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Chip Rinaldi Sabirin

Digital Control for Active Magnetic Bearings in High-Speed Permanent-Magnet Synchronous Machine with 40000 rpm and 40 kW

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Digital Control for Active Magnetic Bearings in High-Speed Permanent-Magnet Synchronous Machine with 40000 min^{-1} and 40 kW

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genehmigte Dissertation

von
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"One's today should be better than yesterday, one's tomorrow should be better than today"

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- C.R. Sabirin -

AUFGABENSTELLUNG

In Verarbeitungsprozessen, die von elektrischen Maschinen angetrieben werden, (z.B. Dreh-, Fräs- und Schleifvorgänge) nimmt die Verarbeitungsqualität mit der Prozessdrehzahl zu. Mit der höheren Drehzahl kann das Bauvolumen der zum Einsatz kommenden elektrischen Maschine bei gleicher Abgabeleistung verringert werden. Dies ist auch vorteilhaft für ihre Anwendungen in begrenztem Bauraum, z.B. in Elektrofahrzeugen. Besonders die elektrischen Permanentmagnet-Synchronmaschinen (PMSM) finden wegen hohen Wirkungsgrads und guter Dynamik immer mehr Anwendung als Antriebe in solchen Prozessen.

Es soll die Weiterentwicklung der magnetisch gelagerten PMSM verfolgt werden. In den Vorgängerarbeiten mit zwei Maschinen M1 und M2, die auf die Nennleistung 40 kW und Nenndrehzahl 40000 min^{-1} ausgelegt sind, wurden bereits in den Experimenten mit kleinerer Leistung und Drehzahl die hohe Erwärmung festgestellt, die beim Nennbetrieb die Grenztemperatur der Wärmeklasse überschreiten würde. Aus diesem Grund wurden Vorschläge erarbeitet, um die elektrischen Verluste zu reduzieren. Es soll hier eine neue magnetisch gelagerte PM-Synchronmaschine M3 (gleiche Nennleistung und Nenndrehzahl) mit optimierter Auslegung gebaut und ihr thermisches Verhalten verifiziert werden.

Die Hauptaufgabe dieser Dissertation befasst sich dann mit der digitalen Regelung des magnetisch gelagerten Rotors der Maschine. Hier wird der Schwerpunkt auf die bestehende Maschine M2 gelegt. Die Auslegungsmethoden der Regelung werden dargestellt und ihre Ergebnisse in Bezug auf das Schwingverhalten des Rotors im stationären und dynamischen Zustand verifiziert. Für die o.g. thermische Untersuchung der Maschine M3 wurden zwei magnetisch gelagerte Rotoren M2 und M3 direkt gekoppelt und dies erforderte wesentliche Modifizierungen an deren Regelung. Die Ergebnisse werden abschließend auch präsentiert.

MOTIVATION

The quality of manufacturing process like milling, turning and polishing, which are driven by electrical machines, can be improved by increasing the rotational speed of the system. With the increasing rotational speed and same mechanical output power, the volume of the applied electrical machines can be reduced, which become its advantage in volume-limited applications, e.g. electric vehicles. The application of especially electrical permanent-magnet synchronous machine (PMSM) has been growing in the last decade due to its high efficiency and good system dynamic.

This thesis deals with the next development of magnetic levitated PMSM, which had been investigated in previous research works. There, two machines M1 and M2 with rated power of 40 kW and rated rotational speed of 40000 min^{-1} were designed and built for this purpose. In the experiments of smaller power and lower speed, it was found out that the heating of the machine already reached a level, which would exceed the *Thermal Class* of the machine during the operation at the rated power and speed. Therefore, potential reduction of the electrical losses were investigated to be applied in the next machine M3 (with similar rated power and rotational speed), which will be presented. Its thermal behaviour will be verified in the experiments.

The main focus of this thesis is the digital control of the magnetic levitated rotor, especially of the machine M2. The design method of the control will be presented and its results will be verified by the measurement of the vibration of the levitated rotor during the rotation at steady-state and transients. During the aforementioned experiments on the thermal behaviour of M3, two magnetic-levitated rotors M2 und M3 were directly coupled to each other. Hence, significant changes of their levitation control were necessary. Their results will be also presented in this thesis.

ZUSAMMENFASSUNG

Magnetisch gelagerte rotatorische elektrische Permanentmagnet-Synchronmaschinen (PMSM) können durch die berührungslose Lagerung mit Magnetlagern eine hohe Drehzahl erreichen. Nur geringe Wartung der Maschine ist erforderlich aufgrund des Verzichts auf mechanische Lager mit entsprechender Lagerreibung und zugehöriges Schmiermittel. Vorteilhaft lässt sich die Dynamik des magnetisch gelagerten Rotors als MIMO-System (*Multiple Inputs, Multiple Outputs*), z.B. die Steifigkeit und die Dämpfung, einstellen.
Die elektrische Permanentmagnet-Synchronmaschine ist für ihren im Vergleich zu anderen elektrischen Maschinen relativ hohen Wirkungsgrad bekannt. Trotzdem entstehen Verluste in den verschiedenen Maschinenteilen, z.B. in den Statorwicklungen und den Eisenblechen. In einer früheren Dissertation wurden zwei magnetisch gelagerte PM-Synchronmaschinen M1 und M2 gebaut [30], um das thermische Verhalten zu untersuchen. Die Maschinen wurden jeweils auf eine Leistung von 40 kW und eine Drehzahl von 40000 min^{-1} ausgelegt.
Hauptsächlich aus den Ergebnissen der Maschine M2 wurden die Möglichkeiten zur Reduzierung der elektrischen Verluste identifiziert. Ausgehend von deren Auslegung wurden die Statorwicklungen und Statorströme der in der vorliegenden Dissertation aufgebauten magnetisch gelagerten PM-Syncronmaschine M3 (gleiche spezifizierte Leistung 40 kW und Drehzahl 40000 min^{-1}) dahingehend modifiziert, um die Kupferverluste des Nennstroms und der Stromverdrängung zu reduzieren. Entsprechend wird die magnetische Flussdichte erhöht, damit die gleiche mechanische Abgabeleistung der Maschine erhalten bleibt. In den thermischen Dauerversuchen mit der Maschine M3 werden die Temperaturen an verschiedenen Stellen in der Maschine gemessen. Die Grenzen der zugelassenen Temperaturen sind durch die Wärmeklasse F 155°C der Wicklungs-Isolierung und die technische Grenztemperatur 170°C der Permanentmagnete gegeben.
Während den o.g. thermischen Dauerversuchen sind die Maschinen M2 und M3 direkt miteinander gekoppelt. Die aktiven Magnetlager der Maschine M2 werden durch entkoppelte analoge PID-Regler geregelt, deren Parameter-Einstellung mit hohem Aufwand verbunden ist. Dies motivierte die Realisierung einer digitalen Regelung für die aktiven Magnetlager der Maschine M3. Die klassiche digitale PID-Regelung wird auf der Maschine M3 eingesetzt, da an der kommerziellen Elektronik keine eigenständige Modifikation der Algorithmen möglich ist. Während den Dauerversuchen wurde das Schwingverhalten der Rotoren M2 und M3 im schwebenden Zustand untersucht, das sehr stark von den neu entstehenden Resonanzen der zwei gekoppelten Rotoren abhängt. Die Unterdrückung der Resonanz-Schwingungen konnte durch die Einfügung von Bandsperre-Filtern erzielt werden.
Der Schwerpunkt in dieser Dissertation wird auf die Untersuchung der digitalen Regelung der aktiven Magnetlager der Maschine M2 als Einzelmaschine gelegt, die dafür auf passende Signalverarbeitung aus selbstgebauten Modulen (Signal- und Leistungselektronik, Implementierung der Regelungsalgorithmen in *C*-Sprache auf µC) und Zukauf-Teilen (Sensoren und Mikrocontroller) umgerüstet wurde. Die Auslegung der digitalen Regelung verwendet die Methode des Zustandsreglers in der LQR-Form, in der geeignete Gewichtungen auf die Zustands- und Eingangsgrößen des magnetgelagerten Rotors durchgeführt wurden. Das Ziel der Methode ist die Ermittlung eines Minimums für die Findung des optimalen Reglers. Die Schätzung der nicht gemessenen Zustandsgrößen erfolgt durch *Luenberger*-Beobachter bzw. *Kalman*-Filter. Die ausführlichen Experimente bis zur Drehzahl von 40000 min^{-1} ($\approx$ 667 Hz) dokumentieren die Eignung der digitalen Regelung, bestehend aus dem Zustandsregler, dem Zustandsschätzer und der Störungskompensation. Diese Ergebnisse, zusammen mit der o.a. optimierten elektromagnetischen und thermischen Auslegung des Antriebs, sollen die Nachweise über die praktische Anwendbarkeit von magnetisch gelagerten elektrischen PM-Synchronmaschinen mit hoher Leistung und hoher Drehzahl bringen und dadurch den Einsatz als kommerzielle Produkte unterstützen.

ABSTRACT

Magnetic levitated rotational electrical permanent-magnet synchronous machines (PMSM) can reach a high speed due to its contactless rotor suspension with active magnetic bearings. Less maintenance is necessary due to the absence of mechanical bearings and its corresponding lubricants. The rotor dynamic as a MIMO-system (*Multiple Inputs, Multiple Outputs*), e.g. its stiffness and damping, can also be adjusted by an appropriate controller.

The electrical PM synchronous machine is well-known for its higher efficiency, compared to other types of electrical machines. However, the losses, in the stator windings and the iron stack sheets, remain the main concern for its design. In a previous thesis, two magnetic levitated PM synchronous machines M1 and M2 were built [30], with rated power of 40 kW and rated speed of 40000 min^{-1}, to serve as devices under test on the thermal behaviours.

Mainly the results of machine M2 showed the potentials to further reduce the electrical losses. Based on the specifications of machine M2, a new machine M3 will be built, at same rated power and speed, with some modifications to reduce the copper losses due to the rated current and current displacement. In order to keep the same rated power, the magnetic flux density is designed with increased value. The machine M3 will be tested and its temperatures at different positions in the machine will be measured to verify its thermal behaviours. The technical limits of the temperatures are determined by the *Thermal Class* F 155°C of the winding insulations and the technical operation limit of the permanent magnets at 170°C.

During the test on the thermal behaviours, the rotors of machines M2 and M3 are directly coupled to each other. The active magnetic bearings of machine M2 are controlled by analogue PID controller, in which its control parameters can not be changed that easily. This is the motivation to apply a digital controller for the active magnetic bearings of machine M3. However, only classical decoupled PID control is implemented there, because the proprietary electronic does not allow modifications from outside on the control algorithms. During the test, the vibrations of the levitated rotor are measured, which depends strongly on the new resonance frequencies which correspond to the direct coupling of both rotors. Cascaded notch-filters are applied to attenuate the vibrations at those frequencies and thus to enable the stable rotor levitation.

The main focus of this thesis is the digital control of the active magnetic bearings of the single machine M2. For this purpose, the signal-processing electronic was newly built, that comprises of self-designed modules (low-volt-, power electronics and implementation of control algorithms in *C language* on μC) and proprietary modules (sensors and μC). The digital control is designed by the method of state-space control of the LQ regulator. It uses weighting factors on the state- and input variables of the magnetic levitated rotor to reach a minimum cost function to determine the optimum controller. The estimation of unmeasured state variables is executed by *Luenberger* observer or *Kalman* filter, respectively. The various experiments up to the speed of 40000 min^{-1} verifies the good performance of the digital control, that comprises of the state-space LQ regulator, the state estimators and the disturbance compensation.

The results, of the vibration of the levitated rotor and of the tests on the thermal behaviours with optimized electromagnetic and thermal design of the machine, shall serve as scientific proofs for the application of magnetic levitated electrical PM synchronous machine in the real technical systems. Beyond that intention, this thesis shall contribute to the acceptance of magnetic levitated electrical machines as emerging commercial products.

ABBREVIATIONS

AC	Alternating Current
ADC	Analogue-Digital Converter
AMB	Active Magnetic Bearing
COG	Center of Gravity
CPU	Central Processing Unit
42 CrMo 4	Chromium-Molybdenum steel
DC	Direct Current
DE	Drive End
DOF	Degree of Freedom
EMF	Electromotive Force
EMI	Electromagnetic Interference
I/O	Input (and) Output
JTAG	Joint Test Action Group
MB	Magnetic Bearing
MIMO	Multiple Inputs Multiple Outputs
NDE	Non-Drive End
NdFeB	Neodymium Iron Boron
NRE	Non-Recurring Engineering
OP	Operating Point
PI	Proportional Integral
PID	Proportional Integral Derivative
PM	Permanent Magnet
PMSM	Permanent Magnet Synchronous Machine
SISO	Single Input Single Output
SPOC-D	Structure-Predefined Optimal Control for Discrete Systems

INDEX OF VARIABLES

Variable	SI-Unit	Description
A_{Cu}	m^2	copper cross-section of phase winding
A_s	m^2	effective magnetic core cross-section of magnetic bearing
A_{pole}	m^2	effective pole cross-section of magnetic bearing
A_z	-	magnitude of damping constant in the complex *s*-plane
a_a	-	number of parallel coil groups
a_i	-	number of parallel wires per turn
$\boldsymbol{B}$		force-input **matrix** of magnetic-levitated rotor, related to center of gravity
$B_{\delta dr}$	T	idealized air-gap flux density of machine
$B_{\delta dr,si}$	T	air-gap flux density at stator bore inner surface of machine
B_n	T	flux density in magnetic bearing, perpendicular to core cross-section
B_r	T	remanence (flux density) of permanent magnet
B_{Fe}	T	flux density in iron
B_{δ}	T	air-gap flux density of magnetic bearing
b_m	m	width of permanent-magnet
b_{slot}	m	average slot width
$b_{mb,p}$	m	pole width of magnetic bearing
$\boldsymbol{C}_{c,dig}$		controllability **matrix** of discrete state-space system
$\boldsymbol{D}_d$		input **matrix** of disturbance vector in magnetic bearings state-space system
ΔD_{sl}	m	undersize of sleeve
d_{Cu}	m	diameter of single copper strand
d_{MB}	$N\cdot s\cdot m^{-1}$	damping of magnetic-levitated rotor
d_r	m	rotor diameter
d_{si}	m	inner stator bore diameter of machine
$d_{mbs,i}$	m	inner stator bore diameter of magnetic bearing
$d_{m,o}$	m	rotor diameter at the magnet surface
$d_{si,*}$	m	(inner or outer) diameter of sleever
E_{sl}	$N\cdot m^{-2}$	*Young*'s modulus of rotor retaining sleeve
E_{kin}	J	kinetic energy of rotating rotor
e_{COG}	m	rotor excentricity, related to center of gravitiy
$\boldsymbol{F}$		system **matrix** of analogue state-space system
$\boldsymbol{F}_{dis}$		system **matrix** of discrete state-space system for disturbance forces
$\boldsymbol{F}_{dig}$		system **matrix** of discrete state-space system for magnetic bearings
F_m	N	mechanical force
F_{mag}	N	effective magnetic pulling force of magnetic bearing
F_{MB}	N	mechanical force on magnetic-levitated rotor
$\boldsymbol{f}$		force **vector** of magnetic-levitated rotor, related to center of gravity
$\boldsymbol{f}_{MB}$		force **vector** of magnetic-levitated rotor, related to magnetic bearings

$\boldsymbol{f}_{d,MB}$		**vector** of disturbance force on magnetic-levitated rotor, related to magnetic bearings
$\boldsymbol{f}_{exc}$		**vector** of total excitation force on magnetic-levitated rotor
f_s	Hz	fundamental frequency of machine winding current
f_{Tr}	Hz	switching frequency of the transistors in the voltage source inverter
f_{Pu}	Hz	pulse frequency of the line-to-line voltage at the output of the voltage source inverter
$f_{r,el}$	Hz	natural frequency of first elastic rotor bending mode
f_x	N	mechanical force on magnetic-levitated rotor in *x*-direction
f_y	N	mechanical force on magnetic-levitated rotor in *y*-direction
$f_{s,i}$	Hz	sampling frequency of current control-loop in magnetic bearings
$f_{s,pos}$	Hz	sampling frequency of position control-loop in magnetic bearings
$\boldsymbol{G}$		gyroscopic **matrix** of magnetic-levitated rotor, related to center of gravity
$\boldsymbol{G}_{ref}$		reference-input **matrix** of magnetic bearings state-space system
$\boldsymbol{G}_i$		input **matrix** of analogue state-space system
$\boldsymbol{G}_{dig}$		input **matrix** of discrete state-space system
$\boldsymbol{G}_{MB}$		gyroscopic **matrix** of magnetic-levitated rotor, related to magnetic bearings
g	$m \cdot s^{-2}$	gravity constant of earth (= 9.81 $m \cdot s^{-2}$)
$\boldsymbol{H}$		output **matrix** of analogue state-space system
$\boldsymbol{H}_{dis}$		output **matrix** of discrete state-space system for disturbance vector
$\boldsymbol{H}_{dig}$		output **matrix** of discrete state-space system for magnetic bearings
$\boldsymbol{H}_{ham}$		*Hamiltonian* control **matrix**
H_{Bessel}	-	transfer function of low-pass *Bessel*-filter
H_{notch}	-	transfer function of notch filter
H_{Fe}	$A \cdot m^{-1}$	magnetic field strength in iron parts
H_{δ}	$A \cdot m^{-1}$	magnetic field strength in air gap
h_s	m	sleeve thickness
h_m	m	height of permanent-magnet
$\mathbf{I}_4$	-	4^{th} order diagonal identity matrix
$\mathbf{I}_8$	-	8^{th} order diagonal identity matrix
I_s	A	stator phase current
I_{sq}	A	stator phase current in phase with U_p
I_{sd}	A	stator phase current perpendicular to U_p
I_x; I_y; I_z	$kg \cdot m^2$	rotor moment of inertia around *x*-, *y*- and *z*-axis
I_{inv}	A	rated current of the voltage source inverter
i	A	electrical current
i_{err}	A	value of electrical current of "violation error" of PWM
i_{ref}	A	reference value of PWM current of magnetic bearing
Δi_{band}	A	band boundary value of PWM reference current i_{ref}
i_0	A	electrical current of bias winding of magnetic bearing
i_c	A	electrical current of control winding magnetic bearing
$\boldsymbol{i}_{MB}$		**vector** of control currents of magnetic bearings
J	-	cost function for design of linear quadratic (LQ) regulator
$J_{rot} = I_{rot}$	$kg \cdot m^2$	rotor moment of inertia around rotational axis
$\boldsymbol{J}$		direct transmission **matrix** of analogue state-space system
$\boldsymbol{J}_{dig}$		direct transmission **matrix** of discrete state-space system
$\boldsymbol{K}_{s,MB}$		displacement-force **matrix**, related to magnetic bearings

		coordinates
$\boldsymbol{K}_{i,\mathrm{MB}}$		current-force **matrix**, related to magnetic bearings coordinates
$\boldsymbol{K}_{\mathrm{fb}}$		state-feedback gain **matrix** of discrete state-space system
$\boldsymbol{K}_{\mathrm{dis}}$		feed-forward disturbance compensation **matrix**
K_{P}	$\mathrm{A \cdot m^{-1}}$	proportional-feedback gain
K_{D}	$\mathrm{A \cdot s \cdot m^{-1}}$	differential-feedback gain
k_{d}	-	distribution factor
k_{p}	-	pitch factor
k_{w}	-	winding factor
k_{δ}	-	flux density factor due to curvature of air gap
k_{2D}	-	flux density factor due to radial/tangential field vectors in the air gap
$k_{\mathrm{m,leak}}$	-	flux density factor due to leakage of the permanent magnets flux in the air gap
k_{seg}	-	flux density factor due to segmentation of permanent magnets
k_{mag}		magnetic constant of magnetic bearing
k_i	$\mathrm{N \cdot m^{-1}}$	current-force coefficient of magnetic bearing
k_s	$\mathrm{N \cdot A^{-1}}$	displacement-force coefficient of magnetic bearing
k_{MB}	$\mathrm{N \cdot m^{-1}}$	stiffness of magnetic-levitated rotor
L_{coil}	H	inductance of magnetic bearings coil, related to control current
$\boldsymbol{L}_{\mathrm{e}}$		**matrix** of *Luenberger*-estimator
$\boldsymbol{L}_{\mathrm{k}}$		**matrix** of *Kalman*-filter
L_0	H	nominal inductance of magnetic bearing coil
L_{s}	H	phase inductance of stator winding
L_{h}	H	self-inductance
$L_{\sigma\mathrm{b}}$	H	leakage inductance of winding end-turn
$L_{\sigma\mathrm{Q}}$	H	slot leakage inductance
$L_{\sigma\mathrm{Z}}$	H	tooth tip leakage inductance
l_{Fe}	m	axial length of iron stack
l_{core}	m	iron path of flux density in magnetic bearings
l_{Cu}	m	length of the phase winding conductor
l_{ov}	m	length of phase winding overhang
l_{mb}	m	axial length of the iron stack of the magnetic bearing
$\boldsymbol{M}$		mass **matrix** of magnetic-levitated rotor, related to center of gravity
$\boldsymbol{M}_{\mathrm{ric}}$		*Riccati* **matrix** for the design of optimal *Kalman*-filter
$\boldsymbol{M}_{\mathrm{MB}}$		mass **matrix** of magnetic-levitated rotor, related to magnetic bearings
M_{e}	$\mathrm{N \cdot m}$	elecromagnetic air-gap torque
M_{mech}	$\mathrm{N \cdot m}$	shaft driving torque
M_{load}	$\mathrm{N \cdot m}$	load torque
m_{phase}	-	phase number
m_{rot}	kg	rotor mass
m_{imb}	kg	equivalent mass of rotor imbalance
N_{c}	-	number of turns per coil
N_{s}	-	number of turns per phase
N_0	-	number of turns of the bias winding of the magnetic bearing
N_{c}	-	number of turns of the control winding of the magnetic bearing
$n=n_{\mathrm{mot}}=n_{\mathrm{mech}}$	$\mathrm{s^{-1}}$	rotational speed
$\boldsymbol{O}_{\mathrm{ob,dig}}$		observability **matrix** of discrete state-space system
P_{el}	W	electrical power

P_δ	W	air-gap "electromagnetic" power
P_{mech}	W	mechanical (shaft) power
$P_{d,0}$	W	no-load losses of electrical machine
$P_{d,total}$	W	total losses of electrical machine
$\boldsymbol{p}$		motion **vector** of magnetic-levitated rotor, related to center of gravity
$\boldsymbol{p}_{MB}$		motion **vector** of magnetic-levitated rotor, related to magnetic bearings
$\boldsymbol{p}_{Se}$		motion **vector** of magnetic-levitated rotor, related to sensors coordinate
p_p	-	pole pair number
p_c	$N \cdot m^{-2}$	residual contact pressure
$p_{c,pre}$	$N \cdot m^{-2}$	pre-stress contact pressure of the rotor retaining sleeve
$p_{\Omega,m}$	$N \cdot m^{-2}$	speed-dependent pressure on magnet
$p_{\Omega,sl}$	$N \cdot m^{-2}$	speed-dependent pressure on sleeve
Q_s	-	total stator slot number
Q_i^*	$bit \cdot A^{-1}$	resolution of A/D-converter on magnetic bearings control current
Q_{pos}^*	$bit \cdot m^{-1}$	resolution of A/D-converter on position sensor signals of magnetic bearings
$\boldsymbol{Q}_u$		weighting **matrix** for inputs vector of magnetic bearings state-space system
$\boldsymbol{Q}_x$		weighting **matrix** for states vector of magnetic bearings state-space system
q_{slot}	-	slot number per phase and pole
R_{coil}	Ω	electrical resistanc eof magnetic bearing coil
R_s	Ω	stator winding resistance per phase
$\boldsymbol{R}_w$		process noise magnitude **matrix** (related to *Kalman* filter)
$\boldsymbol{R}_v$		measurement noise magnitude **matrix** (related to *Kalman* filter)
$r_{sl,i}$	m	inner radius of carbon-glass fibre sleeve
$r_{sl,a}$	m	outer radius of carbon-glass fibre sleeve
r_{sl}	m	average radius of the rotor retaining sleeve
r_m	m	average radius of permanent magnet from sleeve center
r_{rot}	m	rotor radius of imbalance effect
$\boldsymbol{S}_{ric}$		*Riccati* **matrix** for the design of optimal LQ-regulator
s	s^{-1}	*Laplace* operator complex argument
$s_0 = \delta_0$	m	nominal air gap of magnetic bearing
s_{slot}	m	slot opening
T_{sam}	s	sampling time of discrete state-space system
t_{pr}	s	signal propagation delay
t_r ; t_f	s	rise time of signal edge; fall time of signal edge
U_{DC}	V	DC-link supply voltage of the winding of magnetic bearing electromagnets
U_{coil}	V	voltage of magnetic bearings coil
U_{imb}	kg·m	rotor imbalance
U_s	V	stator phase r.m.s. voltage
U_p	V	induced stator voltage
$\boldsymbol{u}_{MB}$		input-variables **vector** of magnetic bearings state-space system
u_{coil}	V	voltage of magnetic bearings coil, which excites the control current
$\boldsymbol{v}(k)$		**vector** of measurement noise of magnetic bearings

v_t	$m \cdot s^{-1}$	circumferential speed of the rotor
W	m	coil span
$\boldsymbol{w}(k)$		**vector** of process noise of magnetic bearings
$\boldsymbol{w}_{ref}$		reference **vector** of magnetic bearing state-space system
$\boldsymbol{X}_{ham,i}$		upper part of **vector** $\boldsymbol{\kappa}_{eigen}$
$\boldsymbol{x}_{MB}$		state-variable **vector** of magnetic bearing state-space system
$\tilde{\boldsymbol{x}}_{MB}$		estimated state-variable **vector** of magnetic bearing state-space system
$\hat{\boldsymbol{x}}_{MB}$		estimation error of state-variable **vector** of magnetic bearing state-space system
x	m	displacement of magnetic-levitated rotor, related to center of gravity
x_A , x_B	m	displacement of magnetic-levitated rotor, related to magnetic bearings
x_{Se}	m	displacement of magnetic-levitated rotor, related to sensor coordinates
$\boldsymbol{y}_{MB}$		output-variable **vector** of magnetic bearing state-space system
y	m	displacement of magnetic-levitated rotor, related to center of gravity
y_A , y_B	m	displacement of magnetic-levitated rotor, related to magnetic bearings
y_{Se}	m	displacement of magnetic-levitated rotor, related to sensor coordinates
z_{mp}	-	the number of magnets side-by-side per pole pitch
$\mathbf{0}_4$	-	4^{th} order zero matrix
α	° (rad)	motion angle of magnetic bearing
α_e	-	pole coverage ratio
α_{core}	° (rad)	magnetic effective angle of magnetic bearing pole
$\alpha_{p,leak}$	-	geometry factor of leakage air-gap flux
α_{ϑ}	K^{-1}	1^{st} order temperature coefficient
β	° (rad)	motion angle of magnetic bearing
δ	m	varying air gap of magnetic bearing
δ_{dr}	m	(magnetically) active air gap between the machine stator and rotor
δ_0	m	nominal air gap of magnetic bearing
δ_{aux}	m	nominal air gap of auxiliary (touch-down) bearing
$\boldsymbol{\varepsilon}$		assumed **vector** of minimum errors for the determination of disturbance feed-forward compensation
η	- (%)	efficiency
$\boldsymbol{\kappa}_{eigen}$		stable part of eigen**vector** of *Hamiltonian* matrix for LQ-regulator
λ_b	-	geometry factor of winding overhang leakage inductance
λ_{dig}	-	poles of closed-loop magnetic bearings discrete state-space system
λ_{Qs}	-	geometry factor of slot leakage inductance
λ_Z	-	geometry factor of tooth-tip leakage inductance
$\boldsymbol{\Lambda}_{ham,i}$		lower part of **vector** $\boldsymbol{\kappa}_{eigen}$
μ_0	$\frac{V \cdot s}{A \cdot m}$	magnetic constant $= 4\pi \cdot 10^{-7} \frac{V \cdot s}{A \cdot m}$
μ_r	-	relative permeability
ν , μ	-	ordinal number of harmonic of voltage or flux density resp.