Electrical Machine Drives Control

An Introduction

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Preface

A basic study of electrical drives is fundamental to an electrical engineering curriculum, and, today, gaining a better academic understanding of the theory and application of controlled-velocity electrical drive technologies is increasingly important. Electrical drives provide superior control properties for a wide variety of processes, and the number of applications for precision-controlled motor drives is increasing. A modern electrical drive accurately controls motor torque and speed with relatively high electromechanical conversion efficiencies, making it possible to considerably reduce energy consumption. Because of the present pervasive use of electric machinery and the associated large energy flows, the introduction of more effective and efficient electrical drives promises significant environmental benefit, and electrical engineers are responding by introducing new and more efficient electrical drives to a myriad of industrial processes.

A controlled-velocity electrical drive combines power electronics, *electric machinery*, a *control system*, and drive mechanisms to apply force or torque to execute any number of desired functions. The term *electric machinery* refers primarily to the electromagnetic mechanical devices that convert electricity to mechanical power or mechanical power to electricity—that is, to electric motors or generators. The term *control system* refers to the control electronics, instrumentation, and coding that monitor the condition of the electric machinery and adjust operating speed and/or match force or torque to load.

With a rigorous introduction to theoretical principles and techniques, this academic reference and research book offers the master of science or doctoral student in electrical engineering a textbook that provides the background needed to carry out detailed analyses with respect to controlled-velocity electrical drives. At the same time, for engineers in general, the text can serve as a guide to understanding the main phenomena associated with electrical machine drives. The edition includes up-to-date theory and design guidelines, taking into account the most recent advances in the field. The years of scientific research activity and the extensive pedagogical skill of the authors have combined to produce this comprehensive approach to the subject matter. The considered electric machinery consists of not only classic rotating machines, such as direct current, asynchronous, and synchronous motors and generators, but also new electric machine architectures that have resulted as the controller and power electronics have continued to develop and as new materials, such as permanent magnets, have been introduced. Examples covered include permanent magnet synchronous machines, switched reluctance machines, and synchronous reluctance machines.

The text is comprehensive in its analysis of existing and emerging electrical drive technologies, and it thoroughly covers the variety of drive control methods. In comparison to other books in the field, this treatment is unique. The authors are experts in the theory and design of electric machinery. They clearly define the most basic electrical drive concepts and go on to explain the critical details while maintaining a solid connection to theory and design of the associated electric machinery. Addressing a number of industrial applications, the authors take their investigation of electrical drives beyond theory to examine a number of practical aspects of control and application. Scalar, vector, and direct torque control methods are thoroughly covered with the nonidealities of direct torque control being given particular focus.

The expert body of knowledge that makes up this book has been built up over a number of years with contributions from numerous colleagues from both the Lappeenranta University of Technology and the University of Žilina in Slovakia. The authors are grateful for their help.

In particular, the authors would like to thank Professor Tapani Jokinen for his extensive contributions in general, Professor Olli Pyrhönen for his expert guidance on the control of synchronous electrical machine drives, Dr. Pasi Peltoniemi for the detailed and valuable example on tuning the control of an electrically excited synchronous machine, and M.Sc. Juho Montonen for his permanent magnet machine analysis. The authors would also like to specifically thank Dr. Hanna Niemelä, who translated some of the included text from its original Finnish. Finally, we give our warmest thanks to our families, who accommodated our long hours of writing, editing, and manuscript preparation.

This academic reference and research book uniquely provides comprehensive materials concerning all aspects of controlled-velocity electrical drive technology including control and operation. The treatise is based on the authors' extensive expertise in the theory and design of electric machinery, and in contrast to existing publications, its handling of electrical drives is solidly linked to the theory and design of the associated electric machinery.

Abbreviations and Symbols

A	magnetic vector potential [Vs/m], linear current density [A/m]
AC	alternating current
AM	asynchronous machine
ASIC	application-specific integrated circuit
A1–A2	armature winding terminals of a DC machine
AlNiCo	aluminium nickel cobalt permanent magnet
A	transmission ratio
B	magnetic flux density, vector [T] [Vs/m^2]
B	magnetic flux density, scalar [T] [Vs/m^2]
BLDC	brushless DC motor
B1–B2	commutating pole winding of a DC machine
C	capacitance [F], machine constant, speed of light [m/s]
C_E	constant, function of machine construction
C_T	torque producing dimensionless factor
C1–C2	compensating winding of a DC machine
$C_{io,i}$	outer or inner capacitance between the ball and the race in the ball bearing [F]
C_g	capacitance between the races of the ball bearing [F]
C_{01}, C_{02}	capacitance of the filter [F]
C_{wf}	capacitance between the stator winding and the stator frame [F]
C_{wr}	capacitance between the stator winding and the rotor core [F]
C_{sr}	capacitance between the stator and rotor cores [F]
c	experimentally determined coefficient, distributed capacitance [F/m]
c/h	duty cycles per hour
c'	capacitance per unit length [F/m]
CENELEC	Comité Européen de Normalisation Electrotechnique
CHP	combined heat and power
CSI	current source inverter
D	diameter [m], friction coefficient, code (drive end)
D1, D2	diode 1, diode 2
$D\Omega$	viscous friction, frictional torque
DC	direct current
DFIG	doubly fed induction generator
DFIM	doubly fed induction motor
DFLC	direct flux linkage control
DTC	direct torque control
D1–D2	series magnetizing winding terminals of a DC machine

d	thickness [m], axis
DOL	Direct On Line
DSC	Direct Self Control
E	electromotive force (emf) [V], RMS, electric field strength [V/m], scalar
E_{PMph}	phase value of emf induced by PM [V]
emf	electromotive force [V]
$\boldsymbol{E}$	electric field strength, vector [V/m]
ESR	equivalent series resistance [Ω]
e	electromotive force [V], instantaneous value $e(t)$ or per-unit value
$\boldsymbol{e}_{\mathrm{s}}$	back electromotive force vector induced by the stator flux linkage ψ_{s} [V] or per-unit value
e_{m}	back electromotive force induced by the air gap flux linkage ψ_{m} [V] or per-unit value
F	force [N], scalar
$\boldsymbol{F}$	force [N], vector
F1, F2	terminals of field winding
FEA	finite element analysis
FLC	flux linkage control
FOC	field oriented control
FPGA	field programmable gate array
F_{m}	magnetomotive force $\oint \boldsymbol{H} \cdot \mathrm{d}\boldsymbol{l}$ [A], (mmf)
FPGA	field-programmable gate array
f	frequency, characteristic oscillation frequency [Hz], or per-unit value
f_{sw}	switching frequency [Hz] or per-unit value
g	distributed conductance [S/m]
G_{m}	transfer function
G_{ce}	closed loop transfer function
GTO	gate turn-off thyristor
H	magnetic field strength [A/m]
h_{PM}	height of permanent magnet material [m]
I	electric current [A], RMS
IE1, 2, 3, 4	efficiency classes
IC	cooling methods
IGBT	insulated-gate bipolar transistor
IGCT	integrated gate-commutated thyristor, integrated gate controlled thyristor
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IM	induction motor
Im	imaginary part
IP	enclosure class
$i(t)$	instantaneous value of current [A]
i_{B}	base value for current [A]
I_{k}, I_{s}	starting current [A]
I_{st}	locked rotor current (starting) [A]
I_{ef}	effective load current [A]
i_{a}	armature current [A]
i_{com}	common current linkage [A]

i_f	field current [A]
$\boldsymbol{i}_m$	magnetizing current space vector [A] or per-unit value
i_{PM}	PM represented by a current source in the rotor [A] or per-unit value
i_{PE}	current in the protective earth wire of the motor cable [A] or per-unit value
i_{mPE}	earthing current [A] or per-unit value
J	moment of inertia [kgm^2], inertia, current density [A/m^2], magnetic polarization [Vs/m^2]
J_m	moment of inertia of the motor [kgm^2]
J_{load}	load moment of inertia [kgm^2]
J_{tot}	total moment of inertia [kgm^2]
j	imaginary unit
K	kelvin, transformation ratio, constant
K_p	amplification
k	coupling factor
k_C	Carter factor
k_d	distribution factor
k_{gain}	gain coefficient
k_p	pitch factor
k_{ri}	reduction factor (current ratio of synchronous machine)
k_{riav}	ratio of magnitudes of the current space vectors
k_{rs}	transformation ratio between stator and rotor
k_{sq},k_{sk}	skewing factor
k_w	winding factor
$k_w N$	effective number of turns
L	inductance [H]
L_c	choke
LCI	load commutated inverter
L_D	total inductance of the direct damper winding [H] or per-unit value
$L_{D\sigma}$	leakage inductance of the direct damper winding [H] or per-unit value
L_d	direct axis synchronous inductance [H] or per-unit value
L_{dD}	mutual inductance between the stator equivalent winding on the d-axis and the direct equivalent damper winding [H] or per-unit value
L_{dF}	mutual inductance between the stator equivalent winding on the d-axis and the field winding (in practice L_{md}) [H] or per-unit value
L'_s	transient inductance [H] or per-unit value
L'_d	direct axis transient inductance [H] or per-unit value
L''_d	direct axis subtransient inductance [H] or per-unit value
L_f	total inductance of the field winding [H] or per-unit value
L_F	inductance of the DC field winding [H] or per-unit value
$L_{f\sigma}$	leakage inductance of the field winding [H] or per-unit value
L_k	short-circuit inductance [H] or per-unit value
$L_{k\sigma}$	mutual leakage inductance between the field winding and the direct damper winding, i.e., the Canay inductance [H] or per-unit value
L_m	magnetizing inductance [H] or per-unit value
L_{md}	magnetizing inductance of an m-phase synchronous machine, in d-axis [H] or per-unit value
L_{mn}	mutual inductance [H] or per-unit value

L_{mq}	quadrature magnetizing inductance [H] or per-unit value
L_Q	total inductance of the quadrature damper winding [H] or per-unit value
$L_{Q\sigma}$	leakage inductance of the quadrature damper winding [H] or per-unit value
L_{pd}	main inductance of a single phase [H] or per-unit value
L_p	main inductance of a single phase [H] or per-unit value
L_q	quadrature axis synchronous inductance [H] or per-unit value
L''_q	quadrature axis subtransient inductance [H] or per-unit value
L_{qQ}	mutual inductance between the stator equivalent winding on the q-axis and the quadrature equivalent damper winding (in practice L_{mq}) [H] or per-unit value
L_0	equivalent inductance [H] or per-unit value
L_{m0}	magnetizing inductance at no load at the rated stator flux level or per-unit value
LSRM	linear switched reluctance machine
L_s	stator synchronous inductance [H] or per-unit value
$L_{s\sigma}$	stator leakage inductance [H] or per-unit value
L_{01}, L_{02}	inductance of the filter [H] or per-unit value
L'	transient inductance [H] or per-unit value
L''	subtransient inductance [H] or per-unit value
L1, L2, L3	network phases
l	length [m], magnetizing route [m], distance [m], relative inductance, distributed inductance [H/m]
l_{cr}	critical cable length [m]
l_e	effective core length [m]
l'	equivalent core length, effective machine length [m], inductance per unit length [H/m]
M	mutual inductance [H], or per-unit value
M	modulation index
MMF	magnetomotive force [A]
m	number of phases, mass [kg]
m_a	amplitude modulation ratio
m_f	frequency modulation ratio
m'	phase number of the reduced system
m_0	constant
N	number of turns in a winding, magnetic north pole, code (nondrive end)
N_p	number of turns of one pole pair
NdFeB	neodymium iron boron permanent magnet
NEMA	National Electrical Manufacturers Association
NPC	neutral point clamped (inverter)
$\boldsymbol{n}$	normal unit vector of the surface
n	number of teeth, number of units determined by the subscript
pu	per unit
P	power, losses [W] or per-unit value
P_{ef}	effective power [W]
P_e	electrical power [W] or per-unit value
P_{el}	electrical power [W] or per-unit value
P_{in}	input power [W] or per-unit value

P_{mec}	mechanical power [W] or per-unit value
PE	protective earth wire of the motor cable
PID	proportional-integrating-differentiating controller
PMSM	permanent magnet synchronous motor (or machine)
PWM	pulse-width-modulation
PM	permanent magnet
PMaSynRM	permanent magnet assisted synchronous reluctance motor
MTPV	maximum torque per volt
MTPA	maximum torque per ampere
P_{ρ}	friction loss [W] or per-unit value
p	number of pole pairs
Q	electric charge [C], number of slots
q	number of slots per pole and phase, instantaneous charge, $q(t)$ [C]
R	resistance [Ω] or per-unit value
R_{ball}	resistance of the ball of the ball bearing [Ω]
R_{ri}	resistance of the inner race of the ball bearing [Ω]
R_{ro}	resistance of the outer race of the ball bearing [Ω]
R_{D}	resistance of the direct damper winding [Ω] or per-unit value
R'_{E}	representing the part of mechanical power associated with R_r
R_{f}	resistance of the field winding [Ω] or per-unit value
R_{F}	resistance of the field winding [Ω] or per-unit value
RM	reluctance machine
RMS	root mean square
R_{s}	stator resistance [Ω]
R_{Q}	resistance of the quadrature damper winding [Ω] or per-unit value
R_{01},R_{02}	resistance of the filter [Ω] or per-unit value
r	radius [m], distributed resistance [Ω/m]
$\boldsymbol{r}$	radius unit vector
S1–S9	duty types of electrical machines
S	apparent power [VA], or per-unit value, surface [m^2]
S	switch, magnetic south pole
SM	synchronous motor
SR	switched reluctance
SRM	switched reluctance motor
SynRM	synchronous reluctance motor
SVM	space vector modulated inverters
S_{st}	maximum permitted starting apparent power [VA] or per-unit value
S_{PE}	power processing ability required by power electronics [VA] or per-unit value
S_U, S_V, S_W	switching function variables
SmCo	samarium cobalt permanent magnet
SynRM	synchronous reluctance machine
s,	slip, Laplace domains operator
s_b	slip at T_b
s_0	base slip value
T	temperature [K] [°C], duration [s], torque [Nm], cycle time of the oscillation [s]
T1, T2	transistor 1, transistor 2

TEFC	totally enclosed fan cooled
T_{sub}	duration of the subsequent of the modulation [s]
ΔT	temperature rise [K] [°C]
$\boldsymbol{T}$	torque space vector [Nm] or per-unit value
T_b	pull out torque, breakdown torque [Nm] or per-unit value
T_{em}	electromagnetic torque [Nm] or per-unit value
T_e	electromagnetic torque [Nm] or per-unit value
T_L	load torque [Nm] or per-unit value
T_{max}	maximal torque [Nm] or per-unit value
T_N	nominal, rated torque [Nm] or per-unit value
$T_{pull\text{-}in}$	synchronizing torque [Nm] or per-unit value
T_s	starting torque [Nm] or per-unit value
T_{wL}	working torque of the load [Nm] or per-unit value
t_0	operating period [s]
t_c	commutation period [s]
t_{cef}	effective cooling period [s]
T_l	starting torque, locked rotor torque [Nm] or per-unit value
T_u	minimum torque [Nm] or per-unit value
T_I	integrating time constant [s]
T_D	differentiating time constant [s]
t	time [s]
$\boldsymbol{t}$	tangential unit vector
t_j	cycle time [s]
t_p	time of pulse propagation (wave propagation time) [s]
t_r	rise time, duration of converter pulse [s]
U	voltage [V], RMS
U_d	supply voltage [V]
$U_{DC,meas}$	measured intermediate voltage [V]
U	depiction of a phase
u	voltage, instantaneous value $u(t)$, incoming voltage [V] or per-unit value
u_{cm}	common mode voltage (star point voltage) [V] or per-unit value
u_r	reflected voltage [V] or per-unit value
u_{drop}	voltage drop estimation error [V] or per-unit value
u_2	forward travelling voltage [V] or per-unit value
u_{DCmE}	voltage from DC link midpoint to PE [V] or per-unit value
Δu	voltage drop [V] or per-unit value
$\Delta U_{DC,offs}$	offset voltage [V] or per-unit value
V	depiction of a phase
VDE	Verband Deutscher Elektroingenieure
VRM	variable reluctance motor
VSI	voltage source inverter
v	speed, velocity, wave velocity, propagation speed of the voltage pulse [m/s]
$\boldsymbol{v}$	vector
W	energy [J], coil span (width) [m]
W	depiction of a phase
W^*, W^x	magnetic co-energy [J]
W_e	magnetic energy (energy stored in magnetic field) [J]

W_{mec}	mechanical work [J]
W_{mt}	energy converted into mechanical work when the transistor is conducting [J]
W_{md}	mechanical work when the diode is conducting [J]
W_{fc}	energy stored in the magnetic field [J]
W_R	energy returning to the voltage source [J]
W_d	energy returned through the diode to the voltage source [J]
w_{ins}	thickness of the insulation layer,[m]
w_{Fe}	thickness of the iron layer,[m]
X	reactance [Ω]
x	coordinate, axis
Y	admittance [S]
y	axis
Z	impedance, nonlinear impedance of the ball bearing [Ω]
Z_m	characteristic impedance of the motor cable [Ω]
Z_s	characteristic impedance of the filter [Ω]
Z_{s01}, Z_{s02}	impedance of the filter [Ω]
Z_0	characteristic impedance [Ω]
z	coordinate, length [m]
z_Q	number of conductors in a slot
α	angle [rad] [°], coefficient, temperature coefficient, relative pole width of the pole shoe
α_i	factor of the arithmetical average of the flux density
α_{PM}	relative permanent magnet width
α_{SM}	relative pole width coefficient for synchronous machines
β	angle [rad] [°]
Γ	energy ratio, cylinder that confines the rotor, integration route
γ	angle, rotor angle [rad] [°], coefficient
γ_c	commutation angle [rad] [°]
γ_D	switch conducting angle, dwelling angle [rad] [°]
γ_0	turn on switching angle [rad] [°]
δ	air gap (length) [m], load angle [rad] [°]
δ_{de}	equivalent air gap (slotting taken into account) in the d-axis [m]
δ_e	equivalent air gap (slotting taken into account) [m]
δ_{ef}	effective air gap (influence of iron taken into account) [m]
δ', δ_0	minimum air gap, (air gap in the middle of the pole shoe) [m]
δ'_0	minimum air gap, influence of slotting is taken into account [m]
δ'_d	equivalent direct axis air gap [m]
δ'_q	equivalent quadrature axis air gap [m]
δ_s	load angle [rad] [°]
δ_m	load angle [rad] [°]
$\Delta\delta_{ef}$	additional effective air gap caused by PM [m]
ε	permittivity [F/m], stroke angle [rad] [°], angle, correction term
ε_r	relative permittivity
ε_0	permittivity of vacuum $8.854 \cdot 10^{-12}$ [F/m]
η	efficiency
$\boldsymbol{\Theta}$	current linkage vector [A] or per-unit value
Θ	current linkage [A], angle [rad] [°]

θ angle [rad] [°]
ϑ angle [rad] [°]
κ angle, current angle [rad] [°], vector position in a sector
λ angle [rad] [°],
μ permeability [Vs/Am],
μ_r relative permeability
μ_0 permeability of vacuum, $4 \cdot \pi \cdot 10^{-7}$ [Vs/Am] [H/m]
ν pulse velocity [m/s], ordinal of harmonic
Π surface [m^2]
ρ resistivity [Ωm], reflection factor (coefficient)
ρ_ν transformation ratio for IM impedance, resistance, inductance
σ leakage factor, ratio of the leakage flux to the main flux, Maxwell stress [N/m^2]
σ_F tension, tension force [Pa]
σ_{Fn} normal tension [Pa]
σ_{Ftan} tangential tension [Pa]
σ_{mec} mechanical stress [Pa]
τ relative time, transmission coefficient, control bit (torque or flux linkage)
τ'_{d0} direct axis transient time constant with an open-circuit stator winding [s]
τ'_d direct axis transient time constant [s]
τ''_d direct axis subtransient time constant [s]
τ''_q quadrature axis subtransient time constant [s]
τ''_{q0} quadrature axis subtransient time constant with open-circuit stator winding [s]
τ_p pole pitch [m]
τ_v phase zone distribution
τ_A armature time constant [s]
τ_{mec} mechanical time constant [s]
$\boldsymbol{\Phi}$ magnetic flux space vector [Wb] [Vs] or per-unit value
Φ magnetic flux [Wb] [Vs]
Φ_δ air gap flux [Wb] [Vs]
Φ_h main magnetic flux [Wb] [Vs]
ϕ magnetic flux, instantaneous value $\phi(t)$ [Wb] [Vs],
φ phase shift angle, power factor angle [rad] [°]
ψ magnetic flux linkage [Vs] or per-unit value
ψ_h flux linkage of a single phase [Vs] or per-unit value
ψ_m air-gap flux linkage [Vs] or per-unit value
$\psi_{s,u}$ stator flux linkage integrated from the converter voltages [Vs] or per-unit value
$\psi_{s,i}$ stator flux linkage calculated from the current model [Vs] or per-unit value
ψ_{s0} initial flux linkage ($\sim\psi_{PM}$) [Vs] or per-unit value
ψ_A armature reaction flux linkage [Vs] or per-unit value
ψ_C compensating winding flux linkage [Vs] or per-unit value
ψ_B commutating pole winding flux linkage [Vs] or per-unit value
ψ_F field winding flux linkage [Vs] or per-unit value
ψ_{PM} permanent magnet flux linkage [Vs] or per-unit value
ψ_{tot} total flux linkage of the machine [Vs] or per-unit value
Ω mechanical angular speed [rad/s] or per-unit value

Ω_{hs}	speed of high speed area starts at Ω_{hs} or per-unit value
ω	electric angular velocity [rad/s], angular frequency [rad/s] or per-unit value

Subscripts

0	section
1	primary, fundamental component, beginning of a phase, locked rotor torque, phase number
2	secondary, end of a phase, phase number
3	phase number
a	armature, shaft
A	armature
arm	armouring
ad	additional
av	average
act	actual
b	base value, peak value of torque, blocking
bar	concerning bar
bearing	concerning bearing
C	capacitor
c	conductor, commutation
cp	constant power
calc	calculated
corr	correction
cr, crit	critical
D	direct, damper
d	direct, direct axis, distribution
DC	direct current
E	back emf (electromotive force)
e	electrical, electric
eff	effective
el	electric, electrical
em	electromagnetic
err	error
est	estimate
ext	external
f,	field, filter
filt	filtered
F	force, field
Fe	iron
grid	concerning a grid
i	internal
k	short circuit, ordinal
L	load
LL	line to line
m	mutual, main, motor, mechanical
M	motor

mag	magnetizing, magnetic
max	maximum
mec	mechanical
meas	measured
min	minimum
N	rated
n	nominal, normal, normalized, normalization, orthogonal component
non-sal	nonsaliency
new	new value
old	old value
p	pole, pitch
ph	phase
pu	per unit value
PM	permanent magnet
q	quadrature, quadrature axis, zone
r	rotor, rotor reference frame
ref	reference
res	reserve
s	stator
sal	saliency
sk	skewing
slipring	concerning a slip ring
sub	subtransient
sum	vector sum of currents
syn	synchronous
sw	switching
t	tangential
tan	tangential
tot	total
tr	transient
triangle	triangle waveform
u	pull-up torque
v	zone, coil
w	end winding leakage flux
x	x-direction, axis
y	y-*direction, axis*
z	z-direction, phasor of voltage phasor graph
δ	air gap
Φ	flux
ν	harmonic
σ	leakage

Superscripts

^,	peak/maximum value, amplitude
′	imaginary, apparent, reduced, referred, virtual, transient
*	base winding, complex conjugate

s stator reference frame
r rotor reference frame
g general reference frame

Boldface symbols are used for space vectors

$\boldsymbol{i}$ current space vector, $\boldsymbol{i} = i_x + ji_y$, $\boldsymbol{i} = ie^{j\theta}$ [A] or per-unit value
i absolute or per-unit value of current space vector
I complex RMS phasor of the current

Contents