Universität Stuttgart

iew
Institut für
Elektrische Energiewandlung

Berichte aus dem Institut für Elektrische Energiewandlung

Samuel Müller

Inductive Electrically Excited Synchronous Machines for Electrical Vehicles

Band 14

Inductive Electrically Excited Synchronous Machines for Electrical Vehicles

Von der Fakultät Informatik, Elektrotechnik
und Informationstechnik der Universität Stuttgart
zur Erlangung der Würde des Doktor-Ingenieurs (Dr.-Ing.)
genehmigte Abhandlung

Vorgelegt von

Samuel Wilhelm Müller

aus Böblingen

Hauptberichterin:	Prof. Dr.–Ing. Nejila Parspour
Mitberichter:	Prof. Dr.–Ing. Dieter Gerling
Tag der mündlichen Prüfung:	07.03.2023

Institut für Elektrische Energiewandlung
der Universität Stuttgart

2023

Berichte aus dem Institut für Elektrische Energiewandlung

Band 14

Samuel Müller

Inductive Electrically Excited Synchronous Machines for Electrical Vehicles

D 93 (Diss. Universität Stuttgart)

Shaker Verlag
Düren 2023

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at http://dnb.d-nb.de.

Zugl.: Stuttgart, Univ., Diss., 2023

Printed in Germany.

ISBN 978-3-8440-9139-7
ISSN 2196-9213

Shaker Verlag GmbH • Am Langen Graben 15a • 52353 Düren
Phone: 0049/2421/99011-0 • Telefax: 0049/2421/99011-9
Internet: www.shaker.de • e-mail: info@shaker.de

Preface

This thesis emerged during my work as research associate at the Institute of Electrical Energy Conversion at the University of Stuttgart. First, I want to express special thanks to my main supervisor Prof. Dr.-Ing. Nejila Parspour, who supported and encouraged me in this work and throughout my work at the Institute.

Further, I would like to thank Prof. Dr.–Ing. Dieter Gerling for co-supervising and the interest in this work.

This project was mainly financed by the Vector Stiftung. I appreciate the support of this work from them, namely Mr. Hinderer, Mr. Litschel and Mr. Schelling. It was essential for the emergence of this work.

A big thank you goes to the workshop, especially to Mr. Hermann Kattner, for supporting the construction of the prototype.

I am very grateful to my colleagues for supporting me in every challenge, the good cooperation and the motivation for this work.

The student theses and research assistants were necessary for the outcome of this thesis. Special thanks go to Julius Weber, Marco Arndt, Christine Futterlieb, Zhimin Li and Fabian Gieck.

Finally, a big thank you goes to my wife Maria, who motivated and supported me to finish this work.

Stuttgart, June 2023 Samuel Wilhelm Müller

Abstract

Due to the strong growth of electromobility, the demand for compact and efficient electric motors is increasing. Currently, mainly permanent magnet synchronous machines are used for electric vehicles. The use of rare earth materials in the magnets is cost-sensitive and decreases the efficiency in the field-weakening range at high speeds. An alternative is the use of electrically excited synchronous machines. Electrically excited synchronous machines are often used as generators. For this purpose, power density, wear and operation over the entire operating range are not relevant but are essential for use in electric vehicles.

This doctoral thesis presents an inductive electrically excited synchronous machine with a contactless energy transmission system. The transmission system is integrated inside the rotor shaft to reduce axial length. The model of an electrically excited synchronous machine is extended by considering saturation. An analytical calculation for the transformation ratio is derived. Furthermore, rotor shape is investigated for operation in field weakening.

During the design process, thermal and mechanical requirements are considered in addition to an electromagnetic design, and the topology selection of the contactless energy transmission system is explained. An electromagnetic optimization method is developed and applied to minimize torque ripple and optimize efficiency in the drive cycle. For this purpose, a vehicle model is used to derive a relevant operating range from the driving cycle. In simulation, the machine losses in the driving cycle are reduced by 40 % compared to referenced permanent magnet excited synchronous machine.

The optimized machine is built as a prototype with an integrated contactless energy transmission system, driven on the test bench and evaluated.

Zusammenfassung

Durch den starken Zuwachs der Elektromobiltät steigt der Bedarf an kompakten und effizienten Elektromotoren. Aktuell werden für Elektrofahrzeuge hauptsächlich permanentmagnetisch erregte Synchronmaschinen eingesetzt. Der Einsatz von seltenen Erden in den Magneten ist sowohl kostensensitiv als auch nachteilig für den Wirkungsgrad im Feldschwächebereich bei hohen Drehzahlen. Eine Alternative ist der Einsatz von elektrisch erregten Synchronmaschinen.
Elektrisch erregte Synchronmaschinen werden häufig als Generatoren eingesetzt. Für diesen Zweck sind Leistungsdichte, Verschleiß und Betrieb im gesamten Betriebsbereich nicht relevant, für den Einsatz in Elektrofahrzeugen jedoch essenziell.

In dieser Doktorarbeit wird eine induktiv elektrisch erregte Synchronmaschine mit kontaktlosem Energieübertragungssystems vorgestellt. Zur Reduktion der axialen Länge ist das Übertragungssystem in den Rotor integriert. Es wird dafür die Modellierung der elektrisch erregten Synchronmaschine um die Berücksichtigung der Sättigung ergänzt und eine analytische Berechnung des, für die Modellierung notwendigen, Übersetztungsverhältnisses hergeleitet. Desweiteren wird das Rotordesign für Betrieb in Feldschwäche untersucht.

Beim Design des Systems werden dabei neben einer elektromagnetischen Auslegung auch thermische und mechanische Anforderungen berücksichtigt sowie eine Topologieauswahl des Überragungssystems erläutert. Eine elektromagnetische Optimierung wird entwickelt und zur Minimierung der Drehmomentwelligkeit und Optimierung des Wirkungsgrades im Fahrzyklus angewandt. Dazu wird mit Hilfe eines Fahrzeugmodells aus dem Fahrzyklus ein relevanter Betriebsbereich abgeleitet.

Die optimierte Maschine wird mit integriertem Übertragungssystem als Prototyp aufgebaut, am Prüfstand in Betrieb genommen und ausgewertet.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

Notation	Description
AC	Alternating current
ADAC	Allgemeiner Deutsche Automobil-Club e. V.
ARTEMIS	Assessment and Reliability of Transport Emission Models and Inventory Systems
AWG	American Wire Gauge
BMW	Bayrische Motorenwerke AG
CAD	Computer-aided design
CET	Contactless energy transfer
D.E.	Drive End
DC	Direct current
DOE	Design of experiments
EC	Equivalent circuit
EESM	Electrically Excited Synchronous Machine
EM	Electrical Machine
EU	European Union
EV	Eletrical Vehicle
FE	Finite element
FEA	Finite element analysis
FOC	Field oriented control
FPGA	Field-programmable gate array

Notation	Description
GA	Genetic algorithm
GFRP	Glass-Fibre Reinforced Plastic
HIL	Hardware-in-the-loop
HWFET	Highway Fuel Economy Driving Schedule
iEESM	Inductive Electrically Excited Synchronous Machine
IEW	Institute of Eletrical Energy Conversion
IGBT	Insulated-Gate Bipolar Transistor
IR	Infrared
LHS	Latin hypercube sampling
LUT	Lookup table
MATLAB	Software „matrix laboratory“ from MathWorks®
MDE	Maximum drive efficiency
ME	Maximum efficiency
MTPA	Maximum torque per ampere
N.D.E.	Non-Drive End
NEDC	New European Driving Cycle
NSGA	Non-dominated sorting genetic algorithm
PLL	Phase-locked loop
PM	Permanent Magnet
PMASR	Permanent Magnet Assisted Synchronous Reluctance Motor
PMSM	Permanent Magnet Synchronous Machine
PWM	Pulse-width modulation
SMC	Soft magnetic composite
SVPWM	Space Vector Pulse Width Modulation
TFM	Transverse Flux Machine
UDDS	Urban Dynamometer Driving Schedule
US06	US driving cylce number 06

Notation	Description
VW	Volkswagen
WLTC	Worldwide harmonized Light vehicles Test Cycle
WLTP	Worldwide harmonized Light vehicles Test Procedure

List of Symbols

Symbol	Unit	Description
a_{eff}	—	Effective transformation ratio
A_{f}	m^2	Vehicle frontal area
$a_{\mathrm{coils,par}}$	—	Number of parallel coils on stator
a_{Pol}	—	Pole coverage factor (ratio of rotor tooth width related toτ_{P})
a_{Saliency}		Saliency ratio
$a_{\mathrm{coils,ser}}$	—	Number of serial coils on stator
$a_{\mathrm{coils,serR}}$	—	Number of serial coils on rotor
a_{turn}	—	Turns ratio
A_{wire}	mm^2	Wire diameter
B	T	Absolute of magnetic flux density
B_{δ}	T	Absolute of air-gap magnetic flux density
$\hat{B}_{\delta}$	T	Maximum of air-gap magnetic flux density
$\hat{B}$	T	Maximum of magnetic flux density
b_{S}	mm	Slot opening
$C_{\mathrm{Batt,eff}}$	kWh	Effective battery capacity
$C_{\mathrm{Batt,n}}$	Ah	Nominal battery capacity
C_{circ}	m	Circumference of a circle
c_{D}	—	Drag coefficient
C_{esson}	$\mathrm{VA}\,{}^{\mathrm{min}}/_{\mathrm{m}^3}$	Esson's utilization factor
$c_{\mathrm{Fe,exc}}$	W	Iron loss coefficient for excess losses

Symbol	Unit	Description
$c_{\mathrm{Fe,eddy}}$	–	Iron loss coefficient for eddy current losses
$c_{\mathrm{Fe,hyst}}$	–	Iron loss coefficient for hysteresis losses
c_{R}	–	Rolling friction coefficient
c_{windage}	$^{\mathrm{Nm}}/_{\mathrm{s}^2}$	Windage loss coefficient
$D_{\mathrm{R,Polesurface}}$	mm	Rotor pole surface diameter
$D_{\mathrm{R,o}}$	mm	Rotor outer diameter
$D_{\mathrm{S,in}}$	m	Stator inner diameter
$D_{\mathrm{S,out}}$	m	Stator outer diameter
D_{Shaft}	mm	Shaft diameter
$D_{\mathrm{S,o}}$	mm	Stator outer diameter
$D_{\mathrm{S,i}}$	mm	Stator inner diameter (stator bore diameter)
e	–	Euler's number
f	$^{1}/_{\mathrm{s}}$	Electrical frequency
F_0	mm^{p}	Auxiliary variable for determination of rotor tooth shape for sinusoidal air-gap flux
$\vec{F}_{\mathrm{a}}$	N	Applied force
F_{Brake}	N	Braking force
$f_{\mathrm{cost,1}}$	–	First cost value
$f_{\mathrm{cost,2}}$	–	Second cost value
F_{D}	N	Drag force
$f_{\mathrm{fund,max}}$	Hz	Maximum fundamental frequency
$\vec{F}_{\mathrm{n}}$	N	Normal force
F_{R}	N	Rolling friction force
f_{sw}	Hz	Swichting frequency
$F_{\mathrm{Traction,EM}}$	N	Traction force due to the electrical machine
$\vec{F}_{\mathrm{w}}$	N	Weight force
$\vec{F}_{\mathrm{w,slope}}$	N	Downhill-slope force
g	–	Gear module
H	$^{\mathrm{A}}/_{\mathrm{m}}$	Absolute of magnetic field

Symbol	Unit	Description
$\hat{H}_{\delta}$	$^{A}/_{m}$	Maximum of air-gap magnetic field
$h_{\mathrm{Poleoffset}}$	mm	Offset of the pole circle center to rotor circle center
$h_{\mathrm{R,coil}}$	mm	Rotor coil height
$h_{\mathrm{R,lam}}$	mm	Rotor lamination height
$h_{\mathrm{R,tip}}$	mm	Rotor tooth tip height
$h_{\mathrm{R,coil}}$	mm	Rotor tooth height
$h_{\mathrm{R,yoke}}$	mm	Rotor yoke height
$h_{\mathrm{S,coil}}$	mm	Stator coil height
$h_{\mathrm{S,lam}}$	mm	Stator lamination height
$h_{\mathrm{S,tip}}$	mm	Stator tooth tip height
$h_{\mathrm{S,yoke}}$	mm	Stator yoke height
h_{yoke}	mm	Yoke height
i	A	Current eletrical current
i_1	A	Primary side current
i_2	A	Secondary side current
$i_2{}'$	A	Secondary side current referred to the primary side
i_{abc}	A	Three phase current
$\underline{i}$	A	Complex current
i_{d}	A	Stator d-axis current in rotor flux reference frame
$i_{\mathrm{dq,meas}}$	A	Measured complex current in d/q frame
$i_{\mathrm{dq,err}}$	A	Complex current deviation in d/q frame
$i_{\mathrm{dq,SP}}$	A	Stator complex setpoint current in d/q frame
$i_{\mathrm{d,SP}}$	A	Stator d-axis setpoint current in rotor flux reference frame
i_{e}	A	Rotor excitation current
i_{e}'	A	Referred rotor excitation current
I_{e}	A	Effective rotor excitation current
$i_{\mathrm{e,max}}$	A	Maximum rotor excitation current
$I_{\mathrm{e,max,lim}}$	A	Limit of the maximum rotor excitation current

Symbol	Unit	Description
$i_{e,SP}$	A	Rotor excitation setpoint current
i_{μ}	A	Magnetization current in d-axis rotor flux reference frame
$\hat{i}$	A	Current peak value
$I_{phase,max}$	A	Maximum effective phase current
i_q	A	Stator q-axis current in rotor flux reference frame
$i_{q,SP}$	A	Stator q-axis setpoint current in rotor flux reference frame
$I_{S,eff}$	A	Effective stator phase current
I_S	A	Stator current
$\underline{i}_S^{dq}$	A	Complex stator current in rotor flux reference frame
$I_{S,eff,max}$	A	Maximum stator current
j	–	Imaginary unit
k	–	Ordinal number of harmonics
K_d	–	Distribution factor
k_{FP}	–	Fix point factor in fitness calculation
$k_{FP,Power}$	–	Fix point factor for power at the corner point
$k_{FP,Torque}$	–	Fix point factor for torque at the corner point
K_p	–	Pitch factor
$k_{\sigma d}$	–	d-axis flux leakage factor
K_{so}	–	Slot opening factor
$K_{w,R,\nu}$	–	Harmonics rotor winding factor
$K_{w,R}$	–	Fundamental rotor winding factor
$K_{w,S}$	–	Fundamental stator winding factor
$k_{yoke,tooth}$	–	Additional yoke to tooth lamination
L_1	H	Primary side inductance
L_{12}	H	Mutual inductance primary side to secondary side
L_{1m}	H	Primary side main inductance
$L_{1\sigma}$	H	Primary side leakage inductance

Symbol	Unit	Description
L_2	H	Secondary side inductance
L_{21}	H	Mutual inductance secondary side to primary side
L_{2m}	H	Secondary side main inductance
$L_{2m}{}'$	H	Secondary side main inductance referred to the primary side
$L_{2\sigma}$	H	Secondary side leakage inductance
$L_{2\sigma}{}'$	H	Secondary side leakage inductance referred to the primary side
l_{act}	m	Axial length of the active parts
L_d	H	Direct inductance
$L_{d,abs}$	H	Absolute d-axis inductance
$L_{d,abs,const.exc.}$	H	Absolute d-axis inductance with constant excitation
$L_{d,diff}$	H	Differential d-axis inductance
L_{de}	H	D-axis and excitation axis mutual inductance
$L_{dq,diff}$	H	Differential coupling inductance from q- and d-axis
$L_{e,diff}$	H	Differential excitation inductance
$L'_{e,diff}$	H	Referred differential excitation inductance
l_{lam}	mm	Lamination length (axial)
L_m	H	Magnetization inductance
$L_{md,abs}$	H	D-axis magnetization inductance
$L_{md,diff}$	H	Differential d-axis magnetization inductance
L_q	H	Quadrature inductance
$L_{q,abs}$	H	Absolute q-axis inductance
$L_{qd,diff}$	H	Differential coupling inductance from d- to q-axis
$L_{q,diff}$	H	Differential q-axis inductance
$L_{\sigma d}$	H	D-axis leakage inductance
$L_{\sigma d,diff}$	H	Differential d-axis leakage inductance
m_{act}	kg	Mass of the active parts
m_{tot}	kg	Total mass

Symbol	Unit	Description
m_{vehicle}	kg	Vehicle mass
m	–	Number of phases
$\mathcal{F}$	A	Magneto-motive force
$\mathcal{F}_{\text{rotor}}$	A	Magneto-motive force on the rotor
n	$^{1}/_{\text{min}}$	Speed
N	–	Number of turns
N_1	–	Primary side number of turns
N_2	–	Secondary side number of turns
N_{C}	–	Turns per coil
n_{CP}	rpm	Machine speed at corner point
$n_{\text{CP,max}}$	rpm	Maximum speed possible with the calculated corner point
n_{meas}	rpm	Measured speed of the electrical machine
n_{EM}	rpm	Speed of the electrical machine
$n_{\text{it,CP}}$	–	Maximum iterations for MTPA optimization for the corner point
$n_{\text{it,CP}}$	–	Maximum iterations for MTPA optimization for the operation point
n_{max}	rpm	Maximum speed
n_{mech}	$^{1}/_{\text{min}}$	Mechanical speed
n_{OP}	rpm	Machine speed in operating point
N_{par}	–	Number of parallel strands
$N_{\text{R,coil}}$	–	Turns per coil on rotor
N_{E}	–	Number of excitation turns
$N_{\text{S,coil}}$	–	Turns per coil on stator
n_{wheel}	rpm	Speed of the wheel
P	W	Effective active eletrical power
p	–	Number of pole pairs
$P_{\text{Cu,DC}}$	W	DC copper loss

Symbol	**Unit**	**Description**
$P_{\mathrm{Cu,AC}}$	W	AC copper loss
$P_{\mathrm{Cu,DC,R}}$	W	Rotor DC copper loss
$P_{\mathrm{Cu,DC,S}}$	W	Stator DC copper loss
$P_{\mathrm{e,max}}$	W	Maximum rotor excitation power
P_{Fe}	W	Iron loss
p_{Fe}	W/m^3	Specific iron loss
$P_{\mathrm{Cu,S}}$	W	Rotor iron loss
$P_{\mathrm{Fe,S}}$	W	Stator iron loss
P_{fric}	W	Friction losses
$P_{\mathrm{loss,CET}}$	W	Losses in the contactless energy transmission system
p_{max}	–	Maximum number of pole pairs
$P_{\mathrm{gen,max}}$	W	Maximum mechanical power in generator mode
$P_{\mathrm{mot,max}}$	W	Maximum mechanical power
$P_{\mathrm{mot,n}}$	W	Nominal mechanical power
$P_{\mathrm{ref,CP}}$	W	Reference Power at corner point
P_{windage}	W	Windage losses
q	–	Slots per pole per phase
q_{R}	–	Number of rotor slots per pole
Q_{S}	–	Number of stator slots
q_{S}	–	Number of stator slots per pole
$\dot{V}_{\mathrm{vent}}$	$\mathrm{m}^3/\mathrm{min}$	Ventilation flow rate
R	Ω	Electrical resistance
R_1	Ω	Primary side resistance
R_2	Ω	Secondary side resistance
$R_2{}'$	Ω	Secondary side resistance referred to the primary side
r_{dyn}	cm	Dynamic wheel radius
R_{e}	MPa	Yield strength
R_{G}	–	Gear ratio
$\mathcal{R}$	$1/\mathrm{H}$	Magnetic reluctance

Symbol	Unit	Description
R_{m}	MPa	Tensile strength
$\mathcal{R}_{\mathrm{Fe,1}}$	$^{1}/_{\mathrm{H}}$	Magnetic reluctance of the iron on the primary side
$\mathcal{R}_{\mathrm{Fe,2}}$	$^{1}/_{\mathrm{H}}$	Magnetic reluctance of the iron on the secondary side
$\mathcal{R}_{\delta\sigma,1}$	$^{1}/_{\mathrm{H}}$	Magnetic reluctance of the airgap in the primary side leakage path
$\mathcal{R}_{\delta\sigma,2}$	$^{1}/_{\mathrm{H}}$	Magnetic reluctance of the airgap in the secondary side leakage path
$\mathcal{R}_{\delta}$	$^{1}/_{\mathrm{H}}$	Magnetic reluctance of the airgap
$\mathcal{R}_{\mathrm{m}}$	$^{1}/_{\mathrm{H}}$	Main magnetic reluctance
$\mathcal{R}_{\sigma1}$	$^{1}/_{\mathrm{H}}$	Primary side leakage magnetic reluctance
$\mathcal{R}_{\sigma2}$	$^{1}/_{\mathrm{H}}$	Secondary side leakage magnetic reluctance
R_{e}	Ω	Rotor resistance
R'_{e}	Ω	Referred rotor restistance
R_{S}	Ω	Stator phase resistance
$r_{\mathrm{S,Slotcorner}}$	mm	Stator slot corner radius
$S_{\%}$	%	Percentage slope
T	Nm	Torque
t	s	Time
T_{CP}	Nm	Torque at corner point
T_{EM}	Nm	Machine
T_{fric}	Nm	Friction torque
$T_{\mathrm{it,dev\%}}$	%	Percental deviation in torque to previous simuliation for termination criterion
T_{mag}	Nm	Magnetic torque
T_{max}	Nm	Maximum torque
T_{ref}	Nm	Reference torque
$T_{\mathrm{ref,CP}}$	Nm	Reference torque at corner point
T_{shaft}	Nm	Mechanical shaft torque
$T_{\mathrm{shaft}\sim}$	Nm	Mechanical shaft torque ripple

Symbol	Unit	Description
T_{wheel}	Nm	Wheel torque
TRV	$\mathrm{kNm}/\mathrm{m}^3$	Torque per rotor volume
$u_{\mathrm{Limit},v}$	–	Boolean indicates voltage limit reached
v	m/s	Speed
v_1	V	Primary side voltage
v_2	V	Secondary side voltage
$v_2{}'$	V	Secondary side voltage referred to the primary side
v_{a}	V	Stator voltage phase a
$v_{\mathrm{abc,SP}}$	V	Three phase setpoint voltage
V_{act}	m^3	Volume of the active elements
v_{b}	V	Stator voltage phase b
$V_{\mathrm{Batt,n}}$	V	Nomninal battery voltage
v_{c}	V	Stator voltage phase c
v_{circ}	m/s	Circumferential speed
$v_{\mathrm{circ,max}}$	m/s	Maximum circumferential speed
v_{d}	V	Stator d-axis voltage in rotor flux reference frame
v_{DC}	V	DC volatage
$v_{\mathrm{dq,ind}}$	V	Complex induced voltage in d/q frame
$v_{\mathrm{dq,SP}}$	V	Complex setpoint voltage in d/q frame
v_{e}	V	Rotor excitation voltage
v'_{e}	V	Referred rotor excitation voltage
$V_{\mathrm{phase,max}}$	V	Maximum effective phase voltage
v_{q}	V	Stator q-axis voltage in rotor flux reference frame
V_{rotor}	m^3	Rotor volume
v_{vehicle}	km/h	Vehicle speed
$\dot{V}_{\mathrm{fl}}$	l/min	Fluid flow rate
w_{tooth}	mm	Tooth width
$w_{\mathrm{R,coil}}$	mm	Rotor coil width
$w_{\mathrm{R,tooth}}$	mm	Rotor tooth width

Symbol	Unit	Description
$w_{\mathrm{R,tip}}$	mm	Rotor tooth tip width
$w_{\mathrm{S,Slot}}$	mm	Stator slot opnen
$w_{\mathrm{S,tooth}}$	mm	Stator tooth width
x_{pos}	mm	X position in 2D plane
y_{pos}	mm	Y position in 2D plane
α_{Skew}	deg	Rotor skewing angle
α_{Slope}	deg	Slope angle
$\alpha_{\mathrm{S,tooth}}$	deg	Stator tooth angle
$\beta_{\mathrm{F_R}}$	rad	Electrical angle of the rotor flux oriented coordinate system
β_{el}	deg	Current angle in d/q
$\beta_{\mathrm{el,initial}}$	deg	Initial current angle in d/q for the optimization process
δ	m	Magnetic air-gap length
$\delta_{\mathrm{CP,Power}}$	W	Allowed deviation from corner point power with derating the fitness values
$\delta_{\mathrm{CP,Torque}}$	Nm	Allowed deviation from corner point torque with derating the fitness values
$\varepsilon_{\mathrm{el}}$	deg	Eletrical angle
$\varepsilon_{\mathrm{el,k}}$	deg	Eletrical angle at discrete time step k
$\varepsilon_{\mathrm{el,k+1}}$	deg	Eletrical angle at next discrete time step after step k
η	–	Efficiency
$\eta_{\mathrm{Axledrive}}$	–	Axle drive efficiency
η_{CET}	–	Efficiency of the contactless energy transmission system
η_{G}	–	Gear efficiency
η_{iEESM}	–	Efficiency of the iEESM
$\eta_{\mathrm{M,max}}$	–	Maximum machine efficiency
η_{OP}	–	Efficiency at operation point
γ	rad	Viewing angle in the air-gap of the eletrcial machine

Symbol	Unit	Description
μ_0	$^{\mathrm{V\,s}}/_{\mathrm{A\,m}}$	Vacuum permeability
λ_d	Vs	d-Axis flux linkage
λ'_e	Vs	Referred excitation flux linkage
λ_q	Vs	q-Axis flux linkage
λ	Vs	Flux linkage
λ_1	Vs	Primary side flux linkage
$\lambda_{1\sigma}$	Vs	Primary side leakage flux linkage
λ_2	Vs	Secondary side flux linkage
λ_m	Vs	Main flux flinkage
$\lambda_{\sigma 2}$	Vs	Secondary side leakage flux linkage
ν	–	Count variable of a sums
ν_T	–	Torque harmonic count
π	–	Mathematical constant
ρ_air	$^{\mathrm{kg}}/_{\mathrm{m}^3}$	Mass density of the air
σ_mech	MPa	Mechanical stress
$\sigma_\mathrm{mech,peak}$	MPa	Mechanical stress in particular points
σ	$^{\mathrm{N}}/_{\mathrm{m}^2}$	Shear stress
τ_P	mm	Pole width (air-gap center)
$\vartheta_\mathrm{EWdg,R}$	°C	Rotor end winding temperature
$\vartheta_\mathrm{EWdg,S}$	°C	Stator end winding temperature
ϑ	°C	Temperature
$\vartheta_\mathrm{vent,in}$	°C	Ventilation air inlet temperature
$\vartheta_\mathrm{vent,out}$	°C	Ventilation air outlet temperature
$\vartheta_\mathrm{fl,in}$	°C	Fluid inlet temperature
$\vartheta_\mathrm{fl,out}$	°C	Fluid outlet temperature
$\vartheta_\mathrm{Wdg,R}$	°C	Rotor winding temperature
$\vartheta_\mathrm{Wdg,S}$	°C	Stator winding temperature
ω	$^{1}/_{\mathrm{s}}$	Electrical angular frequency of the stator