Lehrstuhl für Elektrische Antriebstechnik und Aktorik

Chair of Electrical Drives and Actuators

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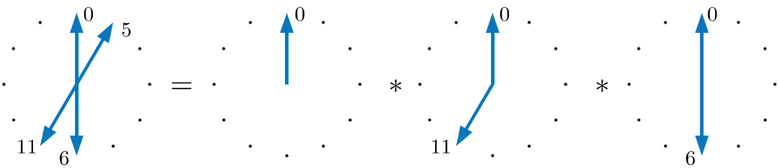
Elektrische Antriebstechnik und Aktorik

Hrsg.: Prof. Dr.-Ing. Dieter Gerling

Boris Dotz

Windings, Design and Optimization of Electrical Machines for Hybrid Traction Applications



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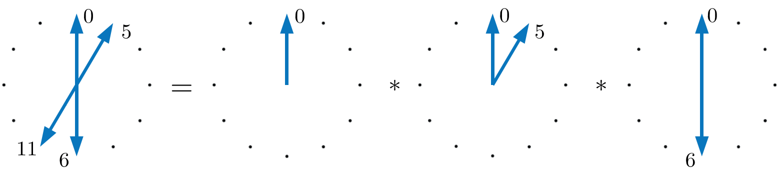

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1. Prof. Dr.-Ing. Dieter Gerling
2. Prof. Dr.-Ing. Bernd Ponick

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Abstract

This research consists of three main parts. The first part extends research on AC windings by utilizing the star of phasors (star of slots) for winding topologies with various numbers of turns per coil or per coil side, as well as for star-delta windings. Following a mathematical approach, possibilities and restrictions on electromagnetic improvements are discussed and main theorems and design guidelines are presented. It is shown that several windings found in the past possess a similar underlying structure, allowing to design more, yet unknown windings. Closed analytical equations for winding factors are derived and several winding examples are illustrated.

The second part contributes to design possibilities of high pole PM machines for hybrid traction applications. Due to high electrical frequency, machine design focuses on low iron and AC losses. The design procedure as well as main design considerations are highlighted, showing trade-offs and final decisions. Following these findings, a 36-slot 28-pole PM machine with irregular air gap, shaped tooth tips and a concentrated winding in delta connection is designed. Numerical and analytical calculations for the electromagnetic, mechanical and thermal domain are presented.

The third part validates derived machine design by measurements performed on a full scale prototype. Manufactured PM machine, test-bench and performed measurements are described in detail. Results are depicted and compared to predicted values. Deviations are analyzed and further optimization possibilities are discussed. It is shown that derived design fulfills set project requirements on torque and powcer and shall be improved further regarding AC losses.

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Contents

Applied Notations and Symbols

A	Current loading in A/m
AJ	Thermal utilization in A/m^3
B_δ	Peak fundamental air gap flux density in T
B_{max}	Maximum allowable flux density in T
$B_{pm,\upsilon}$	Harmonic of rotor permanent magnet flux density with ordinal number υ
B_t	Maximum teeth flux density in T
B_y	Maximum yoke flux density in T
C_{ess}	Esson's Number in VAs/m^3
C_{th}	Thermal copper capacity in J/K
H_t	Tangential magnetic field strength along slot opening in A/m
I_D	Rms current of supplied frequency in the delta branch in A
$I_{D,3}$	Rms current of third harmonic in delta branch in A
$I_{d,q}$	Current in A in direct and quadrature axis, respectively
$I_{D,tot}$	Total rms current in delta branch in A
I_L	Supplied rms line current in A
I_{sc}	Continuous short circuit current in A
J	Current density in A/m^2
$L_{d,q}$	Inductance in H in direct and quadrature axis, respectively
M	Modulation index
$N_1, N_2, \ldots$	Number of turns per phasor
N_{12}	Ratio of effective turns per phasor
N_c	Number of turns per coil
N_{cog}	Cogging torque frequency with respect to one mechanical revolution

N_l	Number of turns of phasor l
Nu	Nusselt number
Ta	Taylor Number
OVR	Overvoltage ratio
P	Mechanical power in W
P_{cu}	Copper losses in W
P_{f}	Bearing friction losses in W
P_{fe}	Iron losses in W
P_{fw}	Mechanical losses in W
P_{mag}	Eddy current losses in magnets in W
P_{w}	Windage losses in W
Q	Number of slots per winding
Q_{D}	Total number of coils connected in delta branch
Q_{Y}	Total number of coils connected in star branch
Q^*	Number of slots per base winding
R_{c}	DC resistance per coil in Ω
R_{dc}	DC resistance per phase in Ω
R_{th}	Thermal resistance of slot copper to iron stack in K/W
T	Torque in Nm
THD	Total harmonic distortion
U_{dc}	DC bus voltage in V
$\hat{U}_{\mathrm{fund}}$	Peak line-line fundamental voltage in V
$\hat{U}_{\nu}$	Line-line voltage harmonic, peak value in V
V_{fe}	Volume of iron stack in m^3
U_{max}	Maximum line-line voltage in V
V_{pm}	Magnetomotive force due to permanent magnets in A
W	Coil width in m
Y_{ν}	Fictive commutator pitch of winding harmonic ν
$\underline{a}_{\nu}, \underline{b}_{\nu}, \underline{c}_{\nu}$	Discrete Fourier coefficients

b_{cu}	Total width of slot copper in m
b_{s}	Slot width in m when approximated by a rectangular shape
b_{so}	Slot opening width in m
c	Correction factor for round wires when calculating AC losses
$\cos(\varphi)$	Power factor
$\cos(\tilde{\varphi})$	Power factor excluding the influence of iron, magnet and additional losses
c_{th}	Specific heat capacity of copper in J/(kgK)
$d_{\mathrm{p,ab}}$	Field penetration depth in m for slots with coil sides a and b
d_{ri}	Rotor inner diameter in m
d_{ro}	Rotor outer diameter in m
d_{si}	Stator inner diameter in m
d_{so}	Stator outer diameter in m
f_{e}	Electrical frequency in Hz
f_{s}	Switching frequency in Hz
h_{NP}	Number of north pole phasors connected in the delta branch
h_{SP}	Number of south pole phasors connected in the delta branch
h	Number of phasors connected in the delta branch in chapter 2, normalized tangential magnetic field strength in chapter 3
h_{c}	Height of one single conductor in m
h_{cu}	Total height of slot copper in m
h_{m}	Magnet height in m
h_{s}	Slot height in m when approximated by a rectangular shape
h_{t}	Teeth height in m
h_{y}	Yoke height in m
$k_{\mathrm{dg},\nu}$	Group factor of winding harmonic ν
$k_{\mathrm{d},\nu}$	Distribution factor of winding harmonic ν
$k_{\mathrm{dz},\nu}$	Zone factor of winding harmonic ν
k_{fe}	Factor for iron loss increase
k_{fill}	Slot fill factor

$k_{\mathrm{p},\nu}$	Pitch factor of winding harmonic ν
k_{r}	Resistance factor due to fundamental harmonic
$k_{\mathrm{r},3}$	Resistance factor due to third harmonic
$k_{\mathrm{r,eff}}$	Effective resistance factor
$k_{\mathrm{s},\nu}$	Shift factor of winding harmonic ν
$k_{\mathrm{so},\nu}$	Slot opening factor of winding harmonic ν
k_{stack}	Stacking factor of iron steel
$k_{\mathrm{w},\nu}$	Winding factor of harmonic ν
$\underline{k}_{\mathrm{w},\nu}$	Complex winding factor of harmonic ν
l_{cs}	Copper length per coil side including the winding overhangs in m
l_{fe}	Length of iron stack in m
l_{tot}	Total axial length in m
l_{w}	Winding overhang length of one coil side in m
l_{wo}	Axial length of winding overhangs in m
m	Number of phases
n_{r}	Rotor rotation speed in 1/s
p	Number of pole pairs per winding
p^*	Number of pole pairs per base winding
p_{cu}	Ohmic loss density in W/m^3
q	Number of slots per pole and phase
q_{d}	Denominator of q
q_{g}	Number of phasors per group
q_{i}	Heat flow in W/m^2
q_{n}	Nominator of q
q_{NP}	Number of phasors per north pole zone
q_{SP}	Number of phasors per south pole zone
s	Shift distance of two windings counted in phasor positions
t	Winding periodicity in chapter 2, otherwise time in s
w_{m}	Magnet width in m

Γ	Distance between + and − zone
$\Phi_{\delta,\mathrm{y,t}}$	Air gap, yoke, teeth magnetic flux in Vs
Ψ_{pm}	Flux linkage due to permanent magnets in Vs
α	Angle between adjacent phasors in the star of phasors
α_l	Angle between the reference phasor and phasor l
α_{pm}	Arithmetical average flux density factor
α_{ps}	Pole shape coverage
$\alpha_{\mathrm{th,out}}$	Heat transfer coefficient at stator outer surface in $\mathrm{W/(m^2K)}$
δ	Air gap height in m
δ_0	Minimum air gap height in m
γ_{fd}	Flux density ratio
κ	Copper resistivity in Ωm
κ_0	Copper resistivity at boundary temperature in Ωm
λ_{s}	Effective thermal slot conductivity in W/(mK)
ν	Winding harmonic with reference to a base winding
$\tilde{\nu}$	Ordinal number of winding harmonic to be set to zero
ω	Electrical angular frequency in 1/s
$\tilde{\varphi}$	Angle between fundamental harmonic current and voltage, excluding the influence of iron, magnet and additional losses
φ_{d}	Additional phase shift of delta phasors
φ_{s}	Angle of the symmetry axis of the geometrical sum of phasors
ρ	Material density in $\mathrm{kg/m^3}$
σ	Electrical conductivity of copper in 1/Ωm
σ_{YS}	Yield strength of electrical steel in Pa
σ_{max}	Maximum mechanical stress in Pa
σ_{tan}	Tangential stress in Pa
τ_{p}	Pole pitch in m
τ_{pm}	Theoretical pole coverage of permanent magnets
τ_{s}	Slot pitch in m

τ_{so}	Slot pitch at the outer slot side in m
τ_{t}	Teeth width in m
ϑ	Temperature in K
ϑ_{mag}	Hot spot temperature of magnets in K
ϑ_{max}	Hot spot temperature in K
$\vartheta_{\mathrm{cool}}$	Cooling temperature in K
ξ_{ab}	Rated conductor height for slots with coil sides a and b