	l_m	magnet length (in dir'n of magnetization)	m
I_c	controller maximum current	$A_{r.m.s.}$	L	inductance	H
J	current density	A/m ²	L_a	aligned inductance	H
J	magnetization	T	L_u	unaligned inductance	H
J	polar moment of inertia	kg m ²	l	stack length	m
J_m	motor inertia	kg m ²	λ	inductance ratio	
J_L	load inertia	kg m ²	M	mutual inductance	H
k	peak/continuous torque ratio (p. 27)		μ	permeability	H/m
			μ_r	relative permeability	

μ_{rec}	relative recoil permeability		θ	angular coordinate; rotor position	deg or rad
n	gear ratio		θ_D	dwelt angle; conduction angle (of main switches)	deg or rad
n	speed	rev/sec			
n	no. of phases or phaselegs (Ch. 7)				
N	speed	r.p.m.			
N	no. of turns		r_0	rotor slot-bottom radius	m
N_p	no. of turns per pole		r_1	rotor outside radius (Ch. 7)	m
N_{ph}	no. of series turns per phase		r_1	stator bore radius (Ch. 4-6)	m
N_r	no. of rotor poles		r_2	stator slot-bottom radius	m
N_s	no. of stator poles		r_3	stator outside radius	m
N_s	no. of series turns per phase of sine-distributed winding or equivalent sine-distributed winding		R	resistance (of phase winding)	Ohm
N_1	no. of turns in coil 1, etc.		R	reluctance	A t/Wb
p	no. of pole pairs		R_g	airgap reluctance	A t/Wb
P	permeance	Wb/A t	s	split ratio (p. 23)	
P_{m0}	magnet permeance	Wb/A t	σ	airgap shear stress	kN/m ² or p.s.i.
P_m	magnet permeance including rotor leakage	Wb/A t	σ	half the skew angle	mech deg or rad
P_{r1}	rotor leakage permeance	Wb/A t	t	time	s
P	power	W	T	temperature	deg C
PC	permeance coefficient		T	torque	Nm
q	no. of slots per pole per phase (Ch. 5)		T_a	average torque	Nm
q	no. of phases (Ch. 7)		TRV	torque per rotor volume	Nm/m ³
			u	magnetic potential	A t
			v	linear velocity	m/s
			v	voltage (instantaneous)	V
			V	voltage (d.c. or r.m.s. d.c.)	V
			V_c	controller max. voltage	V _{r.m.s.}
			V_c	copper volume	m ³

V_m	magnet volume	m^3	ω_b	'base' or 'corner-point' speed	rad/s
V_r	rotor volume	m^3	ω_m	mech. angular velocity ω/p (Ch. 5, 6)	mech rad/s
w	web width	m			
w_m	magnet width	m			
W	energy	J			
W	conversion energy per stroke	J			
W'	coenergy	J			
W_f	stored field energy	J			
x	per-unit reactance	p.u.			
X	reactance	Ohm			
X_s	synchronous reactance	Ohm			
X_{s0}	value of X_s at corner-point	Ohm			
X_d	direct-axis synchronous reactance	Ohm			
X_q	quadrature-axis synchronous reactance	Ohm			
X_σ	armature leakage reactance	Ohm			
y	link width	m			
ψ	flux-linkage (in Ch. 7, of phase winding)	V s or Wb t			
ω	elec. angular velocity = $2\pi f$ (in Ch. 5-6)	elec rad/s			
ω	mech. angular velocity (Ch. 7)	mech rad/s			

Subscripts

a	armature-reaction
a	aligned
a	average
a, b, c	phases a, b, c
d	direct-axis
e	electrical, electromagnetic
g	airgap; airgap flux
L	load
m	mechanical
m, M	magnet
mc	maximum continuous
mp	peak rated
ph	phase
q	quadrature
r	rotor
s	stator
s	saturated
u	unaligned
w	winding factor
0	corner-point or 'base' value
1	fundamental harmonic component
1, 2	pertaining to coils 1, 2 (Ch. 4)
1, 2, 3	phases

Superscripts

u	unsaturated
~	phasor (complex quantity)
^	peak (of sinewave)

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