Design of Rotating Electrical Machines

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About the Authors

Juha Pyrhönen is a Professor in the Department of Electrical Engineering at Lappeenranta University of Technology, Finland. He is engaged in the research and development of electric motors and drives. He is especially active in the fields of permanent magnet synchronous machines and drives and solid-rotor high-speed induction machines and drives. He has worked on many research and industrial development projects and has produced numerous publications and patents in the field of electrical engineering.

Tapani Jokinen is a Professor Emeritus in the Department of Electrical Engineering at Helsinki University of Technology, Finland. His principal research interests are in AC machines, creative problem solving and product development processes. He has worked as an electrical machine design engineer with Oy Strömberg Ab Works. He has been a consultant for several companies, a member of the Board of High Speed Tech Ltd and Neorem Magnets Oy, and a member of the Supreme Administrative Court in cases on patents. His research projects include, among others, the development of superconducting and large permanent magnet motors for ship propulsion, the development of high-speed electric motors and active magnetic bearings, and the development of finite element analysis tools for solving electrical machine problems.

Valéria Hrabovcová is a Professor of Electrical Machines in the Department of Power Electrical Systems, Faculty of Electrical Engineering, at the University of Žilina, Slovak Republic. Her professional and research interests cover all kinds of electrical machines, electronically commutated electrical machines included. She has worked on many research and development projects and has written numerous scientific publications in the field of electrical engineering. Her work also includes various pedagogical activities, and she has participated in many international educational projects.

Preface

Electrical machines are almost entirely used in producing electricity, and there are very few electricity-producing processes where rotating machines are not used. In such processes, at least auxiliary motors are usually needed. In distributed energy systems, new machine types play a considerable role: for instance, the era of permanent magnet machines has now commenced.

About half of all electricity produced globally is used in electric motors, and the share of accurately controlled motor drives applications is increasing. Electrical drives provide probably the best control properties for a wide variety of processes. The torque of an electric motor may be controlled accurately, and the efficiencies of the power electronic and electromechanical conversion processes are high. What is most important is that a controlled electric motor drive may save considerable amounts of energy. In the future, electric drives will probably play an important role also in the traction of cars and working machines. Because of the large energy flows, electric drives have a significant impact on the environment. If drives are poorly designed or used inefficiently, we burden our environment in vain. Environmental threats give electrical engineers a good reason for designing new and efficient electric drives.

Finland has a strong tradition in electric motors and drives. Lappeenranta University of Technology and Helsinki University of Technology have found it necessary to maintain and expand the instruction given in electric machines. The objective of this book is to provide students in electrical engineering with an adequate basic knowledge of rotating electric machines, for an understanding of the operating principles of these machines as well as developing elementary skills in machine design. However, due to the limitations of this material, it is not possible to include all the information required in electric machine design in a single book, yet this material may serve as a manual for a machine designer in the early stages of his or her career. The bibliographies at the end of chapters are intended as sources of references and recommended background reading. The Finnish tradition of electrical machine design is emphasized in this textbook by the important co-authorship of Professor Tapani Jokinen, who has spent decades in developing the Finnish machine design profession. An important view of electrical machine design is provided by Professor Valéria Hrabovcová from Slovak Republic, which also has a strong industrial tradition.

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Tapani Jokinen
Valéria Hrabovcová

Abbreviations and Symbols

A	linear current density [A/m]
$\boldsymbol{A}$	magnetic vector potential [V s/m]
A	temperature class 105 °C
AC	alternating current
AM	asynchronous machine
A1–A2	armature winding of a DC machine
a	number of parallel paths in windings without commutator: per phase, in windings with a commutator: per half armature, diffusivity
$\boldsymbol{B}$	magnetic flux density, vector [V s/m^2], [T]
B_r	remanence flux density [T]
B_{sat}	saturation flux density [T]
B	temperature class 130 °C
B1–B2	commutating pole winding of a DC machine
b	width [m]
b_{0c}	conductor width [m]
b_c	conductor width [m]
b_d	tooth width [m]
b_{dr}	rotor tooth width [m]
b_{ds}	stator tooth width [m]
b_r	rotor slot width [m]
b_s	stator slot width [m]
b_v	width of ventilation duct [m]
b_0	slot opening [m]
C	capacitance [F], machine constant, integration constant
C	temperature class >180 °C
C1–C2	compensating winding of a DC machine
C_f	friction coefficient
c	specific heat capacity [J/kg K], capacitance per unit of length, factor, divider, constant
c_p	specific heat capacity of air at constant pressure
c_{th}	heat capacity
CTI	Comparative Tracking Index
c_v	specific volumetric heat [kJ/K m^3]
D	electric flux density [C/m^2], diameter [m]
DC	direct current

D_r	outer diameter of the rotor [m]
D_{ri}	inner diameter of the rotor [m]
D_s	inner diameter of the stator [m]
D_{se}	outer diameter of the stator [m]
D1–D2	series magnetizing winding of a DC machine
d	thickness [m]
d_t	thickness of the fringe of a pole shoe [m]
E	electromotive force (emf) [V], RMS, electric field strength [V/m], scalar, elastic modulus, Young's modulus [Pa]
E_a	activation energy [J]
$\boldsymbol{E}$	electric field strength, vector [V/m]
E	temperature class 120 °C
E	irradiation
E1–E2	shunt winding of a DC machine
e	electromotive force [V], instantaneous value $e(t)$
e	Napier's constant
F	force [N], scalar
$\boldsymbol{F}$	force [N], vector
F	temperature class 155 °C
FEA	finite element analysis
F_g	geometrical factor
F_m	magnetomotive force $\oint \boldsymbol{H} \cdot \mathbf{d}\boldsymbol{l}$ [A], (mmf)
F1–F2	separate magnetizing winding of a DC machine or a synchronous machine
f	frequency [Hz], Moody friction factor
g	coefficient, constant, thermal conductance per unit length
G	electrical conductance
G_{th}	thermal conductance
H	magnetic field strength [A/m]
H_c, H_{cB}	coercivity related to flux density [A/m]
H_{cJ}	coercivity related to magnetization [A/m]
H	temperature class 180 °C, hydrogen
h	height [m]
h_{0c}	conductor height [m]
h_c	conductor height [m]
h_d	tooth height [m]
h_p	height of a subconductor [m]
h_{p2}	height of pole body [m]
h_s	stator slot height [m]
h_{yr}	height of rotor yoke [m]
h_{ys}	height of stator yoke [m]
I	electric current [A], RMS, brush current, second moment of an area, moment of inertia of an area [m^4]
IM	induction motor
I_{ns}	counter-rotating current (negative-sequence component) [A]
I_o	current of the upper bar [A]
I_s	conductor current

I_u	current of the lower bar, slot current, slot current amount [A]
IC	classes of electrical machines
IEC	International Electrotechnical Commission
Im	imaginary part
i	current [A], instantaneous value $i(t)$
J	moment of inertia [kg m^2], current density [A/m^2], magnetic polarization
$\boldsymbol{J}$	Jacobian matrix
J_{ext}	moment of inertia of load [kg m^2]
J_M	moment of inertia of the motor, [kgm^2]
J_{sat}	saturation of polarization [V s/m^2]
$\boldsymbol{J}_s$	surface current, vector [A/m]
j	difference of the numbers of slots per pole and phase in different layers
j	imaginary unit
K	transformation ratio, constant, number of commutator segments
K_L	inductance ratio
k	connecting factor (coupling factor), correction coefficient, safety factor, ordinal of layers
k_C	Carter factor
k_{Cu}, k_{Fe}	space factor for copper, space factor for iron
k_d	distribution factor
k_E	machine-related constant
$k_{Fe,n}$	correction factor
k_k	short-circuit ratio
k_L	skin effect factor for the inductance
k_p	pitch factor
k_{pw}	pitch factor due to coil side shift
k_R	skin effect factor for the resistance
k_{sat}	saturation factor
k_{sq}	skewing factor
k_{th}	coefficient of heat transfer [W/m^2 K]
k_v	pitch factor of the coil side shift in a slot
k_w	winding factor
k_σ	safety factor in the yield
L	self-inductance [H]
L	characteristic length, characteristic surface, tube length [m]
LC	inductor–capacitor
L_d	tooth tip leakage inductance [H]
L_k	short-circuit inductance [H]
L_m	magnetizing inductance [H]
L_{md}	magnetizing inductance of an m-phase synchronous machine, in d-axis [H]
L_{mn}	mutual inductance [H]
L_{pd}	main inductance of a single phase [H]
L_u	slot inductance [H]
L'	transient inductance [H]
L''	subtransient inductance [H]
L1, L2, L3,	network phases

l	length [m], closed line, distance, inductance per unit of length, relative inductance, gap spacing between the electrodes
$\boldsymbol{l}$	unit vector collinear to the integration path
l'	effective core length [m]
l_{ew}	average conductor length of winding overhang [m]
l_{p}	wetted perimeter of tube [m]
l_{pu}	inductance as a per unit value
l_{w}	length of coil ends [m]
M	mutual inductance [H], magnetization [A/m]
M_{sat}	saturation magnetization [A/m]
m	number of phases, mass [kg],
m_0	constant
N	number of turns in a winding, number of turns in series
N_{f1}	number of coil turns in series in a single pole
Nu	Nusselt number
N_{u1}	number of bars of a coil side in the slot
N_{k}	number of turns of compensating winding
N_{p}	number of turns of one pole pair
N_{v}	number of conductors in each side
N	Nondrive end
$\mathbf{N}$	set of integers
$\mathbf{N}_{\mathrm{even}}$	set of even integers
$\mathbf{N}_{\mathrm{odd}}$	set of odd integers
$\boldsymbol{n}$	normal unit vector of the surface
n	rotation speed (rotation frequency) [1/s], ordinal of the harmonic (sub), ordinal of the critical rotation speed, integer, exponent
n_{U}	number of section of flux tube in sequence
n_{v}	number of ventilation ducts
n_{Φ}	number of flux tube
P	power, losses [W]
P_{in}	input power [W]
PAM	pole amplitude modulation
PMSM	permanent magnet synchronous machine (or motor)
PWM	pulse width modulation
P_1, P_{ad}, P	additional loss [W]
Pr	Prandtl number
P_{ρ}	friction loss [W]
p	number of pole pairs, ordinal, losses per core length
p_{Al}	aluminium content
p^*	number of pole pairs of a base winding
pd	partial discharge
Q	electric charge [C], number of slots, reactive power [VA],
Q_{av}	average number of slots of a coil group
Q_{o}	number of free slots
Q'	number of radii in a voltage phasor graph
Q^*	number of slots of a base winding

Q_{th}	quantity of heat
q	number of slots per pole and phase, instantaneous charge, $q(t)$ [C]
q_{k}	number of slots in a single zone
q_{m}	mass flow [kg/s]
q_{th}	density of the heat flow [W/m^2]
R	resistance [Ω], gas constant, 8.314 472 [J/K mol], thermal resistance, reactive parts
R_{bar}	bar resistance [Ω]
RM	reluctance machine
RMS	root mean square
R_{m}	reluctance [A/V s = 1/H]
R_{th}	thermal resistance [K/W]
Re	real part
Re	Reynolds number
Re_{crit}	critical Reynolds number
RR	Resin-rich (impregnation method)
r	radius [m], thermal resistance per unit length
$\boldsymbol{r}$	radius unit vector
S1–S8	duty types
S	apparent power [VA], cross-sectional area
SM	synchronous motor
SR	switched reluctance
SyRM	synchronous reluctance machine
S_{c}	cross-sectional area of conductor [m^2]
S_{p}	pole surface area [m^2]
S_{r}	rotor surface area facing the air gap [m^2]
$\boldsymbol{S}$	Poynting's vector [W/m^2], unit vector of the surface
s	slip, skewing measured as an arc length
T	torque [N m], absolute temperature [K], period [s]
Ta	Taylor number
Ta_{m}	modified Taylor number
T_{b}	pull-out torque, peak torque [N m]
t_{c}	commutation period [s]
TEFC	totally enclosed fan-cooled
T_{J}	mechanical time constant [s]
T_{mec}	mechanical torque [N m]
T_{u}	pull-up torque [N m]
T_{v}	counter torque [N m]
T_{l}	locked rotor torque, [N m]
t	time [s], number of phasors of a single radius, largest common divider, lifetime of insulation
$\boldsymbol{t}$	tangential unit vector
t_{c}	commutation period [s]
t_{r}	rise time [s]
$t*$	number of layers in a voltage vector graph for a base winding
U	voltage [V], RMS

U	depiction of a phase
U_m	magnetic voltage [A]
U_{sj}	peak value of the impulse voltage [V]
U_v	coil voltage [V]
U1	terminal of the head of the U phase of a machine
U2	terminal of the end of the U phase of a machine
u	voltage, instantaneous value $u(t)$ [V], number of coil sides in a layer
u_{bl}	blocking voltage of the oxide layer [V]
u_c	commutation voltage [V]
u_m	mean fluid velocity in tube [m/s]
V	volume [m^3], electric potential
V	depiction of a phase
V_m	scalar magnetic potential [A]
VPI	vacuum pressure impregnation
V1	terminal of the head of the V phase of a machine
V2	terminal of the end of the V phase of a machine
v	speed, velocity [m/s]
$\boldsymbol{v}$	vector
W	energy [J], coil span (width) [m]
W	depiction of a phase
W_d	energy returned through the diode to the voltage source in SR drives
W_{fc}	energy stored in the magnetic field in SR machines
W_{md}	energy converted to mechanical work while de-energizing the phase in SR drives
W_{mt}	energy converted into mechanical work when the transistor is conducting in SR drives
W_R	energy returning to the voltage source in SR drives
W'	coenergy [J]
W1	terminal of the head of the W phase of a machine
W2	terminal of the end of the W phase of a machine
W_Φ	magnetic energy [J]
w	length [m], energy per volume unit
X	reactance [Ω]
x	coordinate, length, ordinal number, coil span decrease [m]
x_m	relative value of reactance
Y	admittance [S]
Y	temperature class 90 °C
y	coordinate, length, step of winding
y_m	winding step in an AC commutator winding
y_n	coil span in slot pitches
y_Φ	coil span of full-pitch winding in slot pitches (pole pitch expressed in number of slots per pole)
y_v	coil span decrease in slot pitches
y_1	step of span in slot pitches, back-end connector pitch
y_2	step of connection in slot pitches, front-end connector pitch
y_C	commutator pitch in number of commutator segments

Z	impedance [Ω], number of bars, number of positive and negative phasors of the phase
Z_M	characteristic impedance of the motor [Ω]
Z_s	surface impedance [Ω]
Z_0	characteristic impedance [Ω]
z	coordinate, length, integer, total number of conductors in the armature winding
z_a	number of adjacent conductors
z_b	number of brushes
z_c	number of coils
z_p	number of parallel-connected conductors
z_Q	number of conductors in a slot
z_t	number of conductors on top each other
α	angle [rad], [°], coefficient, temperature coefficient, relative pole width of the pole shoe, convection heat transfer coefficient [W/K]
$1/\alpha$	depth of penetration
α_{DC}	relative pole width coefficient for DC machines
α_i	factor of the arithmetical average of the flux density
α_m	mass transfer coefficient [(mol/sm^2)/(mol/m^3) = m/s]
α_{ph}	angle between the phase winding
α_{PM}	relative permanent magnet width
α_r	heat transfer coefficient of radiation
α_{SM}	relative pole width coefficient for synchronous machines
α_{str}	angle between the phase winding
α_{th}	heat transfer coefficient [W/m^2 K]
α_u	slot angle [rad], [°]
α_z	phasor angle, zone angle [rad], [°]
α_ρ	angle of single phasor [rad], [°]
β	angle [rad], [°], absorptivity
Γ	energy ratio, integration route
Γ_c	interface between iron and air
γ	angle [rad], [°], coefficient
γ_c	commutation angle [rad], [°]
γ_D	switch conducting angle [rad], [°]
δ	air gap (length), penetration depth [m], dissipation angle [rad], [°], load angle [rad], [°]
δ_c	the thickness of concentration boundary layer [m]
δ_e	equivalent air gap (slotting taken into account) [m]
δ_{ef}	effective air gap(influence of iron taken into account)
δ_v	velocity boundary layer [m]
δ_T	temperature boundary layer [m]
δ'	load angle [rad], [°], corrected air gap [m]
δ_0	minimum air gap [m]
ε	permittivity [F/m], position angle of the brushes [rad], [°], stroke angle [rad], [°], amount of short pitching
ε_{th}	emissivity
ε_0	permittivity of vacuum 8.854×10^{-12} [F/m]

ζ	phase angle [rad], [°], harmonic factor
η	efficiency, empirical constant, experimental pre-exponential constant, reflectivity
Θ	current linkage [A], temperature rise [K]
Θ_k	compensating current linkage [A]
Θ_Σ	total current linkage [A]
θ	angle [rad], [°]
ϑ	angle [rad], [°]
κ	angle [rad], [°], factor for reduction of slot opening, transmissivity
Λ	permeance, [Vs/A], [H]
λ	thermal conductivity [W/m K], permeance factor, proportionality factor, inductance factor, inductance ratio
μ	permeability [V s/A m, H/m], number of pole pairs operating simultaneously per phase, dynamic viscosity [Pa s, kg/s m]
μ_r	relative permeability
μ_0	permeability of vacuum, $4\pi \times 10^{-7}$ [V s/A m, H/m]
ν	ordinal of harmonic, Poisson's ratio, reluctivity [A m/V s, m/H], pulse velocity
ξ	reduced conductor height
ρ	resistivity [Ω m], electric charge density [C/m^2], density [kg/m^3], reflection factor, ordinal number of a single phasor
ρ_A	absolute overlap ratio
ρ_E	effective overlap ratio
ρ_ν	transformation ratio for IM impedance, resistance, inductance
σ	specific conductivity, electric conductivity [S/m], leakage factor, ratio of the leakage flux to the main flux
σ_F	tension [Pa]
σ_{Fn}	normal tension [Pa]
σ_{Ftan}	tangential tension [Pa]
σ_{mec}	mechanical stress [Pa]
σ_{SB}	Stefan–Boltzmann constant, $5.670\,400 \times 10^{-8}$ W/m^2/K^4
τ	relative time
τ_p	pole pitch [m]
τ_{q2}	pole pitch on the pole surface [m]
τ_r	rotor slot pitch [m]
τ_s	stator slot pitch [m]
τ_u	slot pitch [m]
τ_v	zone distribution
τ'_d	direct-axis transient short-circuit time constant [s]
τ'_{d0}	direct-axis transient open-circuit time constant [s]
τ''_{d0}	direct-axis subtransient open-circuit time constant [s]
τ''_q	quadrature-axis subtransient short-circuit time constant [s]
τ''_{q0}	quadrature-axis subtransient open-circuit time constant [s]
υ	factor, kinematic viscosity, μ/ρ, [Pa s/(kg/m^3)]
Φ	magnetic flux [V s, Wb]
Φ_{th}	thermal power flow, heat flow rate [W]
Φ_δ	air gap flux [V s], [Wb]

ϕ	magnetic flux, instantaneous value $\phi(t)$ [V s], electric potential [V]
φ	phase shift angle [rad], [°]
φ'	function for skin effect calculation
Ψ	magnetic flux linkage [V s]
ψ	electric flux [C],
ψ'	function for skin effect calculation
χ	length/diameter ratio, shift of a single pole pair
Ω	mechanical angular speed [rad/s]
ω	electric angular velocity [rad/s], angular frequency [rad/s]
ΔT	temperature rise [K, °C]
∇T	temperature gradient [K/m, °C/m]
Δp	pressure drop [Pa]

Subscripts

0	section
1	primary, fundamental component, beginning of a phase, locked rotor torque,
2	secondary, end of a phase
Al	aluminium
a	armature, shaft
ad	additional (loss)
av	average
B	brush
b	base value, peak value of torque, blocking
bar	bar
bearing	bearing (losses)
C	capacitor
Cu	copper
c	conductor, commutation
contact	brush contact
conv	convection
cp	commutating poles
cr, crit	critical
D	direct, damper
DC	direct current
d	tooth, direct, tooth tip leakage flux
EC	eddy current
e	equivalent
ef	effective
el	electric
em	electromagnetic
ew	end winding
ext	external
F	force
Fe	iron
f	field

Hy	hysteresis
i	internal, insulation
k	compensating, short circuit, ordinal
M	motor
m	mutual, main
mag	magnetizing, magnetic
max	maximum
mec	mechanical
min	minimum
mut	mutual
N	rated
n	nominal, normal
ns	negative-sequence component
o	starting, upper
opt	optimal
PM	permanent magnet
p	pole, primary, subconductor, pole leakage flux
p1	pole shoe
p2	pole body
ph	phasor, phase
ps	positive-sequence component
pu	per unit
q	quadrature, zone
r	rotor, remanence, relative
res	resultant
S	surface
s	stator
sat	saturation
sj	impulse wave
sq	skew
str	phase section
syn	synchronous
tan	tangential
test	test
th	thermal
tot	total
u	slot, lower, slot leakage flux, pull-up torque
v	zone, coil side shift in a slot, coil
w	end winding leakage flux
x	x-direction
y	y-direction, yoke
ya	armature yoke
yr	rotor yoke
ys	stator yoke
z	z-direction, phasor of voltage phasor graph
δ	air gap