

Contents

Preface	xi
About the Authors	xiii
Abbreviations and Symbols	xv
1 Principal Laws and Methods in Electrical Machine Design	1
1.1 Electromagnetic Principles	1
1.2 Numerical Solution	8
1.3 The Most Common Principles Applied to Analytic Calculation	12
1.3.1 Flux Line Diagrams	16
1.3.2 Flux Diagrams for Current-Carrying Areas	22
1.4 Application of the Principle of Virtual Work in the Determination of Force and Torque	25
1.5 Maxwell's Stress Tensor; Radial and Tangential Stress	32
1.6 Self-Inductance and Mutual Inductance	36
1.7 Per Unit Values	42
1.8 Phasor Diagrams	45
Bibliography	47
2 Windings of Electrical Machines	48
2.1 Basic Principles	49
2.1.1 Salient-Pole Windings	49
2.1.2 Slot Windings	53
2.1.3 End Windings	54
2.2 Phase Windings	54
2.3 Three-Phase Integral Slot Stator Winding	57
2.4 Voltage Phasor Diagram and Winding Factor	64
2.5 Winding Analysis	72
2.6 Short Pitching	74
2.7 Current Linkage of a Slot Winding	81
2.8 Poly-Phase Fractional Slot Windings	94
2.9 Phase Systems and Zones of Windings	97
2.9.1 Phase Systems	97
2.9.2 Zones of Windings	99

2.10	Symmetry Conditions	101
	2.10.1 <i>Symmetrical Fractional Slot Windings</i>	101
2.11	Base Windings	104
	2.11.1 <i>First-Grade Fractional Slot Base Windings</i>	104
	2.11.2 <i>Second-Grade Fractional Slot Base Windings</i>	105
	2.11.3 <i>Integral Slot Base Windings</i>	106
2.12	Fractional Slot Windings	108
	2.12.1 <i>Single-Layer Fractional Slot Windings</i>	108
	2.12.2 <i>Double-Layer Fractional Slot Windings</i>	117
2.13	Single- and Double-Phase Windings	124
2.14	Windings Permitting a Varying Number of Poles	127
2.15	Commutator Windings	129
	2.15.1 <i>Lap Winding Principles</i>	133
	2.15.2 <i>Wave Winding Principles</i>	136
	2.15.3 <i>Commutator Winding Examples, Balancing Connectors</i>	139
	2.15.4 <i>AC Commutator Windings</i>	143
	2.15.5 <i>Current Linkage of the Commutator Winding and Armature Reaction</i>	144
2.16	Compensating Windings and Commutating Poles	146
2.17	Rotor Windings of Asynchronous Machines	149
2.18	Damper Windings	152
	Bibliography	153
3	Design of Magnetic Circuits	155
3.1	Air Gap and its Magnetic Voltage	161
	3.1.1 <i>Air Gap and Carter Factor</i>	161
	3.1.2 <i>Air Gaps of a Salient-Pole Machine</i>	166
	3.1.3 <i>Air Gap of Nonsalient-Pole Machine</i>	172
3.2	Equivalent Core Length	173
3.3	Magnetic Voltage of a Tooth and a Salient Pole	176
	3.3.1 <i>Magnetic Voltage of a Tooth</i>	176
	3.3.2 <i>Magnetic Voltage of a Salient Pole</i>	180
3.4	Magnetic Voltage of Stator and Rotor Yokes	180
3.5	No-Load Curve, Equivalent Air Gap and Magnetizing Current of the Machine	183
3.6	Magnetic Materials of a Rotating Machine	186
	3.6.1 <i>Characteristics of Ferromagnetic Materials</i>	189
	3.6.2 <i>Losses in Iron Circuits</i>	194
3.7	Permanent Magnets in Rotating Machines	203
	3.7.1 <i>History and Development of Permanent Magnets</i>	203
	3.7.2 <i>Characteristics of Permanent Magnet Materials</i>	205
	3.7.3 <i>Operating Point of a Permanent Magnet Circuit</i>	210
	3.7.4 <i>Demagnetization of Permanent Magnets</i>	217
	3.7.5 <i>Application of Permanent Magnets in Electrical Machines</i>	219
3.8	Assembly of Iron Stacks	226
	Bibliography	227

4	Inductances	229
4.1	Magnetizing Inductance	230
4.2	Leakage Inductances	233
	4.2.1 <i>Division of Leakage Flux Components</i>	235
4.3	Calculation of Flux Leakage	238
	4.3.1 <i>Skewing Factor and Skew Leakage Inductance</i>	239
	4.3.2 <i>Air-Gap Leakage Inductance</i>	243
	4.3.3 <i>Slot Leakage Inductance</i>	248
	4.3.4 <i>Tooth Tip Leakage Inductance</i>	259
	4.3.5 <i>End Winding Leakage Inductance</i>	260
	Bibliography	264
5	Resistances	265
5.1	DC Resistance	265
5.2	Influence of Skin Effect on Resistance	266
	5.2.1 <i>Analytical Calculation of Resistance Factor</i>	266
	5.2.2 <i>Critical Conductor Height in Slot</i>	276
	5.2.3 <i>Methods to Limit the Skin Effect</i>	277
	5.2.4 <i>Inductance Factor</i>	278
	5.2.5 <i>Calculation of Skin Effect in Slots Using Circuit Analysis</i>	279
	5.2.6 <i>Double-Sided Skin Effect</i>	287
	Bibliography	292
6	Design Process of Rotating Electrical Machines	293
6.1	Eco-Design Principles of Rotating Electrical Machines	293
6.2	Design Process of a Rotating Electrical Machine	294
	6.2.1 <i>Starting Values</i>	294
	6.2.2 <i>Main Dimensions</i>	297
	6.2.3 <i>Air Gap</i>	305
	6.2.4 <i>Winding Selection</i>	309
	6.2.5 <i>Air-Gap Flux Density</i>	310
	6.2.6 <i>The No-Load Flux of an Electrical Machine and the Number of Winding Turns</i>	311
	6.2.7 <i>New Air-Gap Flux Density</i>	316
	6.2.8 <i>Determination of Tooth Width</i>	317
	6.2.9 <i>Determination of Slot Dimensions</i>	318
	6.2.10 <i>Determination of the Magnetic Voltages of the Air Gap, and the Stator and Rotor Teeth</i>	323
	6.2.11 <i>Determination of New Saturation Factor</i>	326
	6.2.12 <i>Determination of Stator and Rotor Yoke Heights and Magnetic Voltages</i>	326
	6.2.13 <i>Magnetizing Winding</i>	327
	6.2.14 <i>Determination of Stator Outer and Rotor Inner Diameter</i>	329
	6.2.15 <i>Calculation of Machine Characteristics</i>	329
	Bibliography	330

7	Properties of Rotating Electrical Machines	331
7.1	Machine Size, Speed, Different Loadings and Efficiency	331
7.1.1	<i>Machine Size and Speed</i>	331
7.1.2	<i>Mechanical Loadability</i>	333
7.1.3	<i>Electrical Loadability</i>	337
7.1.4	<i>Magnetic Loadability</i>	338
7.1.5	<i>Efficiency</i>	340
7.2	Asynchronous Motor	342
7.2.1	<i>Current Linkage and Torque Production of an Asynchronous Machine</i>	342
7.2.2	<i>Impedance and Current Linkage of a Cage Winding</i>	349
7.2.3	<i>Characteristics of an Induction Machine</i>	356
7.2.4	<i>Equivalent Circuit Taking Asynchronous Torques and Harmonics into Account</i>	361
7.2.5	<i>Synchronous Torques</i>	367
7.2.6	<i>Selection of the Slot Number of a Cage Winding</i>	369
7.2.7	<i>Construction of an Induction Motor</i>	371
7.2.8	<i>Cooling and Duty Types</i>	373
7.2.9	<i>Examples of the Parameters of Three-Phase Industrial Induction Motors</i>	378
7.2.10	<i>Asynchronous Generator</i>	380
7.2.11	<i>Wound Rotor Induction Machine</i>	382
7.2.12	<i>Asynchronous Motor Supplied with Single-Phase Current</i>	383
7.3	Synchronous Machines	388
7.3.1	<i>Inductances of a Synchronous Machine in Synchronous Operation and in Transients</i>	390
7.3.2	<i>Loaded Synchronous Machine and Load Angle Equation</i>	400
7.3.3	<i>RMS Value Phasor Diagrams of a Synchronous Machine</i>	407
7.3.4	<i>No-Load Curve and Short-Circuit Test</i>	417
7.3.5	<i>Asynchronous Drive</i>	419
7.3.6	<i>Asymmetric-Load-Caused Damper Currents</i>	423
7.3.7	<i>Shift of Damper Bar Slotting from the Symmetry Axis of the Pole</i>	424
7.3.8	<i>V Curve of a Synchronous Machine</i>	426
7.3.9	<i>Excitation Methods of a Synchronous Machine</i>	426
7.3.10	<i>Permanent Magnet Synchronous Machines</i>	427
7.3.11	<i>Synchronous Reluctance Machines</i>	456
7.4	DC Machines	468
7.4.1	<i>Configuration of DC Machines</i>	468
7.4.2	<i>Operation and Voltage of a DC Machine</i>	470
7.4.3	<i>Armature Reaction of a DC machine and Machine Design</i>	474
7.4.4	<i>Commutation</i>	475
7.5	Doubly Salient Reluctance Machine	479
7.5.1	<i>Operating Principle of a Doubly Salient Reluctance Machine</i>	479
7.5.2	<i>Torque of an SR Machine</i>	480
7.5.3	<i>Operation of an SR Machine</i>	481

7.5.4	<i>Basic Terminology, Phase Number and Dimensioning of an SR Machine</i>	485
7.5.5	<i>Control Systems of an SR Motor</i>	489
7.5.6	<i>Future Scenarios for SR Machines</i>	491
	Bibliography	492
8	Insulation of Electrical Machines	495
8.1	Insulation of Rotating Electrical Machines	497
8.2	Impregnation Varnishes and Resins	503
8.3	Dimensioning of an Insulation	506
8.4	Electrical Reactions Ageing Insulation	509
8.5	Practical Insulation Constructions	510
8.5.1	<i>Slot Insulations of Low-Voltage Machines</i>	511
8.5.2	<i>Coil End Insulations of Low-Voltage Machines</i>	512
8.5.3	<i>Pole Winding Insulations</i>	512
8.5.4	<i>Low-Voltage Machine Impregnation</i>	513
8.5.5	<i>Insulation of High-Voltage Machines</i>	513
8.6	Condition Monitoring of Insulation	515
8.7	Insulation in Frequency Converter Drives	518
	Bibliography	521
9	Losses and Heat Transfer	523
9.1	Losses	524
9.1.1	<i>Resistive Losses</i>	524
9.1.2	<i>Iron Losses</i>	526
9.1.3	<i>Additional Losses</i>	526
9.1.4	<i>Mechanical Losses</i>	527
9.1.5	<i>Decreasing Losses</i>	529
9.1.6	<i>Economics of Energy Savings</i>	533
9.2	Heat Removal	534
9.2.1	<i>Conduction</i>	534
9.2.2	<i>Radiation</i>	538
9.2.3	<i>Convection</i>	541
9.3	Thermal Equivalent Circuit	548
9.3.1	<i>Analogy between Electrical and Thermal Quantities</i>	548
9.3.2	<i>Average Thermal Conductivity of a Winding</i>	549
9.3.3	<i>Thermal Equivalent Circuit of an Electrical Machine</i>	550
9.3.4	<i>Modeling of Coolant Flow</i>	560
9.3.5	<i>Solution of Equivalent Circuit</i>	565
9.3.6	<i>Cooling Flow Rate</i>	568
	Bibliography	568
	Appendix A	570
	Appendix B	572
	Index	575