Contents

	Preface	1/3
1.1	Recommended Literature	1/5
1.2	Symbols	1/6
2.	Rotating Fields in Electric Machines	2/ 1
2.1	Basic Principles of Calculation of Magnetic Fields	2/ 1
2.2	Simplified Calculation of the Air-Gap Field of Electric Machines	2/ 4
2.3	Generation of Rotating Magnetic Fields	2/ 8
2.4	Winding Arrangements	2/11
3.	Mathematical Analysis of Air-Gap Fields	3/ 1
3.1	Fundamental und Harmonics of Air-Gap Fields	3/ 1
3.2	*FOURIER*-Analysis for Determination of the Fundamental and Harmonics	3/ 3
3.3	*FOURIER*-Analysis of the Field of a Squirrel-Cage Winding	3/11
3.4	*FOURIER*-Analysis of DC-Excited Rotating Fields	3/13
4.	Voltage Induction in Three-Phase Machines	4/ 1
4.1	*FARADAY*'s Law of Induction (1831)	4/ 1
4.2	Voltage Induction in a Stator Coil	4/ 7
4.3	Voltage Induction in a Three-Phase Winding	4/ 9
4.4	Self-Inductance per Phase of a Three-Phase Winding	4/12
4.5	Mutual Inductance of Two Phases of a Three-Phase Winding	4/15
5.	The Slipring Induction Machine	5/ 1
5.1	Principles of Operation of Slipring Induction Machines	5/ 1
5.2	Steady State Behaviour of an Induction Machine	5/ 7
5.3	Asynchronous Energy Conversions	5/17
5.4	Circle Diagram of an Induction Machine	5/19
5.5	Start up of Slipring Induction Machine using Starting Resistors	5/25
5.6	Variable Speed Operation of Slipring Induction Machines	5/27
6.	The Squirrel-Cage Induction Machine	6/ 1
6.1	Currents and Voltages in the Squirrel-Cage	6/ 1
6.2	Current Displacement in the Rotor Bars	6/ 5
6.3	Design of Squirrel-Cages to Increase the Breakaway Torque	6/ 9
6.4	Deviations of the Circle Diagram	6/12
7.	Induction Machine Based Drive Systems	7/ 1
7.1	Typical Work Machines	7/ 1
7.2	Running up of Line-Fed Induction Machines	7/ 3
7.3	Stable and Unstable Working Points – "Quasistatic Stability"	7/ 8
7.4	Braking of Induction Machines	7/10
7.5	Variable Speed Operation of Induction Machines	7/13
7.6	The Subsynchronous Converter Cascade	7/20
7.7	Inverter-Fed Induction Machines	7/23
8.	The Synchronous Machine	8/ 1
8.1	Principles of Operation and Rotor Design	8/ 1
8.2	Stator Equivalent Circuit of a Round-Rotor Machine	8/ 4
8.3	Stator Equivalent Circuit of a Salient-Pole Machine	8/ 9
8.4	Characteristics of Line-Fed Round-Rotor Machines	8/13
8.5	Characteristics of Line-Fed Salient-Pole Machines	8/18
8.6	Balance of Losses of Synchronous Machines	8/20
8.7	Synchronous Generators at Isolated Operation	8/22
9.	Electrically Excited and Permanent Magnet Synchronous Machines	9/ 1
9.1	Electrical Excitation Systems	9/ 1
9.2	No-Load and Short-Circuit Characteristic	9/ 4
9.3	Electrically Excited Synchronous Machines with Damper Winding	9/ 7

9.4	Behaviour of the Damper Winding under Unbalanced Load and Harmonics	9/10
9.5	Permanently Excited Synchronous Machines	9/13
9.6	Starting and Synchronisation of Synchronous Machines	9/18
10.	DC Drives	10/ 1
10.1	Principles of Operation of DC Machines	10/ 1
10.2	Armature Windings	10/ 7
10.3	Induced Voltage and Electromagnetic Torque	10/16
10.4	Armature Reaction and Compensating Winding	10/19
10.5	Commutation of the Armature Current and Use of Commutation Poles	10/22
10.6	Connections of DC Generators and Motors	10/25
10.7	Variable Speed DC Drives	10/33
10.8	Efficiency, Stability and Performance Curves of DC Machines	10/38
10.9	Dynamic Equations of DC Machines	10/40
Appendix:		
	Type Variety of Electrical Machines and Drives	A-1/ 1
1.1	Electrical Motors and Drives	A-1/ 1
1.2	Electrical Generators	A-1/ 6
1.3	Outdated Machine Designs	A-1/11

The Greek alphabet:

$A\ \alpha$	Alpha	$B\ \beta$	Beta	$\Gamma\ \gamma$	Gamma	$\Delta\ \delta$	Delta
$E\ \varepsilon$	Epsilon	$Z\ \zeta$	Zeta	$H\ \eta$	Eta	$\Theta\ \vartheta$	Theta
$I\ \iota$	Jota	$K\ \kappa$	Kappa	$\Lambda\ \lambda$	Lambda	$M\ \mu$	My (mue)
$N\ \nu$	Ny (nue)	$\Xi\ \xi$	Xi	$O\ o$	Omikron	$\Pi\ \pi$	Pi
$P\ \rho$	Rho	$\Sigma\ \sigma$	Sigma	$T\ \tau$	Tau	$\Upsilon\ \upsilon$	Ypsilon
$\Phi\ \varphi$	Phi	$X\ \chi$	Chi	$\Psi\ \psi$	Psi	$\Omega\ \omega$	Omega

Preamble to the Skriptum "Electric Machines and Drives"

Dear Student!

You have been introduced to the basic principles of Electrical Engineering during your bachelor studies. The present lecture shall allow you to obtain a deeper understanding of the three main rotating converters of electrical energy into mechanical energy and vice versa **(induction machine, synchronous machine, DC machine)**. A future M.Sc. of Electrical Engineering has to be able to give not only a qualitative but also a quantitative description of the performance of such machines. Therefore, the **mathematical analysis** of the mentioned machines is important to predict the operational behaviour of the machines in an analytical way. This will allow you to design drives and estimate simple transient effects.

Tools to Prepare for the Examination:
Written examination: A **compilation of exercises** containing examples of questions similar to the ones given in the first part of the examination is available in addition to the examples given in the exercises during the semester. The compilation of exercises also contains **typical theory questions**, as they are asked in the second part of the examination.
Relevant topics: The compilation of exercises and theory questions refer only to the topics that are relevant for the examination. The parts of the text-book, that are not relevant for the examination, are given below.
Way of examination: written: 2.0 h in total

The **text book** is meant to be used as a "look-up-reference" in addition to the lecture. It contains extensive explanations, mathematical derivations and some information that is useful for practical application and is given in addition to the topics that are relevant for the examination. It should be used for reading at home, and that the student should be free to concentrate on the lecture during class.

Labs:
It is my effort to show "physical machines" during my lectures, using pictures, models and some experiments. However, the mathematical theories will always remain "dry", if you do not use the opportunity to operate different machines by yourself in the frame of the **lab** and experience thereby their genuine behaviour and operational characteristics. Therefore, the "**Power lab"** and **the accompanying exercises** of this lecture are an important complement for a fast and good understanding of modern rotating converters of electrical energy.

Further Lectures on Electric Energy Conversion:
Numerous other modern types of machines, such as stepping motors, dynamic servo motors, switched-reluctance and single-phase induction machines, homopolar machines, transversal flux machines, but also the interaction of machine and converter, the mechanical stability and the aim for operating the machines as dynamic as possible etc. cannot be discussed in the present lecture, because of the limited time. You can learn about these topics in the lecture **"Motor Development for Modern Drive Systems"** that is offered in parallel. A deeper analysis of the transient behaviour as well as the design of induction motors and transformers is content of the lecture **"Energy Converters - CAD and System Dynamics"**, whereas the design of synchronous machines and special techniques for large drives are discussed in the lecture **"Large Machines and High Power Drives"** Modern technologies such as magnetic bearings and superconductivity are topics of the lecture **"New Technologies of Electric Energy Converters and Actuators"**. The seminary **"Practical Oriented Design of Electric Drives (PPEA)"** offers the possibility to solve interesting design tasks for drives of hybrid

electric cars, whereas **"Design of electric machines and actuators with numerical field calculation"** introduces you to modern finite element magnetic and thermal calculation, done by yourself under guidance with commercial software packages.

Literature, Master Thesis Projects, Excursions:
Numerous relevant **master thesis projects**, some of them to be carried out in collaboration with industry as well as extensive corresponding literature are available. A selection of **books,** of which some may be used for self study, are cited in this text book. Also, you should use the opportunity to attend an **excursion** which we try to offer in parallel to the lecture. You (and we also) do learn a lot during these visits. I hope that all this will help to that the world of electric machines becomes more transparent for you, in spite of the sometimes dry theory, and that you will take advantage of this during your later professional life.

Chapters of the Text Book, which are NOT Relevant for the Examination:
Generally: Mathematical derivations should be understood, but not learned by heart.
Chapter 2.1
Chapters 6.3 c), 6.4 c), d)
Chapter 7.4 d)
Chapter 8.6
Chapter 9.4
Chapter 10.9
Appendix

If you have **requests, questions or helpful suggestions**, please do not hesitate to contact either me or the assistants of our institute.

With best wishes for your studies

Prof. Andreas Binder Darmstadt, September 2011

1.1 Recommended Literature to Deepen and Complete the Understanding

Out of the extensive, more than 100 years old literature, some older works that explain the fundamental principles of electromagnetic energy conversion are as much recommended as recently published books and articles of regular scientific journals and conference proceedings. A **selection** is given in the following.

Scientific books:

Introductions:

Fischer, R.: Elektrische Maschinen, Hanser, München, 10. Auflage, 2000
Spring, E.: Elektrische Maschinen – eine Einführung, Springer, Berlin 1998
Seinsch, H.-O.: Grundlagen elektrischer Maschinen und Antriebe, Teubner, Stuttgart, 1993
Brosch, P.: Moderne Stromrichterantriebe – Leistungselektronik und Maschinen, Vogel-Verlag, 3. Auflage 1998
Giersch, H.-U.; Harthus, H.; Vogelsang, N.: Elektrische Maschinen, Teubner, Stuttgart, 4. Auflage, 1998
Späth, H.: Elektrische Maschinen und Stromrichter, G. Braun, Karlsruhe, 1984
Kleinrath, H.: Grundlagen elektrischer Maschinen, Akademische Verlagsgesellschaft, Wiesbaden, 1975
Dubey, G.K.: Fundamentals of Electrical Drives, Narosa Publishing, New Delhi, 1995
Hindmarsh, J.: Electrical Machines and their Applications, Pergamon Press, Oxford, 1991
Hindmarsh, J.: Electrical Machines and Drives – Worked Examples, Pergamon Press, Oxford, 1985

Specific Literature:

Kleinrath, H.: Stromrichtergespeiste Drehfeldmaschinen, Springer-Verlag, Wien, 1980
Bödefeld, Th.; Sequenz, H.: Elektrische Maschinen. Eine Einführung in die Grundlagen, Springer-Verlag, Wien, 1971
Müller, G.: Elektrische Maschinen – Grundlagen, Aufbau und Wirkungsweise, VEB Technik, Berlin,6. Auflage, 1985
Müller, G.: Elektrische Maschinen – Betriebsverhalten rotierender elektrischer Maschinen, VEB Technik, Berlin, 1985
Schröder, D.: Elektrische Antriebe (Bände 1 bis 4), Springer, Berlin 1998
Constantinescu, S. et al.: Elektrische Maschinen und Antriebssysteme – Komponenten, Systeme, Anwendungen, Vieweg, 1999
Stölting, H.-D.; Kallenbach, E. (Hrsg.) : Handbuch Elektrische Kleinantriebe, Hanser, München, 2001
Wiedemann, E.; Kellenberger, W.: Konstruktion elektrischer Maschinen, Springer, Berlin, 1967
Kümmel, F.: Elektrische Antriebstechnik, Teil 1: Maschinen, VDE-Verlag, Berlin, 1985
Kümmel, F.: Elektrische Antriebstechnik, Teil 2: Leistungsstellglieder, VDE-Verlag, Berlin, 1986
Kümmel, F.: Elektrische Antriebstechnik, Teil 3: Antriebsregelung, VDE-Verlag, Berlin, 1998
Bohn, T. (Hrsg.): Elektrische Energietechnik, aus: Handbuchreihe Energie, Bd. 4, TÜV Rheinland, 1987
Hering, E.; Vogt, A.; Bressler, K.: Handbuch der Elektrischen Anlagen und Maschinen, Springer, Berlin, 1999
Falk, K.: Der Drehstrommotor – Ein Lexikon für die Praxis, VDE-Verlag GmbH, Berlin Offenbach, 1997

Scientific Journals:

European Transactions on Electrical Power (ETEP), VDE Verlag, Berlin
Elektrie, Verlag Dr.Heide, Berlin
IEE Proceedings – Electric Power Applications, Institution of Electrical Engineers, London, United Kingdom
IEEE Transactions on Industry Applications, Institute of Electric and Electronics Engineers, Industry Application Society, New York, USA
IEEE Transactions on Energy Conversion, Institute of Electric and Electronics Engineers, Power Engineering Society, New York, USA

Proceedings of regular Scientific Conferences:

Proceedings of the International Conference on Electric Machines (ICEM)
Proceedings of the European Power Electronics & Application Conference (EPE)

1.2 Verwendete Symbole / List of symbols

a	-	Anzahl paralleler Wicklungszweige bei Drehfeldmaschinen, aber: HALBE Anzahl paralleler Wicklungszweige bei Gleichstrommaschinen	number of parallel winding branches of poly-phase machines, however: HALF of the number of parallel winding branches of dc machines
A	A/m	Strombelag	electric loading
A	m^2	Fläche	area
b_s, b_r	m	Nutbreite (Stator, Rotor)	slot width (stator, rotor)
b_p	m	Polschuhbreite	width of pole shoe
b_{Stab}	m	Stabbreite	width of bar
B	T	magnetische Induktion (Flussdichte)	magnetic induction (flux density)
c_d, c_q	-	Feldfaktoren der Längs-, Querachse	field factors of d-(direct) and q-(quadrature) axis
c_ϑ	Nm/rad	Ersatzfederkonstante der Synchronmaschine	equivalent spring constant of a synchronous machine
d_{si}	m	Bohrungsdurchmesser	bore diameter
D	As/m^2	elektrische Verschiebung (elektrische Flussdichte)	electric displacement (electric flux density)
E	V/m	elektrische Feldstärke	electric field density
f	Hz	elektrische Frequenz	electric frequency
F	N	Kraft	force
g	-	ganze Zahl	integer
h	m	Höhe	height
H	A/m	magnetische Feldstärke	magnetic field density
I	A	elektrische Stromstärke	electric current
j	-	imaginäre Einheit	imaginary unit
J	A/m^2	elektrische Stromdichte	electric current density
J	kgm^2	polares Trägheitsmoment	moment of inertia
k	-	Ordnungszahl	ordinal number
k_d	-	Zonenfaktor	distribution factor
k_K	-	Leerlauf-Kurzschluss-Verhältnis	no load - short circuit ratio
k_p	-	Sehnungsfaktor	pitch factor
k_R, k_L	-	Stromverdrängungsfaktoren	current displacement factors
k_R	V·s/A	Proportionalitätskonstante der Reaktanzspannung	proportional constant of the reactance voltage
k_w	-	Wicklungsfaktor	winding factor
K	-	Anzahl der Kommutatorsegmente	number of collector segments
l	m	Länge (axial)	length (axial)
L	H	Selbstinduktivität	self inductance
m	-	Strangzahl	number of phases
M	H	Gegeninduktivität	mutual inductance
M	Nm	Drehmoment	torque
M_b	Nm	asynchrones Kippmoment	asynchronous breakdown torque
M_{p0}	Nm	synchrones statisches Kippmoment	synchronous, steady-state breakdown torque
M_s	Nm	Kupplungsmoment, Wellenmoment	shaft torque

M_1	Nm	Anfahrmoment	breakaway torque
n	1/s	Drehzahl	motor speed
N	-	Windungszahl je Strang	number of windings per phase
N_c	-	Spulenwindungszahl	number of windings per coil
p	-	Polpaarzahl	number of pole pairs
P	W	Leistung	power
q	-	Lochzahl (Nuten pro Pol und Strang)	number of slots per pole and phase
Q	-	Nutenzahl	number of slots
R	Ohm	elektrischer Widerstand	electric resistance
s	-	Schlupf	slip
s	m	Weglänge	distance
t	s	Zeit	time
T	s	Zeitkonstante	time constant
u	-	Spulenseiten je Nut und Schicht	number of coils per slot and layer
U	V	elektrische Spannung	electric voltage
U_p	V	Polradspannung	synchronous internal voltage
$ü$, $ü_U$	-	Übersetzungsverhältnis (Spannungsübersetzungsverhältnis)	ratio (voltage ratio)
$ü_I$	-	Stromübersetzungsverhältnis	current ratio
v	m/s	Geschwindigkeit	velocity
V	A	magnetische Spannung	magneto-motive force ("magnetic voltage")
V	m^3	Volumen	volume
W	J	Energie	energy
W	m	Spulenweite	coil width
x	m	Umfangskoordinate	circumferential coordinate
X	Ohm	Reaktanz	reactance
X_d, X_q	Ohm	Längs-, Querreaktanz	d-, q-reactance
y	-	Weite einer Spule, gezählt in Nutteilungen	width of a coil in numbers of slots
z	-	gesamte Leiterzahl	total number of conductors
Z	Ohm	Impedanz	impedance
α_e	-	äquivalente Polbedeckung	pole pitch factor
α	rad	Zündwinkel	firing angle
α_Q	rad	Nutenwinkel (elektrischen Grad)	slot angle (electric degrees)
γ	rad	Umfangswinkel (elektrische Grad)	circumferential angle (electric degrees)
δ	m	Luftspalt	air-gap
φ	rad	Phasenwinkel	phase angle
Φ	Wb	magnetischer Fluss (Scheitelwert)	magnetic flux (peak value)
Ψ	Vs	magnetische Flussverkettung (Scheitelwert)	magnetic flux linkage (peak value)
κ	S/m	elektrische Leitfähigkeit	electric conductivity
μ	-	Ordnungszahl	ordinal number
μ	Vs/(Am)	magnetische Permeabilität	magnetic permeability
μ_0	Vs/(Am)	magnetische Permeabilität des Vakuums ($4\pi \cdot 10^{-7}$ Vs/(Am))	magnetic permeability of vacuum ($4\pi \cdot 10^{-7}$ Vs/(Am))

ν	-	Ordnungszahl	ordinal number
ξ	-	„reduzierte" Leiterhöhe	"reduced" conductor height
η	-	Wirkungsgrad	efficiency
ϑ	rad	Polradwinkel (elektrische Grad)	load angle (electric degrees)
Θ	A	elektrische Durchflutung	Ampere-turns
σ	-	BLONDEL´scher Koeffizient der Gesamtstreuung, Streuziffer	BLONDEL's leakage coefficient
σ_o	-	Streuziffer der Oberfelderstreuung	leakage coefficient of harmonic leakage
τ_c	m	Kommutatorstegteilung	collector segment pitch
τ_Q, τ_s, τ_r	m	Nutteilung allgemein bzw. Stator- und Rotornutteilung	slot pitch in general, stator / rotor slot pitch
τ_p	m	Polteilung	pole pitch
ω	1/s	elektrische Kreisfrequenz	electric angular frequency
Ω	1/s	elektrische Winkelgeschwindigkeit	electric angular speed
ω_m, Ω_m	1/s	mechanische Winkelgeschwindigkeit	mechanic angular speed
Indizes / Subscripts			
a		Anker	armature
av		Mittelwert	average value
b		Bürste, asynchrones Kippen	brush, asynchronous breakdown
c		Spule, Kommutator	coil, collector
com		Kommutierungs-	collector
C		Koerzitiv-	coercive
d		direct (längs), dc (Gleichgröße), Zone (distribution), Verluste (dissipation)	direct, dc (direct current), phase (distribution), losses (dissipation)
D		Dämpferwicklung in der Längsachse	damper winding in direct axis
e		elektrisch, äquivalent	electric, equivalent
f		Feld	field
Fe		Eisen	steel
h		Haupt-	mutual / magnetising
i		induziert	induced
in		zugeführt	fed -
k		Kurzschluss-	short circuit -
m		Magnetisierungs-, magnetisch	magnetising -, magnetic
m		mechanisch	mechanical
m		maximal	maximum
N		Nenn	rated
out		abgegeben	delivered
o		Oberfelder	harmonics
p		Pol, Polrad, Sehnung	pole, rotor (synchronous machine), pitch
q		quer	quadrature
Q		Dämpferwicklung in der Querachse	damper winding in the quadrature axis

Q		Nut	slot
r		Rotor	rotor
R		Reaktanz- (Gleichstrommaschine), Remanenz, Reibung	reactance (DC machine), remanence, friction
s		Stator	stator
s		Welle	shaft
sch		schalt	switching
syn		Synchron	synchronous
sh		Shunt	shunt
v		Vorwiderstand	external resistance
w		Wicklung	winding
W		Wendepol	commutating
δ		Luftspalt	air-gap
σ		Streu-	leakage
0		Leerlauf	no load
1		Anfahrpunkt (s = 1 bei Asynchronmaschine)	breakaway (s = 1 with asynchronous machines)
Notationen / Notations			
i		Kleinbuchstabe: z.B.: elektrische Stromstärke, Augenblickswert	lower case letter: e.g.: electric current, instantaneous value
I		Großbuchstabe: z.B.: elektrische Stromstärke, Effektivwert oder Gleichstrom-Wert	upper case letter: e.g.: electric current, rms or dc value
X, x		Großbuchstabe: z.B. Reaktanz, Kleinbuchstabe: z.B. bezogene Reaktanz (p.u. -Wert)	upper case letter: e.g. reactance, lower case letter: e.g. normalised reactance (p.u.-value)
$\underline{I}$		unterstrichen: komplexe Größen	underlined: complex values
$\hat{I}$		Spitzenwert, Amplitude	peak value, amplitude
I'		auf Ständerwicklungsdaten umgerechnet	as seen from the stator winding
X', X''		transiente, subtransiente Reaktanz	transient, subtransient reactance
$\underline{I}^*$		konjugiert komplexer Wert von $\underline{I}$	conjugated complex value of $\underline{I}$
Re(.)		Realteil von ...	real part of ...
Im(.)		Imaginärteil von ...	imaginary part of ...