

# Index

## A

AC synchronous motor	293
AC Synchronous Motor Drive,	
$\Delta$ -Connection	223
Y-Connection	222
AC Winding Resistance	289
air gap flux density	68
Air Gap Inductance	90, 190
Air Gap Modeling	20
Air Gap Mutual Inductance	195
air gap permeance	22
Air Gap Region Solution	506
air gap shear stress	107
alignment torque	6, 56, 59
alnico magnet	32
American Wire Gauge (AWG)	86
Ampere's law	19
annealing	283
anomalous loss	283
Applied Voltage Solution	300
armature inductance	253
Armature Reaction	97
armature reaction	58, 99, 265
armature reaction magnetic field	287
AWG Wire Gauge Relationships	103
Axial Flux Motors	118

## B

B-H curve	29
$BH_{max}$	35
Back EMF	160
back EMF	48
Back EMF and Torque	72
back EMF constant	73, 105
back EMF shape	200
back iron	9
balanced winding	200

bare wire slot fill factor	101
<i>Bli</i> law	58, 59
<i>Blv</i> law	49, 59
bonded magnet	32
bonding material	86
bread loaf	115, 511
bridge factor	137
brushless DC motor	200
Brushless DC Motor Drive	201
Brushless DC Motor Drive,	
Y-Connection	221
Brushless Motor Fundamentals	63
Buried Magnet Configuration	133
buried magnet motor	115, 126

## C

Carter's coefficient	24
chorded winding	168
circular-arc straight-line modeling	22
circulating current	95, 184, 219
Clark Transformation	240
coenergy	50, 51
Coenergy in the Presence	
of a Permanent Magnet	53
coercive force	33
coercivity	33
Cogging Torque	108
cogging torque	6, 57, 59, 123
Cogging Torque Relationships	271
Coil Connections	183
coil groups	184
Coil Inductance	89
coil offset angles	185
coil pitch	70, 168
coil pitch factor	77
Coil Resistance	84
Coil Span	168
coil throw	70
commutation	7

commutation points	202, 206	electrical steel	29
commutation torque ripple	203	electrical time constant	97, 103, 252, 299
Concentrated Winding	162	electromagnet	6
conductor current density	103	electromotive force (EMF)	18
conservation of energy	55	End Turn Inductance	93
Constancy of $Ni$	104	End Turn Mutual Inductance	197
copper motor	261	end turns	89, 93
Core Loss	30	Energy and Coenergy	50
core loss density	286	Energy and Coenergy	
Core Losses	281	in Doubly-Excited Systems	52
Core Loss Modeling	283	Energy and Coenergy	
Epstein Square Test	282	in Singly-Excited Systems	50
proximity effect	289	Epstein Square Test	282
skin depth	287, 288	excess loss	283
skin effect	289		
core permeability	99, 100		
covered wire slot fill factor	102	<b>F</b>	
current density	87, 103, 117, 271, 527	factor	
<b>D</b>		bare wire slot fill	101
$\Delta$ -Connection	219	bridge	137
demagnetization curve	33	coil pitch	77
normal	35	covered wire slot fill	102
intrinsic	35	distribution	186
Design Guidelines	307	flux concentration	39, 40, 131
Detailed Design	307	leakage	66, 129, 134
Detailed Examples	313	pitch	186
detent position	6	reluctance	67, 130, 135, 157
Diameter versus Length	309	skew	154, 272
direct axis	232	slot correction	143
direct axis inductance	255	slot fill	101
distributed winding	8	stacking	32
distribution factor	186	tooth scale	193
double layer	167	torque saturation	270
double layer lap winding	171	winding	186, 187
double layer winding	167	Faraday's Law	47
$dq0$ Transformation	247	ferrite magnet	32
duty cycle function	295	ferromagnetic material	
<b>E</b>		<i>B-H</i> curve	32
eddy current	30, 281	laminations	31
eddy current loss	30, 31, 285, 285	saturation	30
Electrical and Mechanical		Ferromagnetic Materials	29
Relationships	43	field excitation	201
Electrical Control	199	field intensity ( $H$ )	16
electrical frequency	10	field oriented control	209
electrical position	10	field weakening control	210, 240, 305
		finite element analysis	15
		flux	16
		flux concentration	39
		flux concentration factor	39, 40, 131

- |                                    |             |                                     |               |
|------------------------------------|-------------|-------------------------------------|---------------|
| flux density ( $B$ )               | 16          | Ideal Torque Production             | 201, 206, 212 |
| Flux Linkage                       | 70          | Induced Voltage                     | 47            |
| flux linkage                       | 43, 44, 237 | inductance                          |               |
| Flux Linkage and Inductance        | 43          | air gap                             | 90, 91        |
| flux weakening control             | 240, 305    | armature                            | 253           |
| Force from a Macroscopic Viewpoint | 55          | direct axis                         | 255           |
| Force from a Microscopic Viewpoint | 57          | end turn                            | 93            |
| Force, Torque, and Power           | 53          | mutual                              | 89            |
| Fourier Series                     | 493         | mutual slot leakage                 | 194           |
| Fundamentals of Torque Production  | 199         | phase winding                       | 94            |
| Fractional Pitch Coils             | 77          | quadrature axis                     | 255           |
| Fractional Pitch Magnets           | 80          | self                                | 43            |
| fractional pitch winding           | 70          | slot leakage                        | 91, 92        |
| Fractional Slot Motor              | 82          | Inductance Revisited                | 188           |
| frequency                          |             | Influence of Ferromagnetic Material | 154           |
| fundamental cogging                | 272, 276    | Influence of Skew                   | 152           |
| fundamental electrical             | 11          | Influence of Stator Slots           | 141           |
| fundamental radial force           | 277         | Inner Rotor                         | 115           |
| mechanical                         | 10          | inside-out motor                    | 118           |
| pole passage                       | 11          | integral slot motor                 | 82, 110, 271  |
| slot passage                       | 12          | Interior Permanent Magnet Rotors    | 125           |
| fringing flux                      | 21          | International System of Units (SI)  | 13            |
| Full $H$ -Bridge                   | 217         | intrinsic demagnetization curve     | 35            |
| full pitch winding                 | 70          | ironless motor                      | 121           |
| fundamental electrical frequency   | 11          |                                     |               |
| Fundamentals of Torque Production  | 199         | <b>K</b>                            |               |
|                                    |             | knee                                | 34, 35        |
| <b>G</b>                           |             | keepered                            | 33            |
| General Design Process             | 312         |                                     |               |
| General Drive                      | 212         | <b>L</b>                            |               |
| General Sizing                     | 257         | lamination thickness                | 31, 283       |
| Generator Analysis                 | 225         | laminations                         | 31, 32        |
| Generator Fundamentals             | 223         | Laplace's equation                  | 502           |
| Glossary                           | 553         | law                                 |               |
|                                    |             | Ampere's                            | 19            |
| <b>H</b>                           |             | $Bli$                               | 58, 59        |
| $H$ -bridge                        | 217         | $Bl\vartheta$                       | 49, 59        |
| Halbach Magnetization              | 514         | Faraday's                           | 47            |
| Half Bridge                        | 215         | Lenz's                              | 48            |
| Hall effect devices                | 202         | Lorentz force                       | 57            |
| Henries (H)                        | 18          | leakage factor                      | 66, 129, 134  |
| hysteresis loops                   | 29          | leakage flux                        | 64            |
| hysteresis loss                    | 30, 31, 283 | Lenz's law                          | 48            |
|                                    |             | Line-to-Line Back EMF               | 204           |
| <b>I</b>                           |             | Linear Motors                       | 120           |
| $I^2R$ loss                        | 103         | loading, electrical and magnetic    | 55            |
|                                    |             | Lorentz force                       | 57            |



**O**

ohmic losses	55, 213
Outer Rotor	118
overmodulation	295

**P**

pancake motor	118
Parallel Magnetization	512
permanent magnet	
alnico	32
<i>B-H</i> curve	29
<i>BH<sub>max</sub></i>	35
bonded	32
bread loaf	115, 511
coercive force	33
coercivity	33
demagnetization curve	33
ferrite	33
intrinsic demagnetization curve	35
keepered	33
knee	34, 35
maximum energy product	35
NdFeB	32
neodymium-iron-boron	32
normal demagnetization curve	35
rare earth	32
recoil	33
remanence	33, 35
residual induction	33
reversible temperature coefficient	
samarium-cobalt	32
sintered	32
synchronous motor	200
Permanent Magnets	32
Permanent Magnet	
Magnetic Circuit Model	36
Permeability	28
permeability	
of free space	22
relative	28
relative amplitude	30
relative differential	29
relative recoil	35
permeance	18
permeance coefficient	34, 40
pitch factor	186

phase	7
phase back EMF	161, 164
phase inductance	112
phase offset	169, 170, 182
phase winding	199
pole pair	10
pole passage frequency	11
pole, salient	8
Poles, Slots, Teeth, and Yokes	8
position	
detent	6
electrical	10
mechanical	10
Park Transformation	236
Performances	257
position encoder	206
power factor	209
principle angle	169, 170, 173
printed circuit board motor	120
proximity effect	289
psi	107

**Q**

<i>qd0</i> Transformation	248
quadrature axis	232
quadrature axis inductance	255
quadrature component	209
quality factor	227, 299

**R**

Radial Flux Motors	115
radial force	5, 185, 233, 276
Radial Force Relationships	276
Radial Magnetization	512
rare earth	32
Real Time Implementation	243
recoil	33
reference frame transformation	236
relative permeability	28
relative permeance	143
relative recoil permeability	35
reluctance	18
Reluctance and Mutual Torque	59
reluctance factor	67, 130, 135, 155, 157
Reluctance Torque	112, 210, 254
reluctance torque	6, 56, 59, 112, 123
remanence	33

residual induction	33	heat density	103
resistance	84	leakage flux	92
resistivity	85	liner	329
resolver	206	measure	147
reversible temperature coefficient	35	passage frequency	11
revolutions per minute (rpm)	11	passage losses	287
right hand rule	43	permeance coefficient	92
right hand screw rule	19	pitch	25
rotational losses	282, 286	Slot Constraints	101
rotor	1	Slot Fill Factors	101
Rotor Losses	286	Slot Leakage Inductance	91, 193
Rotor Magnetic Design	123	Slot Leakage Mutual Inductance	196
Rotor Outside Radius	310	Slot Modeling	23
Rotor Type	307	Slot Resistance	103
rotor yoke	9	slotless	117
rotor yoke flux density	259	Slotless Motor Construction	162
rotor yoke width	259	slotted	26
		slotted motor	117
<b>S</b>		solenoidal winding	8
salient poles	8	Space Vector	
samarium-cobalt-magnet	32	Pulse Width Modulation	243
saturation	30	Space Vectors	234
Self Inductance	43	speed voltage	48
Series and Parallel Connections	94	spindle motor	118
shoe	92	Spoke Magnet Configuration	128
shoe design	109	squarewave currents	201
SI units	13	squarewave drive	228
Simulation Equations	251	stacking factor	32
single layer	167	stall current	297
Single Layer Windings	180	stator	1
single tooth coil	160	Stator Losses	286
Single Tooth Coil Equivalence	190	Stator Magnetic Design	141
sintered magnet	32	stator yoke	8
sinusoidal back EMF	1, 166, 188, 206	Stator Yoke Flux	150
sinusoidal currents	206	stator yoke flux density	152, 259
sinusoidal winding distribution	165	stator yoke width	152, 259
Sinusoidally Distributed Winding	165	structural periodicity	275
six step drive	201	structural symmetry	278
skew	111	Surface Mounted Magnets	63
skew angle	154	Surface Permanent Magnet Rotors	124
skew factor	154	SVPWM	243
skin depth	287, 288	Symbols	547
skin effect	289		
slot	8	<b>T</b>	
slot		teeth	8
correction factor	143	temperature coefficient	35
fill factor	101	Tesla (T)	17
fraction	26	thermal resistivity coefficient	85

- |                                |                     |                                    |                 |
|--------------------------------|---------------------|------------------------------------|-----------------|
| Three Phase Motors             | 240                 | Vector and Field Oriented Concepts | 231             |
| tooth body                     | 148, 258, 268, 286  | vector control                     | 209             |
| tooth body flux density        | 148, 258            | <b>W</b>                           |                 |
| tooth body width               | 149, 258            | Webers (Wb)                        | 17              |
| Tooth Flux                     | 146                 | winding                            |                 |
| tooth scale factor             | 193                 | balanced                           | 167, 200        |
| Torque                         | 4                   | chorded                            | 168             |
| torque                         | 4                   | concentrated                       | 8, 162          |
| alignment                      | 6, 56, 59           | distributed                        | 8               |
| angle                          | 234                 | double layer lap                   | 171             |
| cogging                        | 6, 57, 59, 123      | end turns                          | 89, 93          |
| commutation torque ripple      | 203                 | factor                             | 186, 187        |
| constant                       | 73, 105, 200        | fractional pitch                   | 77              |
| detent                         | 6                   | full pitch                         | 70              |
| efficiency                     | 106                 | phase                              | 7, 74, 183, 199 |
| mutual                         | 6, 56, 59, 123      | short pitched                      | 168             |
| mutual torque ripple           | 108                 | single layer                       | 180             |
| reluctance                     | 6, 56, 59, 112, 123 | sinusoidal distributed             | 165             |
| ripple                         | 200                 | solenoidal                         | 8               |
| saturation factor              | 270                 | wave                               | 171             |
| Torque and Back EMF Constants  | 220                 | Winding Factor                     | 186             |
| Torque Constant,               |                     | Winding Layout for                 |                 |
| Back EMF Constant,             |                     | Double Layer Windings              | 171             |
| and Motor Constant             | 105                 | Winding Layout Procedure for       |                 |
| Torque per Unit Rotor Volume   | 107                 | Double Layer Windings              | 180             |
| Torque Ripple                  | 203, 207, 214       | Winding Layout Procedure for       |                 |
| Torque Saturation              | 265                 | Single Layer Windings              | 182             |
| total harmonic distortion      | 328                 | Windings                           | 167             |
| Transformation                 |                     | work                               | 53              |
| Clark                          | 240                 | <b>Y</b>                           |                 |
| $dq0$                          | 247                 | Y-Connected Motor Analysis         | 292             |
| Park                           | 236                 | Y-Connection                       | 218             |
| $qd0$                          | 248                 | yoke                               |                 |
| transformer voltage            | 48                  | rotor                              | 9               |
| trapezoidal back EMF           | 200                 | stator                             | 8               |
| triple- $n$ , triplen          | 214                 | <b>Z</b>                           |                 |
| Two Phase Motors and           |                     | zero radial force                  | 277             |
| the Park Transformation        | 232                 | zero sequence component            | 242             |
| <b>U</b>                       |                     | zero states                        | 246             |
| unbalanced magnetic pull (UMP) | 277, 279            |                                    |                 |
| Units                          | 13                  |                                    |                 |
| <b>V</b>                       |                     |                                    |                 |
| Valid Pole and Slot Counts     |                     |                                    |                 |
| for Double Layer Windings      | 168                 |                                    |                 |