Index

Note: Page number followed by "f," "t," and "b" refer to figures, tables, and boxes, respectively.

```
stationary reference frame d-q current
                                                            regulator, 252-254
Absolute encoder, 375-376
                                                        synchronous frame PI current regulator, gain
Active voltage vector, 301-304, 310
                                                            selection of, 256-259
Actual efficiency and ideal efficiency, 120f
                                                        synchronous reference frame d-q PI current
Air-gap flux-oriented (AFO) control, 212
                                                            regulator, 255-256
Air-gap power, 114
                                                     Alternating current (AC) motors, high-speed
  distribution of, 115f
                                                            operation of, 341
Alnico magnets, 167
                                                        field-weakening control for induction motors,
Alternating current (AC) motors, 1, 2f, 4-7, 6f,
                                                            343 - 357
       36, 39, 95
                                                          classic field-weakening control method, 344
  AC motor drive applications, 266
                                                          maximum torque, producing, 347-357
  AC power supply applications, 266–267
                                                          voltage- and current-limit conditions,
  induction motors, 95-142
                                                            344 - 347
    characteristics of, 112-122
                                                        permanent magnet synchronous motor, 357-370
     determining equivalent circuit parameters for,
                                                          high-speed operation of, 360-366
       128 - 131
                                                          surface-mounted permanent magnet
    effect of rotor resistance, 124-127
                                                            synchronous motor, 366-370
     equivalent circuit of, 104-112
                                                     Alternating current (AC) motors, vector control of,
     fundamentals of, 99-104
                                                            203
    operating modes of, 123-124
                                                        conditions for instantaneous torque control of
     operation regions of, 139-142
                                                            motors, 204-206
     speed control of, 131-138
                                                        induction motor, 206-234
     structure of, 96-99
                                                          combined flux estimation method, 230-232
  position sensors, 373-376
                                                          detuning in the indirect vector control,
     resolver, 373-375
                                                            223 - 225
     rotary encoder, 375-376
                                                          direct vector control based on the rotor flux,
  sensorless control of, 382-387
                                                            212 - 220
  speed estimation using incremental encoder,
                                                          indirect vector control based on the rotor flux,
       377 - 381
                                                            220 - 223
     M method, 378-379
                                                          instantaneous torque control, 207-212
    M/T method, 380-381
                                                          proportional-integral flux controller,
    T method, 379-380
                                                            233 - 234
  synchronous motors, 143-152
                                                          rotor flux linkages estimation based on rotor
     cylindrical rotor synchronous motors,
                                                            voltage equations, 228-230
       144 - 148
                                                          rotor flux linkages estimation based on stator
     salient pole rotor synchronous motors,
                                                            voltage equations, 226-228
       148 - 151
                                                        permanent magnet synchronous motors,
     starting of, 151-152
                                                            234 - 245
Alternating current (AC) motors, current regulator
                                                          Interior Permanent Magnet Synchronous
                                                            Motor, vector control of, 238-245
  complex vector current regulator, 263-264
                                                          Surface-Mounted Permanent Magnet
  feedforward control, 259-262
                                                            Synchronous Motor, vector control of,
     for induction motors, 261
                                                            236 - 238
     for permanent magnet synchronous motors,
                                                     Alternating current (AC) motors modeling and
       261 - 262
                                                            reference frame theory, 153
  hysteresis regulator, 248-250
                                                       d-q axes model of an induction motor,
  ramp comparison current regulator, 250-251
                                                            188 - 197
```

Alternating current (AC) motors modeling and	current control, 408
reference frame theory (Continued)	speed control, 406-408
flux linkage equations in, 190-193	versus direct current motors, 390-391
torque equation in, 193-197	driving principle of, 394–397
voltage equations in, 189-190	Matlab/Simulink simulation, 405b
d-q axes model of permanent magnet	modeling of, 398-405
synchronous motor, 197-201	torque equation, 401-405
flux linkage equations in, 198-200	voltage equations, 398-401
torque equation in, 200-201	versus permanent magnet synchronous motors,
voltage equations in, 198	391-393
inductance between stator and rotor windings,	pulse width modulation techniques, 409-412
160-163	bipolar switching method, 409
permanent magnet synchronous motor, modeling	unipolar switching method, 409-412
of, 163–174	sensorless control of, 412-415
model of, 169-174	based on back-electromotive force, 412-415
structure of, 164–169	Butterworth filter, 231, 231b
reference frame transformation, 174-188	
by complex vector, 185–188	•
d-q reference frame, types of, 175–176	C
by matrix equations, 176–184	Carrier wave, 292b
rotor windings, 158–159	Clark's transformation, 178
stator windings, 157–158	Classification of electric motors, 1, 2 <i>f</i>
Anti-windup control, 73–74	Closed-loop control, 58–60, 58 <i>f</i>
Anti-windup controller, 73–74, 90, 262	feedback control, 58-60
proportional-integral current controller, gains	integral controller (I controller), 59, 59 <i>f</i>
selection procedure of, 74	proportional controller (P controller), 58, 58f
Arago's Disk, 95–96, 96f	proportional—integral controller, 59, 60f
Armature circuit, 42	feedforward control, 60–61, 61 <i>f</i>
Armature voltage control, 45–46, 46f	Closed-loop frequency response, 65, 71 <i>f</i>
Armature winding, 39, 41–42, 42 <i>f</i> , 143–144	Closed-loop transfer function, 52b, 70, 78
Asynchronous motor, 6, 95	Commutation, 396
Average torque control technique, 203	of phase currents, 402f
Axial-flux type BLDC motor, 393–394	torque ripple during, 402–405
Axial-flux type PMSMs, 165–166	Complex vector current regulator, 263–264
	Complex vector synchronous frame current
В	regulator, 263–264, 264 <i>f</i>
	Compound motor, 39
Back calculation method, anti-windup control by,	Configuration of electric motors, 3–4, 3 <i>f</i>
73f, 74f	Constant power region, 48–50, 140–142, 141 <i>f</i> ,
Back-electromotive force (back-EMF), 13b,	350-352, 361-366, 368-370
42–43, 342–343, 345–346, 383	Constant torque region, 48, 139
sensorless control based on, 412–415	operation characteristics in, 140 <i>f</i> , 349–350,
Bandwidth, 65b, 72	349f, 360–361
of speed control, 77	Constant voltage constant frequency (CVCF)
Base speed, 140, 142, 341, 350–351 Birolar switching method, 82, 846, 400, 4006, 4106	inverter, 266–267
Bipolar switching method, 83, 84f, 409, 409f, 410f	Constant volts per Hertz control, 134–136
Blanking time. See Dead time	Continuous modulation, 310–311 Continuous pulse width modulation (CPWM)
Blocked rotor test, 130–131, 130 <i>f</i>	*
Breakdown torque region, 116–117, 139, 142,	methods, 311
142f Problem direct current (PLDC) meters 1, 280	Critical damping, 54
Brushless direct current (BLDC) motors, 1, 389 configuration of, 390–394	Current model, 226, 228–230
	Current source inverter (CSI), 265, 266f
construction of, 393–394 control of, 406–408	Cylindrical motors, 26 Cylindrical rotor configuration, 23, 23 <i>f</i>
CORREOT OF, 400—400	Cymianical fotor configuration, 25, 25j

Cylindrical rotor synchronous motors, 144-148	armature circuit, 42
output power and torque for, 148f	back-electromotive force, 42-43
per phase equivalent circuit of, 146f	mechanical load system, 44
torque of, 147–148	torque, 43-44
Cylindrical stator and rotor configurations, 23f, 96	open-loop control, 57–58, 57f
	operation regions of, 48-50
_	constant power region, 48-50
D	constant torque region, 48
Damping ratio, system responses according to,	power electronic converter for, 82-85
53-54, 54 <i>f</i>	four-quadrant chopper, 82
Dead time, 269-270, 331-338	switching schemes, 83-85
compensation, 336-338	simple driving circuit for, 82f
negative current, 337–338	speed controller design, 75-81, 75f
positive current, 336-337	integral-proportional
effect, 333-336	controller, 79-81
Decoupling control. See Feedforward control	proportional-integral speed controller,
Deep-bar rotor, 125-126	75-79
effective resistance and output torque in, 126f	steady-state characteristics of, 45-50
versus normal rotor, 125f	armature voltage control, 46, 46f
Detuning effects, 224, 224f	field flux control, 47–48, 47f
reference frame error due to, 225f	transient response characteristics of, 50-55
Digital controllers, 37	Direct current (DC) power, 36, 95
Direct current (DC) motors, 1, 2f, 4-5, 5f, 25, 36,	Discontinuous modulation, 310-311
39	Discontinuous PWM techniques, 311-317
block diagram for, 51f	30-degree, 313-317
and brushless direct current motors, 390-391	60-degree, 311–312
capability curve of, 49f	60-degree (± 30-degree), 312
closed-loop control, 58-60, 58f	\pm 120-degree, 312-313
feedback control, 58-60	Distributed winding, 97–98, 100–101, 164, 164f
feedforward control, 60-61, 61f	Double sampling, 338
configuration, 39–42, 40f	Double-cage rotor, 126, 127f
control system, configuration of, 56	Doubly fed machine, 20, 21f, 25f
control system, design consideration of, 61-66	d-q axes current regulators, 252–259
gain margin and phase margin, 63-64	stationary reference frame $d-q$ current
response time/speed of response, 64-65	regulator, 252-254
stability, 62-64	synchronous frame PI current regulator, gain
steady-state error, 65-66	selection of, 256-259
current controller design for, 66-74	for induction motors, 257-258
anti-windup controller, 73-74	for permanent magnet synchronous motors,
PI controller, 66	258-259
proportional-integral current controller,	synchronous reference frame $d-q$ PI current
69-72	regulator, 255-256
current control system, 68f	d-q axes model
direct current motor drive system, simulation of,	of induction motor, 188-197
86-92	flux linkage equations, 190-193
direct current motor modeling, 86-87	torque equation, 193-197
four-quadrant chopper modeling, 91-92	voltage equations, 189-190
mechanical system modeling, 87-89	of permanent magnet synchronous motor,
proportional-integral current controller	197-201
modeling, 89	flux linkage equations, 198-200
proportional-integral speed controller	torque equation, 200-201
modeling, 90	voltage equations, 198
equivalent circuit of, 43f	d-q transformation, 174
modeling of, 42-44	Dynamic braking, 33

Dynamic equation of motion, 27-32	constant torque region, 349-350
gears/pulleys, system with, 31-32	field-weakening region I, 350-352
translational motion and rotational motion,	field-weakening region II, 352-357
combination system of, 30–31	voltage- and current-limit conditions,
Dynamic overmodulation methods, 325-327	344-347
minimum-magnitude-error pulse width	current-limit condition, 346-347
modulation method, 326	voltage-limit condition, 344–346, 346f
minimum-phase-error pulse width modulation	Field-weakening region, 48–50, 139
method, 325–326	Final value theorem, 65
overmodulation method considering the	Flux angle, 210–212
direction of current, 327	Flux estimation method, combined, 230–232
F	Flux linkage equations, in $d-q$ axes, 190–193, 198–200
E	Flux-current characteristic, 9f
Efficiency, defined, 119	magnetic energy in, 13f
Electric and magnetic parts of electric	Flux-producing current, 207-209, 214
motors, 3f	Flux-weakening operation, 364–365
Electric drive system, 35–37, 56 <i>f</i>	concept of, 358f
configuration of, 35f	onset of, 364f
digital controllers, 37	optimal currents in, 365f
electric motors, 36	optimal current vector in, 365f
power electronic converters, 36–37	Flux-weakening region, optimal current trajectory
power supply, 36	in, 366 <i>f</i>
sensors and other ancillary circuits, 37	Force for a current carrying conductor, 44f
Electromagnetic induction, 1, 6, 95	Force on a conductor, 40f
Electromechanical energy conversion, 7, 7f	Forward braking (generating) mode, 35
Electromotive force (EMF), 95–96	Forward motoring mode, 34
	Four-quadrant chopper, 82, 91–92
F	Four-quadrant operation modes, 33–34, 33 <i>f</i>
Faraday's law, 13 <i>b</i> , 99, 107–108	in elevator drive, 34 <i>f</i>
Feedback control, 58–60	Fractional-pitch winding, 108
integral controller, 59, 59f	Frequency modulation index, 295
proportional controller, 58, 58f	Frequency response, 61b
proportional—integral controller, 59, 60f	closed-loop, 71f
Feedforward compensation technique, 336	open-loop, 70 <i>f</i> , 75–76
Feedforward control, 60–61, 61 <i>f</i> , 259–262	Full-bridge inverter, 275, 275 <i>f</i>
for induction motors, 261	
for permanent magnet synchronous motors,	G
261–262	Gain margin, 62–64, 63 <i>f</i>
Feedforward field-oriented control, 223	Gate turn-off (GTO) thyristor, 36–37, 268
Feedforward field-weakening control method,	Gears/pulleys, system with, 31–32
355-357	Generalized rotating transformation, 176
Ferrite (or ceramic) magnets, 167	Generating mode, 32–33
Ferromagnetic materials, 8, 96	<i>β</i> ,
Field flux control, 45, 47–48, 47f	
Field winding, 39, 143–144	Н
Field-oriented control, 203-204, 209-210	Hall effect sensors, 37, 217-220, 226, 395-396,
Field-weakening control for induction motors,	395 <i>b</i> , 408, 412
343-357	Harmonic distortion factor (HDF),
classic field-weakening control method, 344	313–315, 314 <i>f</i>
feedback method, 343	H-bridge circuit, 82, 83f
feedforward method, 343	Hysteresis regulator, 248–250
maximum torque, producing, 347–357	operation principle of, 249f

1	instantaneous torque control, 207-212
Ideal efficiency, 120–122, 120f	flux angle, 210–212
Incremental encoder, 236, 375–376, 375 <i>f</i>	instantaneous torque control method of, 210f
speed estimation using, 377–381	modeling of, 154–163
Induced voltage, 13b, 106, 109	inductance between stator and rotor windings,
for a moving conductor, 252f	160-163
Inductance of the coil, 10f	rotor windings, 158–159
Induction motor, 5-6, 26, 95-142	stator windings, 157–158
back-electromotive force of, 140	motoring mode, 123
capability curve of, 143f	operating modes of, 123-124
characteristics of, 112–122	operation regions of, 139–142, 139f
efficiency, 119–122	breakdown torque region, 142
input power factor, 113	constant power region, 140-141
output torque, 113–117	constant torque region, 139
stable operating point, 117–119	plugging mode, 124
stator current, 112–113	power-flow diagram in, 114f
combined flux estimation method, 230-232	proportional-integral gains for, 257-258
determining equivalent circuit parameters for,	regenerative braking, 123-124
128–131	rotor flux linkages estimation
blocked rotor test, 130–131	based on rotor voltage equations, 228-230
measurement of stator resistance, 128–129	based on stator voltage equations, 226-228
no-load test, 129–130	speed control of, 131-138
detuning in indirect vector control, 223–225	closed-loop speed control, 136-138
direct vector control based on rotor flux,	slip control, 131–133
212–220	synchronous speed control, 133-136
induction motor drive system by the direct	stator and rotor windings of, 154f, 155f
vector control, 215–220	structure of, 96–99, 97 <i>f</i>
relation between <i>d</i> -axis stator current and	rotor, 98-99
rotor flux linkage, 213–214	stator, 97–98
relationship between q -axis stator current and	Inner rotor type, 167–169, 393–394
output torque, 214–215	Instantaneous torque control, 203-204
d-q axes model of, 188–197	of induction motor, 207-212
flux linkage equations in, 190–193	Insulated gate bipolar transistor (IGBT), 36-37,
torque equation in, 193–197	268
voltage equations in, 189–190	switching characteristics of, 332f
effect of rotor resistance, 124–127	Integral controller, 59, 59f
equivalent circuit of, 104–112	Integral windup, 73
rotor circuit, 109–112	Integral-proportional (IP) controller, 79-81
stator circuit, 105–108	Integrated gate-commutated thyristor (IGCT),
feedforward control for, 261	36-37, 268
field-weakening control for, 343–357	Interior permanent magnet synchronous motor
classic field-weakening control method, 344	(IPMSM), 166–167, 169–170, 357–358,
maximum torque, producing, 347–357	360, 362
voltage- and current-limit conditions,	high-speed operation of, 360-366
344–347	constant power region, 361-366
flux controller of, 232–234	constant torque region, 360-361
proportional—integral flux controller,	rotor and its equivalent of, 170f
233–234	rotor configurations of, 167f
fundamentals of, 99–104	self-inductance of, 171
rotating magnetic field, 100–104	surface-mounted permanent magnet
generation mode, 123	synchronous motor, 366-370
indirect vector control based on rotor flux,	constant power region, 368-370
220–223	International Electrotechnical Commission (IEC),
	127

Inverters, 265-288	Maximum torque per voltage (MTPV), 352,
basic circuit, 267f	364–365
single-phase full-bridge inverters, 275–277	Mechanical load system, 27–35, 44, 87f
single-phase half-bridge inverters, 271–274	dynamic equation of motion, 27–32
switching devices for, 268f	gears/pulleys, system with, 31–32
three-phase inverter using switching functions,	translational motion and rotational motion,
283-288	combination system of, 30-31
three-phase square wave inverter (six-step	operation modes of electric motor, 32–35
inverter), 277–283	Mechanical system, 7, 87–89
voltage source inverters, 267–271	Metal oxide semiconductor field effect transistor
output voltage of basic circuit, 269-271	(MOSFET), 268
	Minimum-magnitude-error pulse width modulation
K	method, 326, 326f
	Minimum-phase-error pulse width modulation
Kramer drive system, 133	method, 325–326, 325 <i>f</i>
	Model reference adaptive control (MRAC)
L	method, 385
-	Modulating wave, 292b
Leakage flux, 105	Modulation index (MI), 290
Lenz's law, 13b, 100	Moment of inertia, 28, 28b
Linear modulation range, 293	Motor characteristics according to speed, 342f,
Linear motion device, 13–17, 14 <i>f</i>	343f
Linear region, 9	Motor control system, configuration of, 57f
Line-to-line voltages, 278, 279 <i>f</i> , 282	Movable part, movement of, 14, 14f
Load torque, 29, 30 <i>b</i> Lorentz force, 95–96	Multilevel inverter, 268
Lower switch PWM scheme, 410, 411f, 414f	Mutual-inductance, 19b, 153
Lower Switch F wivi scheme, 410, 411 <i>j</i> , 414 <i>j</i>	between stator as winding and the rotor ar
	winding, 160f
M	between stator winding and magnet, 173f
M method, 378–379, 378 <i>f</i>	
M/T method, 380–381, 381 <i>f</i>	N
Magnetic energy, 8–13	National Electrical Manufacture's Association
in the flux-current characteristic, 13f	(NEMA), 127
Magnetic field energy increment, 21	Naturally sampled PWM, 297
Magnetic flux, 3–4, 8–9, 11 <i>b</i>	Neodymium magnet, 165
Magnetic system, 7, 11f	Neodymium—iron—boron (NdFeB) magnets, 168
Magnetization curve, 9	Neutral voltage, in Y-connected three-phase load,
Magnetizing flux, 105, 145, 157-158	282–283, 283 <i>f</i>
Magnetomotive force (mmf), 10, 11b	Neutral-point clamped inverter, 268
Magnitude invariance transformation, 178	Newton's second law of motion, 27
MATLAB/Simulink, 86-92, 195b, 219b, 244b	No-load test, 129–130, 129f
direct current motor modeling, 86-87	Nonfeedback control. See Open-loop control
four-quadrant chopper modeling, 91-92	N-turn coil, flux linkage of, 9
mechanical system modeling, 87-89	, ,
proportional-integral current controller	
modeling, 89	0
proportional-integral speed controller	Off-going PWM scheme, 410, 411f, 414f
modeling, 90	" $1/\omega_r$ " method, 354
Maximum torque per ampere (MTPA), 237, 348f,	On-going PWM scheme, 410, 411f, 414f
349, 360	Open-loop control, 57–58, 57f
control, 238-239	Open-loop frequency response, 69–70, 70f, 75–76
current-limit circle and MTPA trajectory, 363f	Open-loop transfer function, 69, 75
d-q Axes current commands for, 360 f	Operating principle of electric motors, 3–7

alternating current motor, 5–7, 6f	vector control of Surface-Mounted Permanent
configuration of electric motors, $3-4$, $3f$	Magnet Synchronous Motor, 236-238
direct current motor, 5, 5f	Permanent magnets, 167b
Operation modes of electric motor, 32–35, 33f	temperature effects on, 168
Optical incremental encoder, operating principle	Phase margin, 62–64, 63 <i>f</i>
of, 376, 376 <i>f</i>	Pole voltage, 268
Optimal PWM, 291	and phase voltage, 281t
Outer rotor type, 164, 393-394	Fourier series, 272b
Output torque of three-phase BLDC motor,	of three-phase inverter, 278f
401-405	Pole-zero cancellation, 69, 256-257, 263
torque ripple during the commutation, 402-405	Position observer, 381
Output voltage control of an inverter, 289f	Position sensors, 373–376
Output voltage of basic circuit, 269–271	resolver, 373–375
Overdamping, 54	rotary encoder, 375–376
Overmodulation, 323–331	optical incremental encoder, operating
considering the direction of current, 327	principle of, 376
dynamic overmodulation methods, 325–327	Power bipolar junction transistor (BJT), 36–37
minimum-magnitude-error pulse width	Power electronic converter for DC motors, 36–37
modulation method, 326	82-85
minimum-phase-error pulse width modulation	four-quadrant chopper, 82
method, 325–326	switching schemes, 83–85
overmodulation method considering the	bipolar switching scheme, 83
direction of current, 327	unipolar switching scheme, 83–85, 85f
steady-state overmodulation methods, 327–331	Power invariance transformation, 178
,,·	Power metal oxide semiconductor field effect
	transistor (MOSFET), 36–37
P	Power supply, 36
Park's transformation, 176, 180	Powering mode, 271
Permanent magnet synchronous motor (PMSM),	Prime mover, 1
34, 143, 152, 163, 225, 234–245,	Programmed PWM technique, 290–291
258-259, 373, 382, 390	Proportional controller, 58
and brushless direct current motors, 391-393	Proportional—integral current controller, 59, 60 <i>f</i> ,
configurations, 166f	66, 69–72, 231
different structures for the stator and rotor of,	gains selection procedure of, 74
164 <i>f</i>	modeling, 89
d-q axes model of, 197–201	selection of the bandwidth for current control,
flux linkage equations in, 198-200	71–72
torque equation in, 200–201	Proportional—integral flux controller, 233–234
voltage equations in, 198	Proportional—integral speed controller, 75–79
feedforward control for, 261–262	drawback of, 78–79
flux-weakening control for, 357-370	gains selection procedure of, 77
modeling of, 163–174	selection of the bandwidth of speed control, 77
rotor, 165–169	Proportional—integral speed controller modeling,
stator, 164-165	90
structure of, 164–169	Pull-out torque, 116–117, 147–148
operation region of, 358, 358f	Pulse per revolution (PPR), 375
output power according to speed regions of,	Pulse width modulation (PWM) inverters, 265,
359f	288–310
proportional—integral gains for, 258–259	current measurement, 338–339
rotor of, 165	dead time, 331–338
rotor topologies of, 166f	compensation, 336–338
speed regions of, 359	effect, 333–336
vector control of Interior Permanent Magnet	discontinuous PWM techniques, 311–317
Synchronous Motor, 238–245	30-degree, 313–317
· · · · · · · · · · · · · · · · · · ·	55 degree, 515 517

Peterana winding 274
Reference winding, 374 Regeneration mode, 271
Regeneration mode, 271
Regenerative braking, 33, 123–124
Regular-sampled PWM, 297, 297f
Reluctance, 10, 17
Reluctance motor, 4, 18, 26
Reluctance torque, 18, 238
Remanence, 168
Residual flux density, 168
Resolver, 373–375, 374 <i>f</i>
Reverse braking (generating) mode, 35
Reverse motoring mode, 35
Rotary encoder, 375–376
Rotating machine, 18–26, 18f
direct current motor, 25
induction motor, 26
synchronous motor, 26
Rotating magnetic field, 100–104, 111f
Rotating reference frame, 175–176
Rotation of electric motors, 4, 4f
Rotor, 3
Rotor equivalent circuit, 110, 110f
Rotor flux angle, 212f, 213, 216-220, 223
Rotor flux linkage, 21, 212, 214
Rotor flux linkage vector, 212
Rotor flux-oriented (RFO) control, 212
Rotor reference frame, 176
Rotor voltage equations, rotor flux linkages
estimation based on, 228-230
Rotor windings, 99, 104, 111-112, 143-144
inductance of, 158–159
c
\$
Salient pole rotor synchronous motors, 144,
148-151
equivalent circuit of, 150f
phasor diagram of, 150f
torque of, 149–151
Samarium—cobalt (SmCo) magnets, 167–168
Saturation region, 9
Scalar control method, 203
Scherbius drive system, 133
Self-excited DC motor, 39
Self-inductance, 19, 19b, 19f, 153
Sensorless control, 223
of AC motors, 382-387
of brushless DC motors, 412-415
Sensorless techniques
using characteristics of motor, 385-387
using motor model, 383-385
Sensors and other ancillary circuits, 37
Separately excited DC motor, 39, 204, 205f, 206
Series motor, 39

Shaft type rotary encoders, 375	Stator and rotor windings, 104
Shoot-through condition, 269, 269f	inductance between, 21, 160-163
Short-pitch winding, 108	Stator flux linkage, 21, 105, 144
Shunt motor, 39	Stator flux-oriented (SFO) control, 212
Silicon carbide, 36–37	Stator phase winding, 98f
Simulink block diagram of mechanical load	Stator voltage equations, 170
system, 87f	rotor flux linkages estimation based on,
Single-phase full-bridge inverters, 275–277, 275f	226-228
load voltage, 276f	Stator windings, 97, 97f
operation, 276f	equivalent circuit of, 106f
Single-phase half-bridge inverter, 271–274, 271f	inductance of, 157–158, 159f
Single-phase or three-phase AC voltage sources, 36	Steady-state overmodulation methods, 325, 327–331
Sinusoidal PWM (SPWM), 289, 291–297, 344–345	Step speed command, transient response to, 50, $51f$
line-to-line voltage for, 296f	Stray-load loss, 119
overmodulation on, 298f	Surface-mounted permanent magnet synchronous
pole voltage for, 295f	motor (SPMSM), 165–166, 169, 357–358
voltage modulation range for, 293f	high-speed operation of, 366–370
Six-step inverter, 279–280	Switching schemes, 83–85
MATLAB/Simulink simulation, 287 <i>b</i>	bipolar switching scheme, 83, 84 <i>f</i>
phase voltage of, 290f	unipolar switching scheme, 83–85, 85 <i>f</i>
Slip energy, 133	Switching sequence in two-phase modulation, 310
Slip energy recovery system, 133	Symmetrical space vector pulse width modulation
Slip frequency, 110, 136–138	technique, 304–310
Slip speed, 109	Synchronous frame current regulator, 255 <i>f</i> , 256
Space vector PWM (SVPWM) technique, 290,	and stationary frame regulators, 256f
300–310, 344–345	Synchronous frame PI current regulator, gain
principle of, 302–304	selection of, 256–259
symmetrical space vector pulse width	proportional—integral gains
modulation technique, 304–310	for induction motors, 257–258
Speed control, selection of the bandwidth of, 77	for permanent magnet synchronous motors,
Speed controller design, 75–81, 75 <i>f</i>	258–259
integral-proportional controller, 79–81	Synchronous motors, 5–6, 26, 95, 143–152
proportional—integral speed controller, 75–79	categories of, 164f
drawback of, 78–79	cylindrical rotor synchronous motors, 144–148
gains selection procedure of, 77	phasor diagram for, 148f
speed control bandwidth, selection of, 77	salient pole rotor synchronous motors, 148–151
Speed estimation using incremental encoder,	starting of, 151–152
377–381	synchronization in, 152 <i>f</i>
M method, 378–379	Synchronous reference frame $d-q$ PI current
M/T method, 380–381	regulator, 255–256
T method, 379–380	Synchronous reluctance motor, 20
Speed voltages, 189, 255	Synchronous speed, 6, 20, 104
Speed—torque characteristic of a DC motor in the	Synchronously rotating reference, 176
steady-state, 45f	Synchronously rotating reference, 170
Square wave inverter, 267, 271, 277–278	Т
Squirrel-cage induction motors, 124–125	•
Squirrel-cage rotor, 98–99, 98f	T method, 379–380, 379f
State feedback decoupling control, 262–264, 263 <i>f</i>	Third harmonic injection PWM (THIPWM),
State filter, 381	297–300, 299 <i>f</i>
Stationary reference frame, 175, 178–179	Three-level inverter, 268
d-q current regulator, 252–254	basic circuit used in, 269f
Stator, 3	Three-phase AC voltage source, 36, 99

Three-phase inverter, 278f, 283f pole voltages of, 278f using switching functions, 283–288 Three-phase load, 247, 252–253, 253f	Unstable system, 64 <i>f</i> Upper switch PWM scheme, 410, 411 <i>f</i> , 414 <i>f</i>
current control of, 248f Three-phase modulation, 310 Three-phase square wave inverter (six-step inverter), 277–283 Three-phase windings, 102–104, 102f Torque control system of a DC motor, 206f Torque production, continuous, 7–26 linear motion device, 13–17 magnetic energy, 8–13 rotating machine, 18–26 direct current motor, 25 induction motor, 26 synchronous motor, 26 Torque production in the motor, 204f Torque production in the motor, 204f Torque-producing current, 214–215 Total harmonic distortion (THD), 273–274 Traction drives, 341 Translational motion and rotational motion, combination system of, 30–31 Two-level inverter, 268	Variable Voltage Variable Frequency (VVVF) inverter, 138, 266 Vector control, 138, 204, 217 of Interior Permanent Magnet Synchronous Motor, 238–245 of Surface-Mounted Permanent Magnet Synchronous Motor, 236–238 Voltage equation in d-q axes, 189–190, 198 for a motor, 153 Voltage model, 226–228 Voltage source inverter (VSI), 265, 266f basic circuit configuration of, 267–271 Voltage source inverter, 267–271 output voltage of basic circuit, 269–271 Voltage vector, rotation of, 302f Voltage-limit condition, 344–346, 346f, 364–365
Two-phase modulation, 310, 310f	W Wound rotor, 99, 99 <i>f</i>
Underdamping, 54 Unipolar switching method, 409–412, 409f Unipolar switching scheme, 83–85, 85f Unit feedback system, 65, 65f Unsaturated region, 9	Wound-rotor type induction motors, 99, 132–133 Z Zero voltage vector, 301, 305 Ziegler–Nichols method, 69