

Contents

1	Introduction	1
1.1	General Considerations	2
1.2	Stationary Coils and Rotating Magnetic Field	3
1.3	Electromagnetic Field Equations and Boundary Conditions; Field Distribution in Heteropolar Machines	7
1.4	Fluid Flow and Heat Transfer in Electric Machines; Types of Cooling	13
1.5	Electric, Magnetic, and Thermal Properties of Materials for Electric Machines; Classes of Insulation	17
1.6	Lumped Element Presentation of Electric, Magnetic, Thermal, and Fluid Flow Circuits	41
	References	42
2	Windings	43
2.1	Active Part and End Winding Zone, Air Gap Winding Versus Coils in Slots, Slot Fill Factor	44
2.2	Single- and Double-Layer Windings, Coil Pitch, Skewing, Feasibility	48
2.3	Current Sheet and Air Gap MMF	55
2.4	Spatial Harmonics in Air Gap MMF, Slot-Opening Factor, Winding Factors	56
2.5	Air Gap Permeance, Carter Factor, Air Gap Flux Density Distribution	70
2.5.1	Uneven Air Gap and Homopolar Flux	77
2.5.2	Flux Density Distribution in Eccentric Air Gap of a Slotless Machine	79
2.5.3	Flux Density Distribution in the Air Gap of a Single-Slotted Machine	85
2.5.4	Magnetic Gears	106
2.5.5	Flux Density Distribution in the Air Gap of a Double-Slotted Machine	107

2.5.6	Flux Density Distribution in Eccentric Air Gap of a Single-Slotted Machine	116
2.5.7	The Influence of Saturation	117
2.6	Time-Dependent Excitation, Rotating Field Generation, MMF Wave Speed, Positive and Negative Sequence Components.	119
2.6.1	MMF Waves Generated by Rotating DC-Fed Coil(s) on One Side of Air Gap.	122
2.6.2	MMF Waves Generated by Symmetrically Wound Stationary Coils Carrying Symmetrical Alternating Currents on One Side of Air Gap.	123
2.6.3	The Influence of the Number of Phases	132
2.6.4	MMF Waves Generated by Asymmetrically Wound Stationary Coils Carrying Asymmetrical Alternating Currents on One Side of Air Gap.	135
2.6.5	MMF Waves Generated by Rotating Coil(s) Carrying Constant Frequency Current(s)	141
2.6.6	MMF Waves Generated by Rotating Coil(s) Carrying Variable Frequency Currents on One Side of Air Gap	143
2.6.7	Resulting MMF Waves Generated by Coils on Both Sides of Air Gap	145
2.6.8	Air Gap Flux Density Waves in a Single-Slotted Machine with Linear Magnetization Curve	147
2.6.9	Air Gap Flux Density Waves in a Double-Slotted Machine with Linear Magnetization Curve	149
2.6.10	Air Gap Flux Density Waves in a Slotless Machine with Nonlinear Magnetization Curve	151
2.7	Induced Voltage	153
2.7.1	Rotating Air Gap Flux Density	153
2.7.2	Elliptic Air Gap Flux Density	157
2.7.3	DC Flux Density Traveling at Angular Speed Ω	159
2.8	Fractional Slot Windings: Fundamental and Principal Poles; Single-Tooth Winding	160
2.9	Squirrel Cage Winding	171
2.10	Winding Failures	192
	References	194
3	Magnetic Circuit	195
3.1	A Straightforward Method for the Solution of Flux Distribution in Current-Free Air Gap and Slots	195
3.2	A Straightforward Method for the Solution of Flux Distribution in Air Gap and Slots with Current-Carrying Conductors	203
3.3	A Straightforward Method for Determination of Magnetic Parameters of a Nonlinear Permeance.	210

3.4	An Accelerated Procedure for the Solution of a System of Differential—Algebraic Equations	212
3.5	A Straightforward Method for the Solution of Flux Distribution in Magnets	217
	References	225
4	Machine Parameters	227
4.1	DC Resistance of a Coil	228
4.2	Air Gap Inductance of a Coil in a Machine with Constant Air Gap Width	229
4.3	Air Gap Inductance of a Coil in a Machine with Variable Air Gap Width—Rotational Harmonics of Concatenated Flux	236
4.3.1	Salient Pole Rotor	246
4.3.2	Slotted Rotor.	255
4.4	Mutual Inductance Between Windings in a Machine with Cylindrical Rotor	256
4.5	Slot Leakage Inductance Due to Transverse Field	260
4.5.1	Magnetic Energy Accumulated in One Slot.	260
4.5.2	Magnetic Energy Accumulated in All N Slots	262
4.6	End Winding Leakage Inductance	264
	References	265
5	Skin and Proximity Effect	267
5.1	Analytical Solution for Current Density Redistribution in a Solid Rectangular Conductor in a Slot as a Result of Alternating Leakage Flux: One-Dimensional Skin Effect.	268
5.2	Analytical Solution for Current Density Redistribution in an Arbitrarily Shaped Solid Conductor in a Slot as a Result of Alternating Leakage Flux	280
5.2.1	Exact Solution.	281
5.2.2	Approximate Solution.	285
5.3	Analytical Solution for Current Density Redistribution in a Solid Rectangular Conductor in a Slot as a Result of Impressed Alternating Leakage Flux: One-Dimensional Proximity Effect	289
5.4	One-Dimensional Skin and Proximity Effect in Solid Conductors of a Coil in a Slot: Average Values of Skin Effect Factors for All Conductors in a Slot and for All Slots of a Phase	295
5.5	Coil Manufacturing Techniques for Suppression of Current Redistribution Due to Skin Effect: Roebel Bar, Ringland Bar, Willyoung Bar, Strand Transposition	297

5.5.1	Multi-turn Coil with Straight Strands	298
5.5.2	Multi-turn Coil with All Strands Twisted	301
5.5.3	Multi-turn Coil with Arbitrarily Twisted Strands	302
5.5.4	Transposed Strands Within a Slot: Roebel Bar, Ringland Bar, Willyoung Bar	306
5.6	Analytical Method for the Determination of Three-Dimensional Proximity Effect in Strands in the End Winding Zone; Circulating Currents	307
5.7	Skin Effect in a Ferromagnetic, Conducting Half-Space	307
5.8	The Influence of Saturation on Skin Effect in Iron	311
5.9	Skin Effect in a Thin Plate	312
5.10	Skin Effect in a Solid Ferromagnetic Cylinder	313
5.11	Losses in Surface-Mounted Permanent Magnets.	315
	References	315
6	Force and Torque	317
6.1	Magnetic Field as a Medium in Which Electromechanical Energy Conversion Takes Place, the Role of Accumulated Magnetic Energy	318
6.2	Shear Force on Contact Surfaces Between Media with Different Permeabilities	319
6.3	Force Due to External Field Acting on Current-Carrying Conductors in Slots of Electric Machines	326
6.4	Torque as a Function of Air Gap Quantities	327
6.4.1	Constant Air Gap Width	328
6.4.2	Variable Air Gap Width	332
6.5	Spectral Components of Torque in a Constant Width Air Gap	335
6.5.1	Symmetrically Wound Polyphase Machine Fed Symmetrically with Sinusoidal Currents	335
6.5.2	Symmetrically Wound Machine Fed with Sinusoidal Unbalanced Currents	346
6.5.3	Single-Phase Operation of a Rotating Field Machine	351
6.6	Spectral Components of Torque in a Machine with Uneven Air Gap: Slotting, Salient Poles, and Rotor Eccentricity	356
6.7	Side Effects of Accumulated Magnetic Energy: Radial Air Gap Force, Forces on Conductors in Slots and on Slot Wedges	360
6.7.1	Unbalanced Magnetic Pull Caused by Rotor Eccentricity	364
6.7.2	Radial Forces on Conductors in Slots	365
6.8	Forces on Conductors in End Winding	367

6.9	Torque as a Function of Terminal Quantities	368
6.10	A Method for Direct Measurement of Electromagnetic Torque in Large Synchronous Machines	374
	References	375
7	Thermal Design of Rotating Field Electric Machines	377
7.1	Types of Cooling	378
7.2	Rated Torque and Rated Power	379
7.3	Hydraulic Resistances and Fan Curves	380
7.3.1	Friction Factor for Coolant Expanding in Axial Direction Through Air Gap	381
7.3.2	Pressure Loss Coefficients for Radial Cooling Ducts	383
7.3.3	Pressure Loss Coefficients for End Winding with Form-wound Coils	384
7.3.4	Fan Curve	385
7.4	Coolant Distribution in Electric Machines, Pressure, and Volumetric Flow Rate in Elements of Its Hydraulic Network	386
7.5	Finite Difference Solution of Temperature Distribution in Electric Machines—Thermal Node Potential Equations	390
7.6	Thermal Networks of Electric Machines and Methods for Their Solution	393
7.7	Transient Heating of a Hollow Conductor	402
	References	409
8	General Principles of AC Machine Design	411
8.1	Introduction	411
8.2	Sizing Equations of an Induction Machine	412
8.3	Sizing Equations of a Synchronous Machine	424
	References	429
	Appendix	431
	Index	461

<http://www.springer.com/978-3-319-39079-6>

The Art and Science of Rotating Field Machines Design:
A Practical Approach

Ostovic, V.

2017, XX, 463 p. 318 illus., Hardcover

ISBN: 978-3-319-39079-6