

# Index

## A

ac controller, 8, 422  
 ac source, 82  
 ac voltage controller. *See* controller, ac  
 ac-ac cycloconverters, 8, 422  
 ac-side inductance, 402, 406  
 Active power line conditioning (APLC), 14  
 ac-to-ac conversion, 8–10  
 ac-to-dc conversion, 5, 8–10  
 Air gap. *See* Magnetic circuits  
 Air-gapped cores. *See* Magnetic circuits  
 Alloys, 496  
 Aluminum, 496  
 Ampere's law, 497, 498, 499  
 Angular position, 7  
 Angular speed, 7  
 Apparent powers, 90, 93  
 Average conduction losses, 26  
 Average power, 90, 91, 92, 93, 94  
 Average power dissipation, 26

## B

Bandwidth, 22  
 Bardeen, John, 5  
 Batteries, 6  
 Bipolar junction transistors (BJTs), 13, 20, 38, 41, 58  
   Darlington-connected, 43, 67  
   saturation collector-emitter voltage, 43  
 Bidirectional flow, 36, 82  
 Bipolar output voltage converters, 171  
 BJT. *See* Bipolar junction transistors  
 Boost cascade with *LC* output filter, 166  
 Boost converter, 132, 147–153  
   average capacitor voltage, 152  
   average input and output currents, 149  
   basic topology and voltage gain, 147  
   critical inductance, 151

  diode implementation, 148  
   equivalent modes, 148  
   equivalent transformer circuit, 150  
   output ripple voltage, 151  
 Boost ZVT PWM converter, 321  
   equivalent circuit, 322  
   simplified equivalent circuit, 321  
   waveforms, 324  
 Boost-buck cascade, 160, 161  
   one-switch equivalent circuit, 161  
   two-switch implementation, 161  
 Boost-derived isolated converters, 213, 232  
   block diagram representation, 333  
 Bratman, Walter, 5  
 Buck cascade with *LC* input filter, 166  
 Buck converter, 136–146  
   average input and output currents, 140  
   continuous conduction mode (ccm), 141  
   critical inductance value, 141  
   filter capacitor, 137  
   operation, 136  
   output voltage ripple, 142  
   steady-state equations, 136, 139  
   voltage conversion, 139  
   volt-second principle, 137  
   waveforms, 139, 142  
 Buck-boost cascade, 160  
 Buck-boost converter, 154–158, 216  
   critical inductance, 157  
   equivalent circuits, 155  
   output voltage ripple, 157  
   switch implementation, 154  
   transistor diode implementation, 154  
   voltage conversion ratio, 155  
 Buck-Cuk cascade, 164

## C

Capacitors, 106–110  
   network, 96  
   steady response, 108  
   transient response, 107  
 Carrier frequency, 476  
 Cascade, boost-buck, 160, 161  
 Cascade converters. *See* Fourth-order converters  
 Cascode converters. *See* Fourth-order converters  
 Catch winding, 215  
 Characteristic equation, 76  
 Characteristic impedance, 79  
 Choppers. *See* dc-dc converters, 10  
 Circuit, critically damped, 77, 78  
 Circuit liner, one-port, 94  
 Circuit protection, 22  
 Circuits, rectifier, 332, 333  
 Classification of soft-switching. *See* Soft-switching converters  
 Closed-loop control, 25  
 Cobalt, 496  
 Component concepts, 75  
 Computer simulation, 564  
 Conditioning, active power line (APLC), 14  
 Conduction, continuous, 132  
 Conduction losses, average, 26  
 Conduction power losses, 26  
 Continuous conduction, 132  
 Control, closed-loop, 25  
 Control characteristic curves, 172  
 Controlled inverter circuits, 382  
 Controlled rectifier circuits, 382  
 Controlled rectifiers or thyristor converters, 8  
 Controller, ac, 8, 422  
 Controller, ac voltage. *See* Controller, ac  
 Conversion, ac-to-ac, 8–10  
 Conversion, ac-to-dc, 5, 8–10  
 Conversion, dc-dc, 8–10  
 Conversion function, 14

- Converter, flyback, 138, 210, 232–236
    - basic topology, 233
    - continuous conduction mode, 236
    - conversion ratio, 235
    - critical inductance value, 236
    - with magnetizing inductor, 233
    - modes of operation, 235
    - output voltage ripple, 236
    - single-ended converter, 232
    - waveforms, 234
  - Converter, forward, 210–223
    - with core reset circuit, 220
    - modes of operation, 220
    - two-switch, 223
    - waveforms, 222
  - Converters, fourth-order, 133, 159, 165
  - Copper losses, 210
  - Core losses, 210
  - Core material and types, 505, 519, 520
    - core arrangements, 520
    - ferrite cores, 520
    - high- $Q$  inductors, 519
    - laminated iron, 519
    - nonmagnetic, 520
    - pot ore, 520
    - powdered iron, 519
    - toroid core, 520
  - Cores, air-gapped. *See* Magnetic circuits
  - Cores, lamination, 519
  - Critical inductance. *See* dc-dc converters
  - Critically damped circuit, 77, 78
  - Cross-sectional area, 499
  - Cuk converter, 132, 134, 164, 528
  - Curie temperature, 509
  - Current limit, 45
    - magnetically coupled inductor representation, 164, 166
    - transistor-diode implementation, 166
    - two-switch implementation, 166
  - Currents, average input and output, 149
  - Current-source inverters (CSIs). *See* Inverters
  - Curriculum design, 563
  - Cycloconversion. *See* Conversion, ac-ac
  - Cycloconverters, ac-ac, 8, 422
- D**
- Damped resonant frequency, 78
  - Damping factor, 78
  - Damping ratio, 78
  - Darlington transistor, 43, 67
  - Darlington-connected BJT. *See* Bipolar junction transistors (BJTs)
  - dc excitation, 76
  - dc power station, 4
  - dc regulator, switching. *See* dc-dc conversion
  - dc transformer model, 196
  - dc-dc converters, 129, 209, 263, 426
  - dc-to-ac inversion, 8–11
  - dc-to-dc conversion, 8–10. *See also* dc-dc converters
  - dc-to-dc resonant converter. *See* Soft-switching converter
  - Delay angle, 385
  - Diacs, 13. *See also* Switching diode circuits
  - Diode circuits, 14, 36, 40
  - Diode switching circuit. *See* Diode circuits
  - Diodes, 13, 38–43
    - fast-recovery, 40
    - $pn$  junction, 38, 40
    - power-handling capabilities, 38
    - reverse recovery charge, 40
    - reverse recovery time, 38
    - reverse voltage blocking, 36
    - rise and fall times, 25, 43
    - Schottky, 39
    - second breakdown problem, 41
    - snappiness, 40
    - soft-recovery, 40
  - Discontinuous conduction mode, 173–183
  - Displacement current, 497
  - Displacement power factor, 105
  - Distortion power factor, 105
- Distributed power system (DPS), 16**
- Divergence. *See* Maxwell's equations**
- Driver circuit, 22**
- Duty ratio, 24. *See also* dc-dc converters**
- boost converter, 179–181
  - buck converter, 173–175
  - buck-boost converter, 182–183
- E**
- Eatkins-Johnson converter, 260
  - Edison, Thomas, 3
  - Electrical applications, 14
  - Electrochemical applications, 14
  - Electromagnetic interference (EMI), 3, 5, 16, 263
  - Electromechanical conversion system, 5, 14, 525
  - emf. *See* Magnetic circuits
- F**
- Fast recovery. *See* Diodes
  - Ferrite cores. *See* Core material and types
  - Ferrites, 496
  - Ferromagnetics. *See* Magnetic circuits
  - Fifth harmonics, 451
  - Filters, 451
  - Firing angle, 385
  - Flexible ac transmission system (FACTS), 14, 16
  - Flux density. *See* Magnetic circuits
  - Flux lines. *See* Magnetic circuits
  - Flyback converter. *See* Converter, flyback
  - Forced commutating, 63
  - Forward converter. *See* Converter, forward
  - Forward current, 25, 36
  - Forward voltage, 25
  - Fourier analysis, 98–105
    - even symmetry, 100
    - frequency, 100
    - function symmetry, 100
    - fundamental components, 99, 102
    - fundamental frequency, 99
    - half-wave symmetry, 100

## 568 Index

- Fourier analysis (*continued*)  
 odd symmetry, 100  
 periodic function, 98  
 spectrum, 100  
 theorem, 98
- Fourier coefficients. *See*  
 Fourier analysis
- Fourier equations, 101, 82
- Fourier series, 531
- Fourth-order converters, 133,  
 159, 165
- Free-wheeling diode, 138
- Frequency modulation index,  
 459, 461
- Fringing effect. *See* Magnetic  
 circuits
- Fringing flux *See* Magnetic  
 circuits
- Fuel cells, 5
- Full-bridge boost-derived  
 converter, 238
- Full-bridge converter, 210,  
 226–238
- Full-bridge inverters, 437–446  
 active load, 450  
 approximate analysis, 443  
 equivalent circuit, 444  
 fundamental value, 438  
 generalized analysis, 444  
 harmonics, 441, 443  
 modes of operation, 440  
 output voltage, 439, 441  
 power factor, 443  
 resistive load, 437  
*R-L* load, 441  
 series *RL* and *RLC* load, 447,  
 449  
 switching sequence, 438,  
 439, 444  
 total harmonic distortion,  
 443, 449  
 tri-state inverters, 439  
 various types of loads, 446  
 waveforms, 442
- Full-wave bridge rectifier. *See*  
 ac-dc converters
- Full-wave diode rectifiers,  
 337–357  
 ac-side inductance, 357  
 center-tap transformer, 359  
 circuit modes of operation, 358  
 commutation inductance, 356  
 inductive load, 356  
 leakage inductance, 359  
 normalized outputs, 358  
 resistive load, 337  
 simplified equivalent circuit,  
 359  
 waveforms, 337, 357
- Full-wave phase-controlled  
 rectifiers, 391–393  
 constant load, 397  
 control characteristic, 396  
 delay angle, 392  
 with flyback SCR, 407–409  
 fundamental component,  
 397, 398  
 inductive load, 393  
 infinite load inductance, 395  
 with load voltage source,  
 403  
 modes of operation, 393  
 power factor, 392, 396, 397  
 regulation curve, 409  
 resistive load, 391  
 total harmonic distortion, 401  
 two SCRs and a flyback  
 diode, 399  
 waveforms, 391–395, 397
- Fundamental component. *See*  
 Fourier analysis
- Fundamental frequency. *See*  
 Fourier analysis
- G**
- Gap, air. *See* Magnetic circuits
- Gate-turn-off (GTO) thyristors,  
 13, 20, 38, 58, 63, 64  
 switching characteristics, 63  
 gate triggering, 384
- Gaulard, L., 4
- Gauss's law, 501
- Germanium transistor, 5
- Gibbs, J. D., 4
- H**
- Half-bridge boost-derived  
 converter, 237  
 center-tap transformer  
 implementation, 237  
 full-wave output rectifier,  
 238  
 modes of operation, 240  
 single-inductor  
 implementation, 237  
 two possible switching  
 sequences, 238
- Half-bridge inverter circuit  
 average transistor and diode  
 currents, 432, 433  
 center-tap, 437  
 equivalent circuit, 430  
 inductive load, 436  
 inductive-resistive load, 429  
 resistive load, 426  
 large splitting capacitors,  
 427  
 MOSFET implementation,  
 431  
 waveforms, 426, 430, 433
- Half-wave controlled rectifiers,  
 385–390  
 ac-side reactance, 404  
 angle of retard, 387  
 average output voltage, 386  
 block diagram, 402  
 equivalent circuit, 390  
 inductive load, 387, 388  
 free-wheeling, 389  
 flyback SCR, 404–406  
 inversion, 390  
 normalized output voltage,  
 386  
 resistive load, 385  
 total harmonic distortion,  
 386  
 waveforms, 385, 388, 389,  
 390
- Half-wave diode rectifier,  
 334–351  
 ac-side inductance, 348  
 applications, 335  
 average load current, 335  
 average output voltage, 334  
 capacitive load, 344, 345,  
 352  
 circuit, 334  
 commutative inductance, 353  
 diode rms current, 356  
 equivalent circuits, 338, 339,  
 345  
 flyback diode, 342  
 half-wave rectifier with  
 inductive load, 348  
 inductive load, 336, 338  
 line regulation, 340  
 load regulation, 340  
 normalized curves, 352  
 ripple voltages, 335  
 voltage source in the dc side,  
 348  
 waveforms, 210, 224, 334,  
 338, 342, 345, 348
- Harmonic analysis, 452
- Harmonic cancellation, 451

Harmonic elimination, 451  
 Harmonic reduction, 451  
 Harmonics content, 90, 98,  
 455, 452, 476, 489  
 Heat sinks, 22  
 High-order harmonics, 22  
 Hard recovery, 40  
 High-frequency dc-to-dc  
 switching converters, 210,  
 129  
 HVDC, 14, 67

**I**

Ideal switch, 25. *See also*  
 Switching  
 Incandescent lamp, 3  
 Inductance, ac-side, 402, 406  
 Inductance, critical. *See* dc-dc  
 converters  
 Inductors, 22, 106–112, 509  
 coil, 509  
 current commutation, 110,  
 112  
 Faraday's law, 509  
 flux, 509  
 flux linkage, 509  
 Lenz's law, 509  
 Maxwell's equation, 509  
 network, 96  
 steady-state response, 110,  
 112  
 transient response, 106, 109,  
 111  
 turns, 509  
 Industrial electronics, 5  
 Instantaneous power, 31, 91,  
 94, 488  
 Insulated gate bipolar transistor  
 (IGBT), 13, 20, 38, 57, 58  
*npn* transistor, 57  
*pn* transistor, 57  
 Integrated circuits (ICs), 3  
 Inversion, 333, 382. *See also*  
 dc-ac inversion  
 Inverters  
 basic block diagram, 423, 424  
 current-source inverters  
 (CSIs), 424, 487  
 line commutation, 423  
 sinusoidal PWM, 423. *See*  
*also* dc-ac inverters  
 uniform pulse width  
 modulation (PWM), 423  
 voltage-source inverters  
 (VSIs), 424

Inverter configurations, 425  
 biphasic, 425  
 full-bridge, 425  
 half-bridge, 425, 426  
 output voltage control, 425  
 single-phase inverter  
 arrangements, 425  
 Isolated converters  
 buck, 213–227  
 Cuk, 242, 243, 254  
 modes of operation, 218  
 with negative output  
 voltage, 216  
 with positive output voltage,  
 216  
 SEPIC, 254  
 voltage gain, 218  
 waveforms, 219  
 Isolation transformers, 129. *See*  
*also* Transformers

**K**

Kirchhoff's current law (KCL),  
 32–33  
 Kirchhoff's voltage law  
 (KVL), 32, 83

**L**

Laboratory design, 565  
 Lagging power factor, 96  
 Lamination cores, 519  
 Laplace transformations, 550  
 LC filter, 24  
 Leading power factor, 96  
 Leakage current, 25  
 Leakage flux, 505  
 Leakage inductances, 210  
 Light-activated SCR (LASCR),  
 67  
 Line commutation, 333. *See*  
*also* Inverters  
 Line current harmonics, 101  
 Line regulation, 25  
 Linear electronic systems, 5  
 Linear one-port circuit, 94  
 Linear regulators, 22, 24, 25, 128  
 block diagram, 129  
 dc-dc converters, 15  
 power supplies, 263  
 Line-frequency transformers, 5  
 Load regulation, 25  
 Losses  
 average conduction, 26  
 copper, 210  
 core, 210

**M**

Magnetic circuits, 494,  
 500–502  
 air gap, 505, 525, 526  
 B-H magnetizing curve, 506,  
 507, 508  
 coercive force, 508  
 conductance, 502  
 conductivity, 502  
 cross-sectional area, 502  
 demagnetization, 508  
 dipoles, 508  
 domains, 508  
 electric circuits, 501  
 ferromagnetic material,  
 506  
 field intensity, 496, 497–499,  
 506–508  
 flux, 502, 506, 507  
 flux density, 496, 502, 506  
 flux lines, 496  
 fringing, 406  
 geometry, 502  
 hysteresis, 507  
 inductance, 502  
 KCL, 501  
 KVL, 501  
 magnetic structure, 506  
 magnetization, 508  
 mmf, 501, 502  
 moment, 507  
 Ohm's law, 502  
 permanent magnetization,  
 507, 508  
 permeability, 496, 514  
 permeance, 502  
 relative permeability, 496  
 reluctance, 501, 502  
 residual flux, 507  
 saturation, 496, 507  
 spinning, 507  
 Magnetic coupling, 129  
 Magnetic flux densities. *See*  
 Magnetic circuits  
 Magnetic materials, 495, 499,  
 506–508  
 diamagnetics, 495, 496  
 paramagnetics, 495, 496  
 ferromagnetics, 495, 496,  
 508  
 Magnetizing inductance,  
 210  
 Magnetomotive force (mmf).  
*See* Magnetic circuits  
 Mathcad, 476

## 570 Index

- MATLAB, 13  
 Matrix representation, 30  
 Maxwell's equations, 497, 498  
 Mercury-arc rectifiers, 5  
 Metal oxide semiconductor field-effect transistor (MOSFET). *See* MOSFET  
 Mn-Zn ferrites. *See* Ferrites  
 Modulation indices. *See* Pulse-width modulation (PWM)  
 MOS-BJT, 68  
 MOS-controlled thyristor (MCT), 13, 20, 38, 58, 64–66  
   *n*-FET, 65  
   *n*-MCT, 65  
   *npn* and *pnp* transistors, 65  
   *p*-FET, 65  
   *p*-MCT, 65–66  
   switching characteristics, 66  
   symbol, 65  
 MOSFET, 13, 20, 38, 58, 46–57  
   current limit, 56  
   cutoff regions, 51  
   electron mobility, 52  
   enhancement types, 51  
   device symbols, 47  
   diode implementation, 159  
   D-MOSFET, 48  
   drain-to-source, 49  
   gate-to-source, 49  
   input capacitance, 50  
   internal body diode, 49, 50  
   internal capacitors, 49  
   *i*-*v* characteristics, 47  
   junction capacitances, 50, 53  
   large-signal equivalent circuit model, 53  
   length of the channel, 52–53  
   Miller theorem, 54–55  
   *n*-channel depletion-mode, 47  
   *n*-channel enhancement-mode, 47, 52  
   *on*-state resistance, 49, 56  
   output capacitance, 50, 53  
   parasitic BJT, 56  
   *p*-channel depletion-mode, 47  
   *p*-channel enhancement-mode, 47  
   regions of operation, 51, 52  
   safe operation area, 55–56  
   second breakdown limit, 56  
   small-signal equivalent circuit, 55  
   S-MOSFET, 48  
   temperature effect, 56  
   transfer capacitance, 50  
   U-MOSFET, 48  
   vertical cross-sectional view, 48  
   V-MOSFET, 48  
   voltage limit, 56  
   width of the channel, 52  
 Motor-generator set, 5  
 Multi-output converters, 251, 255  
 Multiple outputs, 131
- N**  
 Natural response, 82. *See also* Switching diode circuits, Switching SCR circuits  
 Naturally commutating converters, 333  
 Nickel, 496  
 Ni-Zn ferrites. *See* Ferrites  
 Nomenclature, 16  
 Nonidealities in dc-dc converters  
   boost converter, 189  
   boost inductor current, 190  
   boost voltage gain, 193  
   buck converter, 197, 198  
   inductor resistance, 186, 187  
   switch resistance, 192  
   switching and conduction losses, 186  
   transistor and diode voltage drops, 186, 191  
 Nonisolated dc-dc converters, 128. *See also* dc-dc converters  
 Nonsinusoidal waveform, 95, 98, 101  
*n*-phase half-wave rectifier, 379
- O**  
*Off* state 42. *See also* Switching  
*On* state 42. *See also* Switching  
 Output harmonics. *See* Harmonics content  
 Overdamping, 77, 78  
 Overdrive factor, 41
- P**  
 Parallel connected SCR circuits, 403  
 Parallel resonant *RLC*. *See RLC* circuit  
 Phase-controlled converters, 14. *See also* Controlled rectifier circuits  
 Phase-controlled inverter, 382, 384  
 Phasor-domain analysis, 92, 98  
 Photovoltaic cells, 5  
 Polyphase ac system, 5. *See also* Three-phase transformers  
 Position, angular, 7  
 Post-filtering, 128  
 Power, average, 90, 91, 92, 93, 94  
 Power computations, 75  
 Power conversion technology, 2, 5, 11, 12, 21  
 Power density, 22, 130  
 Power devices, 13, 37–67  
   comparison of, 67  
   future trends in, 67  
   smart, 68  
 Power diodes. *See* Diodes  
 Power dissipation, average, 26  
 Power distribution systems, 4  
 Power electronics, 1  
   applications of, 14  
   block diagram, 7  
   control stage, 2, 5  
   conversion, 1, 5, 11, 12, 21  
   defined, 1, 12  
   education, 563  
   future trend in, 15  
   history of, 3  
   power stage, 5  
   recent growth in, 2, 20  
   textbooks, 553–555  
   types of, 1  
 Power factor, 95, 97, 104, 105  
 Power factor angle, 93, 95  
 Power flow, 90  
   bidirectional, 91  
   unidirectional input-to-output, 91  
 Power ICs, 15, 68  
 Power MOSFET. *See* MOSFET  
 Power quality factor, 78  
 Power SCR. *See* Rectifier, silicon-controlled (SCR)  
 Power semiconductor devices. *See* Power devices

- Power semiconductor technology, 2
- Power systems and drive curriculum, 564
- Power-handling capabilities, 21, 25, 38
- Power-processing circuit, 90
- Powers, apparent, 90, 93
- PSPICE, 13
- Push-pull converter, 210, 227
  - current-fed, 231
  - equivalent circuit, 228
  - voltage gain, 229
  - waveforms, 227, 230, 231
- Pulse-width modulation (PWM), 10, 13, 76, 131, 263. *See also* Pulse-width-modulation inverters
- Pulse-width-modulation inverters, 457–460
  - amplitude modulation index, 459
  - block diagram, 457
  - carrier signal, 459
  - control signal, 459
  - equal-pulse (uniform), 459, 460, 490
  - frequency modulation index, 459, 461
  - half-cycle control, 458, 462
  - $k$ -pulse inverter, 462
  - maximum conduction angle, 461
  - methods, 458
  - nonsinusoidal, 458
  - $n$ th harmonic component, 463, 464
  - number of pulses, 460
  - one-pulse output, 460
  - pulse width, 461
  - reference single, 459
  - seven-pulse output, 461
  - sinusoidal, 458
  - THD, 464
  - three-pulse output, 461
  - two-pulse output, 460
  - waveforms, 459
- PWM. *See* Pulse-width modulation (PWM); dc-ac inversion
- Q**
- Quality factor, 78
- Quasi-resonant converters. *See* Soft-switching converters
- Quasi-squarewave converters. *See* Soft-switching converters
- R**
- Reactive power, 90
- Real power. *See* Average power
- Rectification, 8, 332, 333
- Rectifier, silicon-controlled (SCR), 13, 38, 58
  - base-to-collector current, 61
  - collector-to-base saturation current, 61
  - depletion layer, 60
  - forced commutation, 58
  - forward blocking region, 59
  - forward breakover voltage, 59
  - holding current, 58
  - ideal switching characteristics, 59
  - $i$ - $v$  characteristics, 59
  - latch device, 58
  - latching current, 58
  - max reverse voltage, 59
  - $n$ pn transistors, 60
  - off* state, 58
  - on* state, 60
  - $pn$  transistors, 61
  - reverse avalanche region, 59
  - trigger mechanism, 60
  - two-transistor analogy, 61
  - switching characteristics, 59
  - symbol, 59
- Rectifier circuits, 332, 333
- Regulated power supplies. *See* dc-dc converters
- Regulator. *See* Linear regulators
- Reliability, 5
- Resonant converters, 76
- Resonant frequency, 78
- Resonant  $RLC$  circuit. *See*  $RLC$  circuit
- Retard angle, 387
- Reverse blocking voltage, 25
- Reverse-conducting thyristor (RCT), 67
- Reverse current, 25
- Ripple voltage, 133
- $RLC$  circuit, 78, 76, 79, 81, 83, 107
- Root mean square (rms), 90
- S**
- Saber, 13
- Saturation collector-emitter voltage, 43
- Second-order voltage converter, 133
- Semiconductor devices, 22. *See also* Switching
- SEPIC converters, 132, 134, 159
- Series connected SCR circuits, 403
- Series resonant  $RLC$ . *See*  $RLC$  circuit
- Shockley, William, 5
- Schottky diode, 39
- Silicon-controlled rectifier (SCR). *See* Rectifier, silicon-controlled (SCR)
- Simulation, computer, 564
- Single-ended forward converter, 213, 216, 219
  - with magnetizing inductance, 219
- Single-output converter, 255
- Single-phase ac controller, 492
- Single-phase rectifier circuits, 332
  - capacitive load, 332
  - full-bridge, 31
  - inductive load, 332
  - resistive load, 332
  - voltage source in the dc side, 332
- Single-pole, double-throw switch, 134, 159
- Single-pole, single-throw switch, 133
- Sinusoidal PWM inverters, 423, 465, 467, 490. *See also* dc-to-ac inversion analysis, 470
  - approximating analysis, 472, 477
  - basic concept, 465
  - bipolar PWM output waveform, 468
  - dc duty cycle, 466
  - exact expression, 473
  - frequency of modulation, 466
  - modulation function, 467
  - modulation gain, 466, 468
  - output voltage harmonics, 471

## 572 Index

- Sinusoidal PWM inverters,  
(*continued*)  
reference signal, 468  
sawtooth function, 468  
signal generation, 468  
simplified buck converter, 465  
single-pulse inverter, 467  
spectrum plot, 477  
switching schemes, 468  
triangular approximation,  
471  
triangular signal, 468  
unipolar PWM output, 469
- Sinusoidal waveforms, 94, 531,  
539  
bidirectional voltage circuit,  
545  
full-wave, 543  
half-wave, 540  
half-wave SCR, 544  
half-wave symmetric, 531  
harmonic coefficients, 542  
harmonic spectrum plots,  
545  
harmonics, 544  
odd harmonics, 531  
rectified full-wave SCR  
voltage, 545  
shifted half-wave, 541
- Six-pulse SCR inverter, 2
- Smart power, 16
- Snappiness, 40
- Snubber circuits, 68, 266  
dissipative, 68  
nondissipative, 68  
passive, 68  
switching loci, 69  
turn-on, 68  
turn-off, 68
- Soft-recovery diodes, 40. *See also* Diodes
- Soft-switching converters, 262,  
264  
advantages and  
disadvantages, 263, 265  
circuit blocks, 264  
class E resonant converters,  
265  
classification, 265  
conventional PWM  
converter, 262  
dc link resonant inverters,  
265  
full-resonance converters,  
265  
hard switching, 262  
multi-resonant converters,  
265  
parallel resonant converter  
(PRC), 265  
quasi-resonant converters  
(single-ended), 265  
quasi-squarewave  
converters, 265  
resonance concept, 263  
resonant converters, 262  
resonant versus conventional  
PWM, 264  
series-resonant converter  
(SRC), 265  
soft-switching techniques,  
264  
zero-clamped topologies, 265  
zero-clamped-current (CC),  
265  
zero-clamped-voltage (CV),  
265  
zero-current switching  
(ZCS), 263, 265, 267  
zero-current transition  
(ZCT), 265  
zero-voltage switching  
(ZVS), 263, 265  
zero-voltage transition  
(ZVT), 265
- Soft-switching dc-dc  
converters. *See* Soft-  
switching converters
- Source, ac, 82
- Speed, angular, 7
- Sprague, Frank, 3
- Square waveform, 7, 22,  
531–540  
half-wave symmetric, 533  
harmonics, 532, 536, 434  
multi-level square  
waveforms, 434  
multi-pulse square  
waveforms, 536  
multi-pulse waveforms, 434  
odd harmonics, 533  
single-pulse waveforms,  
435  
three-level square  
waveform, 533  
three-step waveform, 540  
two-step waveforms, 538–539
- Stanley, William, 4
- Static induction transistors  
(SITs), 13, 20, 38, 58
- Static induction thyristors  
(SITHs), 13, 20, 38, 58
- Static inverters, 422. *See also*  
dc-to-ac inversion
- Static switching, 15
- Step-down converter. *See* dc-dc  
converters
- Step-up converter. *See* dc-dc  
converters
- Step-up/down converter. *See*  
dc-dc converters
- Stokes's theorem, 497
- Switch, ideal, 25. *See also*  
Switching
- Switching  
characteristics, 25, 44, 38  
circuits, 39, 75, 76, 88  
devices, 20  
function, 30–32  
implementation, 36  
loci, 69, 266  
losses, 266  
matrix, 31  
speed, 21  
trajectory, 26  
transition, 320  
turn-off losses, 11  
types of switches, 36  
utilization factor, 199  
waveforms, 26, 44
- Switching dc regulator. *See* dc-  
dc converters
- Switching diode circuits, 14,  
36, 40, 82, 88
- Switching SCR circuits, 88, 89
- Switch-mode power supplies  
(SMPS), 10, 131. *See also*  
dc-dc converters
- T**
- Tesla, Nikola, 3
- Third harmonic, 451
- Three-output flyback  
converter, 252
- Three-output half-bridge buck-  
derived converter, 252
- Three-phase circuits. *See also*  
Linear regulators  
connections, 362  
delta-connected, 19  
line currents, 19  
line-to-line voltages,  
362  
phase voltages, 18–19  
phasor diagram, 362

- representation, 18
  - wye-connected, 18, 362
  - Three-phase controlled half-wave rectifier, 409, 410
  - average output voltage, 410
  - highly inductive load, 411
  - output voltage, 410
  - resistive load, 410
  - waveforms, 410
  - Three-phase full-bridge
    - controlled rectifiers, 411, 412
    - average output voltage, 412
    - equivalent circuits, 415
    - highly inductive, 413
    - line-to-line voltage, 413
    - resistive load, 412
  - Three-phase full-wave rectifier, 31, 365–368, 371
    - ac-side inductance, 368, 369, 371
    - average output voltage, 367
    - circuit under resistive load, 365
    - commutation inductance, 365, 370
    - conduction angles, 367, 370
    - equivalent circuit, 366
    - highly inductive load, 367
    - power factor, 378
    - waveforms, 366
  - Three-phase half-wave rectifier
    - circuits, 360, 361
    - average output voltage, 361
    - capacitive-load rectifier, 364
    - half-wave rectifier, 360, 368
    - infinite load inductance, 363
    - $m$ -phase half-wave rectifier, 360
    - resistive-load, 360, 361
    - voltage ripple, 365
    - waveforms, 361, 363
  - Three-phase inverters, 478–481, 490
    - conduction angle, 479
    - current-source inverter, 485
    - frequency spectra, 486
    - fundamental components, 482
    - full-bridge current-source inverter, 485
    - line-to-line voltages, 480
    - practical dc current source implementation, 485
    - switching sequence, 479
    - waveforms, 485
    - wye load, 479
  - Three-phase transformers, 520.
    - See also* Transformers
    - configuration, 522
    - delta-connected, 521
    - neutral point, 521
    - schematic representation, 522
    - single three-winding, 522
    - three single two-winding, 522
    - three-set of windings on
      - common core, 522
      - wye-connected, 521, 522
  - Time-domain analysis, 92
  - Thyristors. *See* Rectifier, silicon-controlled (SCR)
  - Topology and voltage gain, basic, 147
  - Toroidal coil. *See* Magnetic circuits
  - Toroidal structure, 498, 499.
    - See also* Magnetic circuits
  - Total harmonic distortion, 103, 454
  - Transformations, Laplace, 550
  - Transformer configurations, 211–212
    - center-tap, 9, 212
    - comparison, 213
    - core excitation, 213
    - full-bridge, 211
    - half-bridge, 211
    - push-pull, 211
    - reset mechanism, 213
    - single-ended, 211
  - Transformers, 9, 22, 495–519.
    - See also* Three-phase transformers
    - air gap, 518
    - copper loss, 515, 519
    - current transformers, 511
    - dot notation, 512
    - eddy current losses, 519
    - equations, 516
    - equivalent circuit, 210
    - Faraday's law, 511, 516
    - ideal, 511, 516
    - isolation, 511
    - leakage flux, 513
    - leakage inductances, 514
    - losses, 511
    - magnetic core, 510, 511, 514
    - magnetizing current, 515, 519
    - magnetizing inductance, 514
    - model with losses, 515
    - mutual and leakage fluxes, 516
    - mutual inductances, 516, 517
    - nonideal, 513
    - operating frequencies, 510
    - power rating, 510
    - with  $RLC$  load, 513
    - saturation, 518
    - self-inductances, 517
    - types, 511
    - windings, 510
  - Transistors, bipolar junction (BJTs), 13, 20, 38, 58, 41–41
    - Darlington-connected, 43, 67
    - saturation collector-emitter voltage, 43
  - Transmission system, 5
  - Triac, 13, 36, 64
    - equivalent circuit, 65
    - $i$ - $v$  characteristics, 64
    - switching characteristics, 64, 65
  - Triple Darlington, 42
  - Tungsten, 496
  - Two- and four-quadrant modes of operation, 384
  - Two-angle shift control, 452
  - Two-push-pull inverters, 453
- ## U
- Uncontrolled ac-dc converters, 14
  - Uncontrolled diode circuits, 332, 333. *See also* ac-to-dc conversion
  - Uncontrolled rectifiers, 382.
    - See also* ac-to-dc conversion
  - Underdamping, 77, 78
  - Unidirectional converters, 332
  - Uniform pulse-width modulation (PWM), 423
  - Uninterruptible power supply (UPS), 63, 423
  - Unregulated input voltage, 130
  - Useful functions, 549–551
    - definite integrals, 550
    - derivatives and integrals, 550
    - Laplace transformations, 550
    - trigonometric identities, 549



## 574 Index

**V**

Vacuum tubes, 5  
VHF/UHF amplifiers, 64  
Voltage, average capacitor, 152  
Voltage, saturation collector-emitter, 43  
Voltage blocking, 36  
Voltage divider, 24  
Voltage gain, basic topology and, 147  
Voltage limit, 45  
Voltage-source inverters (VSIs), 424

**W**

Waveforms. *See also*  
Sinusoidal waveforms;  
Square waveform  
sawtooth, 7  
sinusoidal, 94  
triangular, 7  
Web-based teaching, 563  
Weber. *See* Magnetic circuits  
Weinberg converter, 213, 244, 245  
circuit topology, 245  
converter waveforms, 248

equivalent circuits, 248  
simplified one-switch  
equivalent, 247  
switching waveforms, 245  
voltage gain equation, 247  
Westinghouse, George, 3

**Z**

Zener diodes, 38, 130  
Zener regulator, 22, 24  
Zero *on*-state voltage, 25  
Zero-current switching  
topologies, 267. *See also*  
Soft-switching converters  
boost converter, 277–285  
buck resonant converter,  
269–276  
buck-boost converter,  
285–290  
conventional converters, 269  
L-type switch, 267  
M-type switch, 267  
steady-state analysis, 268  
Zero-current transition (ZCT)  
converters, 319, 320  
PWM switching cell, 320

Zero-voltage switching  
topologies, 290–303. *See also* Soft-switching  
converters  
buck-boost converter,  
301–303  
half-wave MOSFET  
implementation, 292  
MOSFET implementation,  
291  
MOSFET switch with fast  
flyback diode, 291  
M-type or L-type, 290  
quasi-resonant boost,  
297–300  
quasi-resonant buck,  
292–297  
resonant switch  
arrangements, 292  
steady-state analysis,  
292  
Zero-voltage transition (ZVT)  
converters, 319, 320. *See also* Soft-switching  
converters  
Zinc, 496

# Index

## A

ac controller, 8, 422  
 ac source, 82  
 ac voltage controller. *See* controller, ac  
 ac-ac cycloconverters, 8, 422  
 ac-side inductance, 402, 406  
 Active power line conditioning (APLC), 14  
 ac-to-ac conversion, 8–10  
 ac-to-dc conversion, 5, 8–10  
 Air gap. *See* Magnetic circuits  
 Air-gapped cores. *See* Magnetic circuits  
 Alloys, 496  
 Aluminum, 496  
 Ampere's law, 497, 498, 499  
 Angular position, 7  
 Angular speed, 7  
 Apparent powers, 90, 93  
 Average conduction losses, 26  
 Average power, 90, 91, 92, 93, 94  
 Average power dissipation, 26

## B

Bandwidth, 22  
 Bardeen, John, 5  
 Batteries, 6  
 Bipolar junction transistors (BJTs), 13, 20, 38, 41, 58  
   Darlington-connected, 43, 67  
   saturation collector-emitter voltage, 43  
 Bidirectional flow, 36, 82  
 Bipolar output voltage converters, 171  
 BJT. *See* Bipolar junction transistors  
 Boost cascade with *LC* output filter, 166  
 Boost converter, 132, 147–153  
   average capacitor voltage, 152  
   average input and output currents, 149  
   basic topology and voltage gain, 147  
   critical inductance, 151

  diode implementation, 148  
   equivalent modes, 148  
   equivalent transformer circuit, 150  
   output ripple voltage, 151  
 Boost ZVT PWM converter, 321  
   equivalent circuit, 322  
   simplified equivalent circuit, 321  
   waveforms, 324  
 Boost-buck cascade, 160, 161  
   one-switch equivalent circuit, 161  
   two-switch implementation, 161  
 Boost-derived isolated converters, 213, 232  
   block diagram representation, 333  
 Bratman, Walter, 5  
 Buck cascade with *LC* input filter, 166  
 Buck converter, 136–146  
   average input and output currents, 140  
   continuous conduction mode (ccm), 141  
   critical inductance value, 141  
   filter capacitor, 137  
   operation, 136  
   output voltage ripple, 142  
   steady-state equations, 136, 139  
   voltage conversion, 139  
   volt-second principle, 137  
   waveforms, 139, 142  
 Buck-boost cascade, 160  
 Buck-boost converter, 154–158, 216  
   critical inductance, 157  
   equivalent circuits, 155  
   output voltage ripple, 157  
   switch implementation, 154  
   transistor diode implementation, 154  
   voltage conversion ratio, 155  
 Buck-Cuk cascade, 164

## C

Capacitors, 106–110  
   network, 96  
   steady response, 108  
   transient response, 107  
 Carrier frequency, 476  
 Cascade, boost-buck, 160, 161  
 Cascade converters. *See* Fourth-order converters  
 Cascode converters. *See* Fourth-order converters  
 Catch winding, 215  
 Characteristic equation, 76  
 Characteristic impedance, 79  
 Choppers. *See* dc-dc converters, 10  
 Circuit, critically damped, 77, 78  
 Circuit liner, one-port, 94  
 Circuit protection, 22  
 Circuits, rectifier, 332, 333  
 Classification of soft-switching. *See* Soft-switching converters  
 Closed-loop control, 25  
 Cobalt, 496  
 Component concepts, 75  
 Computer simulation, 564  
 Conditioning, active power line (APLC), 14  
 Conduction, continuous, 132  
 Conduction losses, average, 26  
 Conduction power losses, 26  
 Continuous conduction, 132  
 Control, closed-loop, 25  
 Control characteristic curves, 172  
 Controlled inverter circuits, 382  
 Controlled rectifier circuits, 382  
 Controlled rectifiers or thyristor converters, 8  
 Controller, ac, 8, 422  
 Controller, ac voltage. *See* Controller, ac  
 Conversion, ac-to-ac, 8–10  
 Conversion, ac-to-dc, 5, 8–10  
 Conversion, dc-dc, 8–10  
 Conversion function, 14

- Converter, flyback, 138, 210, 232–236
    - basic topology, 233
    - continuous conduction mode, 236
    - conversion ratio, 235
    - critical inductance value, 236
    - with magnetizing inductor, 233
    - modes of operation, 235
    - output voltage ripple, 236
    - single-ended converter, 232
    - waveforms, 234
  - Converter, forward, 210–223
    - with core reset circuit, 220
    - modes of operation, 220
    - two-switch, 223
    - waveforms, 222
  - Converters, fourth-order, 133, 159, 165
  - Copper losses, 210
  - Core losses, 210
  - Core material and types, 505, 519, 520
    - core arrangements, 520
    - ferrite cores, 520
    - high- $Q$  inductors, 519
    - laminated iron, 519
    - nonmagnetic, 520
    - pot ore, 520
    - powdered iron, 519
    - toroid core, 520
  - Cores, air-gapped. *See* Magnetic circuits
  - Cores, lamination, 519
  - Critical inductance. *See* dc-dc converters
  - Critically damped circuit, 77, 78
  - Cross-sectional area, 499
  - Cuk converter, 132, 134, 164, 528
  - Curie temperature, 509
  - Current limit, 45
    - magnetically coupled inductor representation, 164, 166
    - transistor-diode implementation, 166
    - two-switch implementation, 166
  - Currents, average input and output, 149
  - Current-source inverters (CSIs). *See* Inverters
  - Curriculum design, 563
  - Cycloconversion. *See* Conversion, ac-ac
  - Cycloconverters, ac-ac, 8, 422
- D**
- Damped resonant frequency, 78
  - Damping factor, 78
  - Damping ratio, 78
  - Darlington transistor, 43, 67
  - Darlington-connected BJT. *See* Bipolar junction transistors (BJTs)
  - dc excitation, 76
  - dc power station, 4
  - dc regulator, switching. *See* dc-dc conversion
  - dc transformer model, 196
  - dc-dc converters, 129, 209, 263, 426
  - dc-to-ac inversion, 8–11
  - dc-to-dc conversion, 8–10. *See also* dc-dc converters
  - dc-to-dc resonant converter. *See* Soft-switching converter
  - Delay angle, 385
  - Diacs, 13. *See also* Switching diode circuits
  - Diode circuits, 14, 36, 40
  - Diode switching circuit. *See* Diode circuits
  - Diodes, 13, 38–43
    - fast-recovery, 40
    - $pn$  junction, 38, 40
    - power-handling capabilities, 38
    - reverse recovery charge, 40
    - reverse recovery time, 38
    - reverse voltage blocking, 36
    - rise and fall times, 25, 43
    - Schottky, 39
    - second breakdown problem, 41
    - snappiness, 40
    - soft-recovery, 40
  - Discontinuous conduction mode, 173–183
  - Displacement current, 497
  - Displacement power factor, 105
  - Distortion power factor, 105
- Distributed power system (DPS), 16**
- Divergence. *See* Maxwell's equations**
- Driver circuit, 22**
- Duty ratio, 24. *See also* dc-dc converters**
- boost converter, 179–181
  - buck converter, 173–175
  - buck-boost converter, 182–183
- E**
- Eatkins-Johnson converter, 260
  - Edison, Thomas, 3
  - Electrical applications, 14
  - Electrochemical applications, 14
  - Electromagnetic interference (EMI), 3, 5, 16, 263
  - Electromechanical conversion system, 5, 14, 525
  - emf. *See* Magnetic circuits
- F**
- Fast recovery. *See* Diodes
  - Ferrite cores. *See* Core material and types
  - Ferrites, 496
  - Ferromagnetics. *See* Magnetic circuits
  - Fifth harmonics, 451
  - Filters, 451
  - Firing angle, 385
  - Flexible ac transmission system (FACTS), 14, 16
  - Flux density. *See* Magnetic circuits
  - Flux lines. *See* Magnetic circuits
  - Flyback converter. *See* Converter, flyback
  - Forced commutating, 63
  - Forward converter. *See* Converter, forward
  - Forward current, 25, 36
  - Forward voltage, 25
  - Fourier analysis, 98–105
    - even symmetry, 100
    - frequency, 100
    - function symmetry, 100
    - fundamental components, 99, 102
    - fundamental frequency, 99
    - half-wave symmetry, 100

## 568 Index

- Fourier analysis (*continued*)  
 odd symmetry, 100  
 periodic function, 98  
 spectrum, 100  
 theorem, 98
- Fourier coefficients. *See*  
 Fourier analysis
- Fourier equations, 101, 82
- Fourier series, 531
- Fourth-order converters, 133,  
 159, 165
- Free-wheeling diode, 138
- Frequency modulation index,  
 459, 461
- Fringing effect. *See* Magnetic  
 circuits
- Fringing flux *See* Magnetic  
 circuits
- Fuel cells, 5
- Full-bridge boost-derived  
 converter, 238
- Full-bridge converter, 210,  
 226–238
- Full-bridge inverters, 437–446  
 active load, 450  
 approximate analysis, 443  
 equivalent circuit, 444  
 fundamental value, 438  
 generalized analysis, 444  
 harmonics, 441, 443  
 modes of operation, 440  
 output voltage, 439, 441  
 power factor, 443  
 resistive load, 437  
*R-L* load, 441  
 series *RL* and *RLC* load, 447,  
 449  
 switching sequence, 438,  
 439, 444  
 total harmonic distortion,  
 443, 449  
 tri-state inverters, 439  
 various types of loads, 446  
 waveforms, 442
- Full-wave bridge rectifier. *See*  
 ac-dc converters
- Full-wave diode rectifiers,  
 337–357  
 ac-side inductance, 357  
 center-tap transformer, 359  
 circuit modes of operation, 358  
 commutation inductance, 356  
 inductive load, 356  
 leakage inductance, 359  
 normalized outputs, 358  
 resistive load, 337  
 simplified equivalent circuit,  
 359  
 waveforms, 337, 357
- Full-wave phase-controlled  
 rectifiers, 391–393  
 constant load, 397  
 control characteristic, 396  
 delay angle, 392  
 with flyback SCR, 407–409  
 fundamental component,  
 397, 398  
 inductive load, 393  
 infinite load inductance, 395  
 with load voltage source,  
 403  
 modes of operation, 393  
 power factor, 392, 396, 397  
 regulation curve, 409  
 resistive load, 391  
 total harmonic distortion, 401  
 two SCRs and a flyback  
 diode, 399  
 waveforms, 391–395, 397
- Fundamental component. *See*  
 Fourier analysis
- Fundamental frequency. *See*  
 Fourier analysis
- G**
- Gap, air. *See* Magnetic circuits
- Gate-turn-off (GTO) thyristors,  
 13, 20, 38, 58, 63, 64  
 switching characteristics, 63  
 gate triggering, 384
- Gaulard, L., 4
- Gauss's law, 501
- Germanium transistor, 5
- Gibbs, J. D., 4
- H**
- Half-bridge boost-derived  
 converter, 237  
 center-tap transformer  
 implementation, 237  
 full-wave output rectifier,  
 238  
 modes of operation, 240  
 single-inductor  
 implementation, 237  
 two possible switching  
 sequences, 238
- Half-bridge inverter circuit  
 average transistor and diode  
 currents, 432, 433  
 center-tap, 437  
 equivalent circuit, 430  
 inductive load, 436  
 inductive-resistive load, 429  
 resistive load, 426  
 large splitting capacitors,  
 427  
 MOSFET implementation,  
 431  
 waveforms, 426, 430, 433
- Half-wave controlled rectifiers,  
 385–390  
 ac-side reactance, 404  
 angle of retard, 387  
 average output voltage, 386  
 block diagram, 402  
 equivalent circuit, 390  
 inductive load, 387, 388  
 free-wheeling, 389  
 flyback SCR, 404–406  
 inversion, 390  
 normalized output voltage,  
 386  
 resistive load, 385  
 total harmonic distortion,  
 386  
 waveforms, 385, 388, 389,  
 390
- Half-wave diode rectifier,  
 334–351  
 ac-side inductance, 348  
 applications, 335  
 average load current, 335  
 average output voltage, 334  
 capacitive load, 344, 345,  
 352  
 circuit, 334  
 commutative inductance, 353  
 diode rms current, 356  
 equivalent circuits, 338, 339,  
 345  
 flyback diode, 342  
 half-wave rectifier with  
 inductive load, 348  
 inductive load, 336, 338  
 line regulation, 340  
 load regulation, 340  
 normalized curves, 352  
 ripple voltages, 335  
 voltage source in the dc side,  
 348  
 waveforms, 210, 224, 334,  
 338, 342, 345, 348
- Harmonic analysis, 452
- Harmonic cancellation, 451

Harmonic elimination, 451  
 Harmonic reduction, 451  
 Harmonics content, 90, 98,  
 455, 452, 476, 489  
 Heat sinks, 22  
 High-order harmonics, 22  
 Hard recovery, 40  
 High-frequency dc-to-dc  
 switching converters, 210,  
 129  
 HVDC, 14, 67

**I**

Ideal switch, 25. *See also*  
 Switching  
 Incandescent lamp, 3  
 Inductance, ac-side, 402, 406  
 Inductance, critical. *See* dc-dc  
 converters  
 Inductors, 22, 106–112, 509  
 coil, 509  
 current commutation, 110,  
 112  
 Faraday's law, 509  
 flux, 509  
 flux linkage, 509  
 Lenz's law, 509  
 Maxwell's equation, 509  
 network, 96  
 steady-state response, 110,  
 112  
 transient response, 106, 109,  
 111  
 turns, 509  
 Industrial electronics, 5  
 Instantaneous power, 31, 91,  
 94, 488  
 Insulated gate bipolar transistor  
 (IGBT), 13, 20, 38, 57, 58  
*npn* transistor, 57  
*pn* transistor, 57  
 Integrated circuits (ICs), 3  
 Inversion, 333, 382. *See also*  
 dc-ac inversion  
 Inverters  
 basic block diagram, 423, 424  
 current-source inverters  
 (CSIs), 424, 487  
 line commutation, 423  
 sinusoidal PWM, 423. *See*  
*also* dc-ac inverters  
 uniform pulse width  
 modulation (PWM), 423  
 voltage-source inverters  
 (VSIs), 424

Inverter configurations, 425  
 biphasic, 425  
 full-bridge, 425  
 half-bridge, 425, 426  
 output voltage control, 425  
 single-phase inverter  
 arrangements, 425  
 Isolated converters  
 buck, 213–227  
 Cuk, 242, 243, 254  
 modes of operation, 218  
 with negative output  
 voltage, 216  
 with positive output voltage,  
 216  
 SEPIC, 254  
 voltage gain, 218  
 waveforms, 219  
 Isolation transformers, 129. *See*  
*also* Transformers

**K**

Kirchhoff's current law (KCL),  
 32–33  
 Kirchhoff's voltage law  
 (KVL), 32, 83

**L**

Laboratory design, 565  
 Lagging power factor, 96  
 Lamination cores, 519  
 Laplace transformations, 550  
 LC filter, 24  
 Leading power factor, 96  
 Leakage current, 25  
 Leakage flux, 505  
 Leakage inductances, 210  
 Light-activated SCR (LASCR),  
 67  
 Line commutation, 333. *See*  
*also* Inverters  
 Line current harmonics, 101  
 Line regulation, 25  
 Linear electronic systems, 5  
 Linear one-port circuit, 94  
 Linear regulators, 22, 24, 25, 128  
 block diagram, 129  
 dc-dc converters, 15  
 power supplies, 263  
 Line-frequency transformers, 5  
 Load regulation, 25  
 Losses  
 average conduction, 26  
 copper, 210  
 core, 210

**M**

Magnetic circuits, 494,  
 500–502  
 air gap, 505, 525, 526  
 B-H magnetizing curve, 506,  
 507, 508  
 coercive force, 508  
 conductance, 502  
 conductivity, 502  
 cross-sectional area, 502  
 demagnetization, 508  
 dipoles, 508  
 domains, 508  
 electric circuits, 501  
 ferromagnetic material,  
 506  
 field intensity, 496, 497–499,  
 506–508  
 flux, 502, 506, 507  
 flux density, 496, 502, 506  
 flux lines, 496  
 fringing, 406  
 geometry, 502  
 hysteresis, 507  
 inductance, 502  
 KCL, 501  
 KVL, 501  
 magnetic structure, 506  
 magnetization, 508  
 mmf, 501, 502  
 moment, 507  
 Ohm's law, 502  
 permanent magnetization,  
 507, 508  
 permeability, 496, 514  
 permeance, 502  
 relative permeability, 496  
 reluctance, 501, 502  
 residual flux, 507  
 saturation, 496, 507  
 spinning, 507  
 Magnetic coupling, 129  
 Magnetic flux densities. *See*  
 Magnetic circuits  
 Magnetic materials, 495, 499,  
 506–508  
 diamagnetics, 495, 496  
 paramagnetics, 495, 496  
 ferromagnetics, 495, 496,  
 508  
 Magnetizing inductance,  
 210  
 Magnetomotive force (mmf).  
*See* Magnetic circuits  
 Mathcad, 476

## 570 Index

- MATLAB, 13  
 Matrix representation, 30  
 Maxwell's equations, 497, 498  
 Mercury-arc rectifiers, 5  
 Metal oxide semiconductor field-effect transistor (MOSFET). *See* MOSFET  
 Mn-Zn ferrites. *See* Ferrites  
 Modulation indices. *See* Pulse-width modulation (PWM)  
 MOS-BJT, 68  
 MOS-controlled thyristor (MCT), 13, 20, 38, 58, 64–66  
   *n*-FET, 65  
   *n*-MCT, 65  
   *npn* and *pn*p transistors, 65  
   *p*-FET, 65  
   *p*-MCT, 65–66  
   switching characteristics, 66  
   symbol, 65  
 MOSFET, 13, 20, 38, 58, 46–57  
   current limit, 56  
   cutoff regions, 51  
   electron mobility, 52  
   enhancement types, 51  
   device symbols, 47  
   diode implementation, 159  
   D-MOSFET, 48  
   drain-to-source, 49  
   gate-to-source, 49  
   input capacitance, 50  
   internal body diode, 49, 50  
   internal capacitors, 49  
   *i*-*v* characteristics, 47  
   junction capacitances, 50, 53  
   large-signal equivalent circuit model, 53  
   length of the channel, 52–53  
   Miller theorem, 54–55  
   *n*-channel depletion-mode, 47  
   *n*-channel enhancement-mode, 47, 52  
   *on*-state resistance, 49, 56  
   output capacitance, 50, 53  
   parasitic BJT, 56  
   *p*-channel depletion-mode, 47  
   *p*-channel enhancement-mode, 47  
   regions of operation, 51, 52  
   safe operation area, 55–56  
   second breakdown limit, 56  
   small-signal equivalent circuit, 55  
   S-MOSFET, 48  
   temperature effect, 56  
   transfer capacitance, 50  
   U-MOSFET, 48  
   vertical cross-sectional view, 48  
   V-MOSFET, 48  
   voltage limit, 56  
   width of the channel, 52  
 Motor-generator set, 5  
 Multi-output converters, 251, 255  
 Multiple outputs, 131
- N**  
 Natural response, 82. *See also* Switching diode circuits, Switching SCR circuits  
 Naturally commutating converters, 333  
 Nickel, 496  
 Ni-Zn ferrites. *See* Ferrites  
 Nomenclature, 16  
 Nonidealities in dc-dc converters  
   boost converter, 189  
   boost inductor current, 190  
   boost voltage gain, 193  
   buck converter, 197, 198  
   inductor resistance, 186, 187  
   switch resistance, 192  
   switching and conduction losses, 186  
   transistor and diode voltage drops, 186, 191  
 Nonisolated dc-dc converters, 128. *See also* dc-dc converters  
 Nonsinusoidal waveform, 95, 98, 101  
*n*-phase half-wave rectifier, 379
- O**  
*Off* state 42. *See also* Switching  
*On* state 42. *See also* Switching  
 Output harmonics. *See* Harmonics content  
 Overdamping, 77, 78  
 Overdrive factor, 41
- P**  
 Parallel connected SCR circuits, 403  
 Parallel resonant *RLC*. *See RLC* circuit  
 Phase-controlled converters, 14. *See also* Controlled rectifier circuits  
 Phase-controlled inverter, 382, 384  
 Phasor-domain analysis, 92, 98  
 Photovoltaic cells, 5  
 Polyphase ac system, 5. *See also* Three-phase transformers  
 Position, angular, 7  
 Post-filtering, 128  
 Power, average, 90, 91, 92, 93, 94  
 Power computations, 75  
 Power conversion technology, 2, 5, 11, 12, 21  
 Power density, 22, 130  
 Power devices, 13, 37–67  
   comparison of, 67  
   future trends in, 67  
   smart, 68  
 Power diodes. *See* Diodes  
 Power dissipation, average, 26  
 Power distribution systems, 4  
 Power electronics, 1  
   applications of, 14  
   block diagram, 7  
   control stage, 2, 5  
   conversion, 1, 5, 11, 12, 21  
   defined, 1, 12  
   education, 563  
   future trend in, 15  
   history of, 3  
   power stage, 5  
   recent growth in, 2, 20  
   textbooks, 553–555  
   types of, 1  
 Power factor, 95, 97, 104, 105  
 Power factor angle, 93, 95  
 Power flow, 90  
   bidirectional, 91  
   unidirectional input-to-output, 91  
 Power ICs, 15, 68  
 Power MOSFET. *See* MOSFET  
 Power quality factor, 78  
 Power SCR. *See* Rectifier, silicon-controlled (SCR)  
 Power semiconductor devices. *See* Power devices

- Power semiconductor technology, 2
- Power systems and drive curriculum, 564
- Power-handling capabilities, 21, 25, 38
- Power-processing circuit, 90
- Powers, apparent, 90, 93
- PSPICE, 13
- Push-pull converter, 210, 227  
   current-fed, 231  
   equivalent circuit, 228  
   voltage gain, 229  
   waveforms, 227, 230, 231
- Pulse-width modulation (PWM), 10, 13, 76, 131, 263. *See also* Pulse-width-modulation inverters
- Pulse-width-modulation inverters, 457–460  
   amplitude modulation index, 459  
   block diagram, 457  
   carrier signal, 459  
   control signal, 459  
   equal-pulse (uniform), 459, 460, 490  
   frequency modulation index, 459, 461  
   half-cycle control, 458, 462  
   *k*-pulse inverter, 462  
   maximum conduction angle, 461  
   methods, 458  
   nonsinusoidal, 458  
   *n*th harmonic component, 463, 464  
   number of pulses, 460  
   one-pulse output, 460  
   pulse width, 461  
   reference single, 459  
   seven-pulse output, 461  
   sinusoidal, 458  
   THD, 464  
   three-pulse output, 461  
   two-pulse output, 460  
   waveforms, 459
- PWM. *See* Pulse-width modulation (PWM); dc-ac inversion
- Q**
- Quality factor, 78
- Quasi-resonant converters. *See* Soft-switching converters
- Quasi-squarewave converters. *See* Soft-switching converters
- R**
- Reactive power, 90
- Real power. *See* Average power
- Rectification, 8, 332, 333
- Rectifier, silicon-controlled (SCR), 13, 38, 58  
   base-to-collector current, 61  
   collector-to-base saturation current, 61  
   depletion layer, 60  
   forced commutation, 58  
   forward blocking region, 59  
   forward breakover voltage, 59  
   holding current, 58  
   ideal switching characteristics, 59  
   *i-v* characteristics, 59  
   latch device, 58  
   latching current, 58  
   max reverse voltage, 59  
   *npn* transistors, 60  
   *off* state, 58  
   *on* state, 60  
   *pn* transistors, 61  
   reverse avalanche region, 59  
   trigger mechanism, 60  
   two-transistor analogy, 61  
   switching characteristics, 59  
   symbol, 59
- Rectifier circuits, 332, 333
- Regulated power supplies. *See* dc-dc converters
- Regulator. *See* Linear regulators
- Reliability, 5
- Resonant converters, 76
- Resonant frequency, 78
- Resonant *RLC* circuit. *See* *RLC* circuit
- Retard angle, 387
- Reverse blocking voltage, 25
- Reverse-conducting thyristor (RCT), 67
- Reverse current, 25
- Ripple voltage, 133
- RLC* circuit, 78, 76, 79, 81, 83, 107
- Root mean square (rms), 90
- S**
- Saber, 13
- Saturation collector-emitter voltage, 43
- Second-order voltage converter, 133
- Semiconductor devices, 22. *See also* Switching
- SEPIC converters, 132, 134, 159
- Series connected SCR circuits, 403
- Series resonant *RLC*. *See* *RLC* circuit
- Shockley, William, 5
- Schottky diode, 39
- Silicon-controlled rectifier (SCR). *See* Rectifier, silicon-controlled (SCR)
- Simulation, computer, 564
- Single-ended forward converter, 213, 216, 219  
   with magnetizing inductance, 219
- Single-output converter, 255
- Single-phase ac controller, 492
- Single-phase rectifier circuits, 332  
   capacitive load, 332  
   full-bridge, 31  
   inductive load, 332  
   resistive load, 332  
   voltage source in the dc side, 332
- Single-pole, double-throw switch, 134, 159
- Single-pole, single-throw switch, 133
- Sinusoidal PWM inverters, 423, 465, 467, 490. *See also* dc-to-ac inversion analysis, 470  
   approximating analysis, 472, 477  
   basic concept, 465  
   bipolar PWM output waveform, 468  
   dc duty cycle, 466  
   exact expression, 473  
   frequency of modulation, 466  
   modulation function, 467  
   modulation gain, 466, 468  
   output voltage harmonics, 471

## 572 Index

- Sinusoidal PWM inverters,  
(*continued*)  
reference signal, 468  
sawtooth function, 468  
signal generation, 468  
simplified buck converter, 465  
single-pulse inverter, 467  
spectrum plot, 477  
switching schemes, 468  
triangular approximation,  
471  
triangular signal, 468  
unipolar PWM output, 469
- Sinusoidal waveforms, 94, 531,  
539  
bidirectional voltage circuit,  
545  
full-wave, 543  
half-wave, 540  
half-wave SCR, 544  
half-wave symmetric, 531  
harmonic coefficients, 542  
harmonic spectrum plots,  
545  
harmonics, 544  
odd harmonics, 531  
rectified full-wave SCR  
voltage, 545  
shifted half-wave, 541
- Six-pulse SCR inverter, 2
- Smart power, 16
- Snappiness, 40
- Snubber circuits, 68, 266  
dissipative, 68  
nondissipative, 68  
passive, 68  
switching loci, 69  
turn-on, 68  
turn-off, 68
- Soft-recovery diodes, 40. *See also* Diodes
- Soft-switching converters, 262,  
264  
advantages and  
disadvantages, 263, 265  
circuit blocks, 264  
class E resonant converters,  
265  
classification, 265  
conventional PWM  
converter, 262  
dc link resonant inverters,  
265  
full-resonance converters,  
265  
hard switching, 262  
multi-resonant converters,  
265  
parallel resonant converter  
(PRC), 265  
quasi-resonant converters  
(single-ended), 265  
quasi-squarewave  
converters, 265  
resonance concept, 263  
resonant converters, 262  
resonant versus conventional  
PWM, 264  
series-resonant converter  
(SRC), 265  
soft-switching techniques,  
264  
zero-clamped topologies, 265  
zero-clamped-current (CC),  
265  
zero-clamped-voltage (CV),  
265  
zero-current switching  
(ZCS), 263, 265, 267  
zero-current transition  
(ZCT), 265  
zero-voltage switching  
(ZVS), 263, 265  
zero-voltage transition  
(ZVT), 265
- Soft-switching dc-dc  
converters. *See* Soft-  
switching converters
- Source, ac, 82
- Speed, angular, 7
- Sprague, Frank, 3
- Square waveform, 7, 22,  
531–540  
half-wave symmetric, 533  
harmonics, 532, 536, 434  
multi-level square  
waveforms, 434  
multi-pulse square  
waveforms, 536  
multi-pulse waveforms, 434  
odd harmonics, 533  
single-pulse waveforms,  
435  
three-level square  
waveform, 533  
three-step waveform, 540  
two-step waveforms, 538–539
- Stanley, William, 4
- Static induction transistors  
(SITs), 13, 20, 38, 58
- Static induction thyristors  
(SITHs), 13, 20, 38, 58
- Static inverters, 422. *See also*  
dc-to-ac inversion
- Static switching, 15
- Step-down converter. *See* dc-dc  
converters
- Step-up converter. *See* dc-dc  
converters
- Step-up/down converter. *See*  
dc-dc converters
- Stokes's theorem, 497
- Switch, ideal, 25. *See also*  
Switching
- Switching  
characteristics, 25, 44, 38  
circuits, 39, 75, 76, 88  
devices, 20  
function, 30–32  
implementation, 36  
loci, 69, 266  
losses, 266  
matrix, 31  
speed, 21  
trajectory, 26  
transition, 320  
turn-off losses, 11  
types of switches, 36  
utilization factor, 199  
waveforms, 26, 44
- Switching dc regulator. *See* dc-  
dc converters
- Switching diode circuits, 14,  
36, 40, 82, 88
- Switching SCR circuits, 88, 89
- Switch-mode power supplies  
(SMPS), 10, 131. *See also*  
dc-dc converters
- T**
- Tesla, Nikola, 3
- Third harmonic, 451
- Three-output flyback  
converter, 252
- Three-output half-bridge buck-  
derived converter, 252
- Three-phase circuits. *See also*  
Linear regulators  
connections, 362  
delta-connected, 19  
line currents, 19  
line-to-line voltages,  
362  
phase voltages, 18–19  
phasor diagram, 362



- representation, 18
  - wye-connected, 18, 362
  - Three-phase controlled half-wave rectifier, 409, 410
  - average output voltage, 410
  - highly inductive load, 411
  - output voltage, 410
  - resistive load, 410
  - waveforms, 410
  - Three-phase full-bridge
    - controlled rectifiers, 411, 412
    - average output voltage, 412
    - equivalent circuits, 415
    - highly inductive, 413
    - line-to-line voltage, 413
    - resistive load, 412
  - Three-phase full-wave rectifier, 31, 365–368, 371
    - ac-side inductance, 368, 369, 371
    - average output voltage, 367
    - circuit under resistive load, 365
    - commutation inductance, 365, 370
    - conduction angles, 367, 370
    - equivalent circuit, 366
    - highly inductive load, 367
    - power factor, 378
    - waveforms, 366
  - Three-phase half-wave rectifier
    - circuits, 360, 361
    - average output voltage, 361
    - capacitive-load rectifier, 364
    - half-wave rectifier, 360, 368
    - infinite load inductance, 363
    - $m$ -phase half-wave rectifier, 360
    - resistive-load, 360, 361
    - voltage ripple, 365
    - waveforms, 361, 363
  - Three-phase inverters, 478–481, 490
    - conduction angle, 479
    - current-source inverter, 485
    - frequency spectra, 486
    - fundamental components, 482
    - full-bridge current-source inverter, 485
    - line-to-line voltages, 480
    - practical dc current source implementation, 485
    - switching sequence, 479
    - waveforms, 485
    - wye load, 479
  - Three-phase transformers, 520.
    - See also* Transformers
    - configuration, 522
    - delta-connected, 521
    - neutral point, 521
    - schematic representation, 522
    - single three-winding, 522
    - three single two-winding, 522
    - three-set of windings on
      - common core, 522
      - wye-connected, 521, 522
  - Time-domain analysis, 92
  - Thyristors. *See* Rectifier, silicon-controlled (SCR)
  - Topology and voltage gain, basic, 147
  - Toroidal coil. *See* Magnetic circuits
  - Toroidal structure, 498, 499.
    - See also* Magnetic circuits
  - Total harmonic distortion, 103, 454
  - Transformations, Laplace, 550
  - Transformer configurations, 211–212
    - center-tap, 9, 212
    - comparison, 213
    - core excitation, 213
    - full-bridge, 211
    - half-bridge, 211
    - push-pull, 211
    - reset mechanism, 213
    - single-ended, 211
  - Transformers, 9, 22, 495–519.
    - See also* Three-phase transformers
    - air gap, 518
    - copper loss, 515, 519
    - current transformers, 511
    - dot notation, 512
    - eddy current losses, 519
    - equations, 516
    - equivalent circuit, 210
    - Faraday's law, 511, 516
    - ideal, 511, 516
    - isolation, 511
    - leakage flux, 513
    - leakage inductances, 514
    - losses, 511
    - magnetic core, 510, 511, 514
    - magnetizing current, 515, 519
    - magnetizing inductance, 514
    - model with losses, 515
    - mutual and leakage fluxes, 516
    - mutual inductances, 516, 517
    - nonideal, 513
    - operating frequencies, 510
    - power rating, 510
    - with  $RLC$  load, 513
    - saturation, 518
    - self-inductances, 517
    - types, 511
    - windings, 510
  - Transistors, bipolar junction (BJTs), 13, 20, 38, 58, 41–41
    - Darlington-connected, 43, 67
    - saturation collector-emitter voltage, 43
  - Transmission system, 5
  - Triac, 13, 36, 64
    - equivalent circuit, 65
    - $i$ - $v$  characteristics, 64
    - switching characteristics, 64, 65
  - Triple Darlington, 42
  - Tungsten, 496
  - Two- and four-quadrant modes of operation, 384
  - Two-angle shift control, 452
  - Two-push-pull inverters, 453
- ## U
- Uncontrolled ac-dc converters, 14
  - Uncontrolled diode circuits, 332, 333. *See also* ac-to-dc conversion
  - Uncontrolled rectifiers, 382.
    - See also* ac-to-dc conversion
  - Underdamping, 77, 78
  - Unidirectional converters, 332
  - Uniform pulse-width modulation (PWM), 423
  - Uninterruptible power supply (UPS), 63, 423
  - Unregulated input voltage, 130
  - Useful functions, 549–551
    - definite integrals, 550
    - derivatives and integrals, 550
    - Laplace transformations, 550
    - trigonometric identities, 549

## 574 Index

**V**

Vacuum tubes, 5  
VHF/UHF amplifiers, 64  
Voltage, average capacitor, 152  
Voltage, saturation collector-emitter, 43  
Voltage blocking, 36  
Voltage divider, 24  
Voltage gain, basic topology and, 147  
Voltage limit, 45  
Voltage-source inverters (VSIs), 424

**W**

Waveforms. *See also*  
Sinusoidal waveforms;  
Square waveform  
sawtooth, 7  
sinusoidal, 94  
triangular, 7  
Web-based teaching, 563  
Weber. *See* Magnetic circuits  
Weinberg converter, 213, 244, 245  
circuit topology, 245  
converter waveforms, 248

equivalent circuits, 248  
simplified one-switch  
equivalent, 247  
switching waveforms, 245  
voltage gain equation, 247  
Westinghouse, George, 3

**Z**

Zener diodes, 38, 130  
Zener regulator, 22, 24  
Zero *on*-state voltage, 25  
Zero-current switching  
topologies, 267. *See also*  
Soft-switching converters  
boost converter, 277–285  
buck resonant converter,  
269–276  
buck-boost converter,  
285–290  
conventional converters, 269  
L-type switch, 267  
M-type switch, 267  
steady-state analysis, 268  
Zero-current transition (ZCT)  
converters, 319, 320  
PWM switching cell, 320

Zero-voltage switching  
topologies, 290–303. *See also* Soft-switching  
converters  
buck-boost converter,  
301–303  
half-wave MOSFET  
implementation, 292  
MOSFET implementation,  
291  
MOSFET switch with fast  
flyback diode, 291  
M-type or L-type, 290  
quasi-resonant boost,  
297–300  
quasi-resonant buck,  
292–297  
resonant switch  
arrangements, 292  
steady-state analysis,  
292  
Zero-voltage transition (ZVT)  
converters, 319, 320. *See also* Soft-switching  
converters  
Zinc, 496