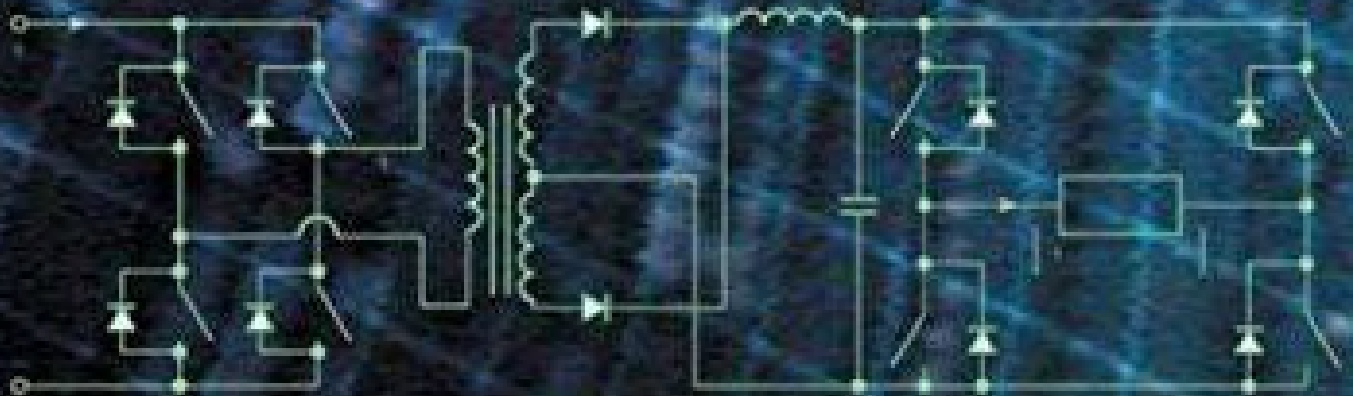


POWER ELECTRONICS

CIRCUITS, DEVICES,
AND APPLICATIONS

THIRD EDITION



MUHAMMAD H. RASHID

Power Electronics Circuits, Devices, and Applications

Muhammad.H.Rashid Power Electronics Circuits, Devices & Applications

Muhammad Harunur Rashid

Ph.D., Fellow IEE
Professor of Electrical Engineering
PURDUE UNIVERSITY Calumet



Prentice Hall, Englewood Cliffs, New Jersey 07632

www.EngineeringBooksPdf.com

NINTENDO-1074, p. 2
Nintendo v. Resonant
IPR2025-01098

Contents

PREFACE xvii

ACKNOWLEDGMENTS xx

CHAPTER 1 INTRODUCTION 1

- 1-1 Applications of Power Electronics, 1
- 1-2 Power Semiconductor Devices, 3
- 1-3 Control Characteristics of Power Devices, 8
- 1-4 Types of Power Electronic Circuits, 8
- 1-5 Design of Power Electronics Equipment, 12
- 1-6 Peripheral Effects, 13
- Summary, 13
- References, 14
- Review Questions, 14

vii

CHAPTER 2 DIODE CIRCUITS AND RECTIFIERS 15

- 2-1 Introduction, 15
- 2-2 Diodes with RC and RL Loads, 15
- 2-3 Diodes with LC and RLC Loads, 18
- 2-4 Freewheeling Diodes, 23
- 2-5 Recovery of Trapped Energy with a Diode, 25
- 2-6 Single-Phase Half-Wave Rectifiers, 29
- 2-7 Performance Parameters, 29
- 2-8 Single-Phase Full-Wave Rectifiers, 33
- 2-9 Multiphase Star Rectifiers, 38
- 2-10 Three-Phase Bridge Rectifiers, 41
- 2-11 Rectifier Circuit Design, 44
- 2-12 Effects of Source and Load Inductances, 49
- Summary, 50
- References, 51
- Review Questions, 51
- Problems, 52

CHAPTER 3 THYRISTOR COMMUTATION TECHNIQUES 56

- 3-1 Introduction, 56
- 3-2 Natural Commutation, 57
- 3-3 Forced Commutation, 57
 - 3-3.1 Self-Commutation, 58
 - 3-3.2 Impulse Commutation, 60
 - 3-3.3 Resonant Pulse Commutation, 64
 - 3-3.4 Complementary Commutation, 67
 - 3-3.5 External Pulse Commutation, 69
 - 3-3.6 Load-Side Commutation, 69
 - 3-3.7 Line-Side Commutation, 69
- 3-4 Commutation Circuit Design, 71
- 3-5 Commutation Capacitors, 74
- Summary, 74
- References, 74
- Review Questions, 75
- Problems, 75

CHAPTER 4 CONTROLLED RECTIFIERS 77

- 4-1 Introduction, 77
- 4-2 Principle of Phase-Controlled Converter Operation, 78
- 4-3 Single-Phase Semiconverters, 80
- 4-4 Single-Phase Full Converters, 84
- 4-5 Single-Phase Dual Converters, 87

- 4-6 Single-Phase Series Converters, 90
- 4-7 Three-Phase Half-Wave Converters, 95
- 4-8 Three-Phase Semiconverters, 99
- 4-9 Three-Phase Full Converters, 101
- 4-10 Three-Phase Dual Converters, 105
- 4-11 Power Factor Improvements, 107
 - 4-11.1 Extinction Angle Control, 108
 - 4-11.2 Symmetrical Angle Control, 110
 - 4-11.3 Pulse-Width-Modulation Control, 112
 - 4-11.4 Sinusoidal Pulse-Width Modulation, 114
- 4-12 Design of Converter Circuits, 115
- 4-13 Effects of Load and Source Inductances, 117
 - Summary, 119
 - References, 119
 - Review Questions, 120
 - Problems, 121

CHAPTER 5 STATIC SWITCHES 124

- 5-1 Introduction, 124
- 5-2 Single-Phase AC Switches, 125
- 5-3 Three-Phase AC Switches, 127
- 5-4 Three-Phase Reversing Switches, 127
- 5-5 AC Switches for Bus Transfer, 130
- 5-6 DC Switches, 130
- 5-7 Solid-State Relays, 132
- 5-8 Design of Static Switches, 133
 - Summary, 134
 - References, 134
 - Review Questions, 134
 - Problems, 135

CHAPTER 6 AC VOLTAGE CONTROLLERS 137

- 6-1 Introduction, 137
- 6-2 Principle of On–Off Control, 138
- 6-3 Principle of Phase Control, 140
- 6-4 Single-Phase Bidirectional Controllers with Resistive Loads, 142
- 6-5 Single-Phase Controllers with Inductive Loads, 145
- 6-6 Three Phase Half-Wave Controllers, 148
- 6-7 Three-Phase Full-Wave Controllers, 154
- 6-8 Three-Phase Bidirectional Delta-Connected Controllers, 157
- 6-9 Single-Phase Transformer Tap Changers, 161
- 6-10 Cycloconverters, 166

- 6-10.1 Single-Phase Cycloconverters, 166
- 6-10.2 Three-Phase Cycloconverters, 168
- 6-10.3 Reduction of Output Harmonics, 169
- 6-11 Design of AC Voltage-Controller Circuits, 172
- 6-12 Effects of Source and Load Inductances, 175
 - Summary, 176
 - References, 176
 - Review Questions, 176
 - Problems, 177

CHAPTER 7 DC CHOPPERS 180

- 7-1 Introduction, 180
- 7-2 Principle of Step-Down Operation, 180
- 7-3 Step-Down Choppers with RL Load, 183
- 7-4 Principle of Step-Up Operation, 186
- 7-5 Performance Parameters, 189
- 7-6 Switching-Mode Regulators, 189
 - 7-6.1 Buck Regulators, 190
 - 7-6.2 Boost Regulators, 193
 - 7-6.3 Buck–Boost Regulators, 196
 - 7-6.4 Cúk Regulators, 199
 - 7-6.5 Limitations of Single-Stage Conversion, 204
- 7-7 Thyristor Chopper Circuits, 204
 - 7-7.1 Impulse-Commutated Choppers, 205
 - 7-7.2 Effects of Source and Load Inductance, 210
 - 7-7.3 Impulse-Commutated Three-Thyristor Choppers, 210
 - 7-7.4 Resonant Pulse Choppers, 212
- 7-8 Chopper Circuit Design, 215
- 7-9 Magnetic Considerations, 221
 - Summary, 221
 - References, 221
 - Review Questions, 222
 - Problems, 223

CHAPTER 8 INVERTERS 226

- 8-1 Introduction, 226
- 8-2 Principle of Operation, 227
- 8-3 Performance Parameters, 228
- 8-4 Single-Phase Bridge Inverters, 230
- 8-5 Three-Phase Inverters, 233
- 8-6 Voltage Control of Single-Phase Inverters, 239
 - 8-6.1 Single-Pulse-Width Modulation, 240

- 8-6.2 Multiple-Pulse-Width Modulation, 241
- 8-6.3 Sinusoidal Pulse-Width Modulation, 243
- 8-6.4 Modified Sinusoidal Pulse-Width Modulation, 245
- 8-6.5 Phase-Displacement Control, 246
- 8-7 Voltage Control of Three-Phase Inverters, 247
- 8-8 Harmonic Reductions, 248
- 8-9 Series Resonant Inverters, 251
 - 8-9.1 Series Resonant Inverters with Unidirectional Switches, 252
 - 8-9.2 Series Resonant Inverters with Bidirectional Switches, 259
- 8-10 Forced-Commutated Thyristor Inverters, 264
 - 8-10.1 Auxiliary-Commutated Inverters, 265
 - 8-10.2 Complementary-Commutated Inverters, 266
- 8-11 Current-Source Inverters, 273
- 8-12 Variable DC Link Inverter, 276
- 8-13 Inverter Circuit Design, 276
- 8-14 Magnetic Considerations, 279
 - Summary, 279
 - References, 279
 - Review Questions, 280
 - Problems, 281

CHAPTER 9 POWER SUPPLIES 284

- 9-1 Introduction, 284
- 9-2 DC Power Supplies, 285
 - 9-2.1 Switched-Mode DC Power Supplies, 285
 - 9-2.2 Resonant DC Power Supplies, 288
 - 9-2.3 Bidirectional Power Supplies, 289
- 9-3 AC Power Supplies, 290
 - 9-3.1 Switched-Mode AC Power Supplies, 290
 - 9-3.2 Resonant AC Power Supplies, 291
 - 9-3.3 Bidirectional AC Power Supplies, 291
- 9-4 Multistage Conversions, 292
- 9-5 Magnetic Considerations, 293
 - Summary, 294
 - References, 294
 - Review Questions, 294
 - Problems, 295

CHAPTER 10 DC DRIVES 296

- 10-1 Introduction, 296
- 10-2 Basic Characteristics of DC Motors, 297
- 10-3 Single-Phase Drives, 300
 - 10-3.1 Single-Phase Half-Wave Converter Drives, 301

10-3.2	Single-Phase Semiconverter Drives, 302
10-3.3	Single-Phase Full-Converter Drives, 303
10-3.4	Single-Phase Dual-Converter Drives, 304
10-4	Three-Phase Drives, 307
✓10-4.1	Three-Phase Half-Wave Converter Drives, 308
10-4.2	Three-Phase Semiconverter Drives, 308
10-4.3	Three-Phase Full-Converter Drives, 308
10-4.4	Three-Phase Dual-Converter Drives, 309
10-5	Chopper Drives, 313
10-5.1	Principle of Power Control, 313
10-5.2	Principle of Regenerative Brake Control, 315
10-5.3	Principle of Rheostatic Brake Control, 317
10-5.4	Principle of Combined Regenerative and Rheostatic Brake Control, 319
10-5.5	Two/Four-Quadrant Chopper Drives, 319
10-5.6	Multiphase Choppers, 321
10-6	Closed-Loop Control of DC Drives, 323
10-6.1	Open-Loop Transfer Function, 324
10-6.2	Closed-Loop Transfer Function, 328
10-6.3	Phase-Locked-Loop Control, 330
10-6.4	Microcomputer Control of DC Drives, 332
	Summary, 333
	References, 333
	Review Questions, 334
	Problems, 335

CHAPTER 11 AC DRIVES 339

11-1	Introduction, 339
11-2	Induction Motor Drives, 340
11-2.1	Performance Characteristics, 341
11-2.2	Stator Voltage Control, 347
11-2.3	Rotor Voltage Control, 349
11-2.4	Frequency Control, 356
11-2.5	Voltage and Frequency Control, 358
11-2.6	Current Control, 361
11-2.7	Voltage, Current, and Frequency Control, 364
11-2.8	Closed-Loop Control of Induction Motors, 365
11-3	Synchronous Motor Drives, 369
11-3.1	Cylindrical Rotor Motors, 370
11-3.2	Salient-Pole Motors, 373
11-3.3	Reluctance Motors, 374
11-3.4	Permanent-Magnet Motors, 375
11-3.5	Closed-Loop Control of Synchronous Motors, 376

Summary, 377
References, 378
Review Questions, 379
Problems, 380

CHAPTER 12 POWER SEMICONDUCTOR DIODES 383

- 12-1 Introduction, 383
- 12-2 Diode Characteristics, 383
- 12-3 Power Diode Types, 386
 - 12-3.1 General-Purpose Diodes, 386
 - 12-3.2 Fast-Recovery Diodes, 387
 - 12-3.3 Schottky Diodes, 387
- 12-4 Performance Parameters, 388
- 12-5 Effects of Forward and Reverse Recovery Time, 402
- 12-6 Series-Connected Diodes, 406
- 12-7 Parallel-Connected Diodes, 408
 - Summary, 409
 - Review Questions, 409
 - Problems, 410

CHAPTER 13 POWER TRANSISTORS 412

- 13-1 Introduction, 412
- 13-2 Bipolar Junction Transistors, 413
 - 13-2.1 Steady-State Characteristics, 413
 - 13-2.2 Switching Characteristics, 418
 - 13-2.3 Performance Parameters, 424
 - 13-2.4 Base Drive Control, 436
- 13-3 Power MOSFETs, 440
 - 13-3.1 Steady-State Characteristics, 442
 - 13-3.2 Switching Characteristics, 444
 - 13-3.3 Performance Parameters, 445
 - 13-3.4 Gate Drive, 452
- 13-4 MOSIGTs, 452
- 13-5 Series and Parallel Operation, 457
- 13-6 di/dt and dv/dt Limitations, 458
- 13-7 Isolation of Gate and Base Drives, 461
 - 13-7.1 Pulse Transformers, 462
 - 13-7.2 Optocouplers, 462
 - Summary, 463
 - References, 464
 - Review Questions, 464
 - Problems, 466

CHAPTER 14 THYRISTORS 468

- 14-1 Introduction, 468
- 14-2 Thyristor Characteristics, 468
- 14-3 Two-Transistor Model of Thyristor, 470
- 14-4 Thyristor Turn-On, 472
- 14-5 di/dt Protection, 474
- 14-6 dv/dt Protection, 476
- 14-7 Thyristor Turn-Off, 478
- 14-8 Thyristor Types, 479
 - 14-8.1 Phase Control Thyristors, 480
 - 14-8.2 Fast-Switching Thyristors, 480
 - 14-8.3 Gate-Turn-Off Thyristors, 481
 - 14-8.4 Bidirectional Triode Thyristors, 482
 - 14-8.5 Reverse-Conducting Thyristors, 482
 - 14-8.6 Static Induction Thyristors, 483
 - 14-8.7 Light-Activated Silicon-Controlled Rectifiers, 484
 - 14-8.8 FET-Controlled Thyristors, 484
- 14-9 Performance Parameters, 485
 - 14-9.1 SCR Parameters, 485
 - 14-9.2 GTO Parameters, 494
- 14-10 Series Operation of Thyristors, 504
- 14-11 Parallel Operation of Thyristors, 507
- 14-12 Thyristor Firing Circuits, 507
 - Summary, 509
 - References, 510
 - Review Questions, 510
 - Problems, 511

CHAPTER 15 PROTECTION OF DEVICES AND CIRCUITS 514

- 15-1 Introduction, 514
- 15-2 Cooling and Heat Sinks, 514
- 15-3 Snubber Circuits, 520
- 15-4 Reverse Recovery Transients, 521
- 15-5 Supply- and Load-Side Transients, 527
- 15-6 Voltage Protection by Selenium Diodes and Metal-Oxide Varistors, 529
- 15-7 Current Protections, 531
 - 15-7.1 Fusing, 531
 - 15-7.2 Fault Current with AC Source, 538
 - 15-7.3 Fault Current with DC Source, 540
 - Summary, 541
 - References, 541
 - Review Questions, 542
 - Problems, 542

APPENDIX A	THREE-PHASE CIRCUITS	545
APPENDIX B	MAGNETIC CIRCUITS	549
APPENDIX C	SWITCHING FUNCTIONS OF CONVERTERS	554
APPENDIX D	TRANSIENT ANALYSIS	560
APPENDIX E	FOURIER ANALYSIS	564
APPENDIX F	LISTING OF COMPUTER PROGRAMS IN IBM-PC BASICA	567
BIBLIOGRAPHY		578
INDEX		580

(e) From Eq. (8-3), $V_1 = 0.45V_s$ and

$$\left(\sum_{n=3,5,7,\dots}^{\infty} V_n^2 \right)^{1/2} = (V_0^2 - V_1^2)^{1/2} = 0.2176V_s$$

From Eq. (8-5), $\text{THD} = 0.2176V_s/(0.45V_s) = 48.34\%$.

(f) From Eq. (8-2),

$$\left[\sum_{n=3,5,\dots}^{\infty} \left(\frac{V_n}{n^2} \right)^2 \right]^{1/2} = \left[\left(\frac{V_3}{3} \right)^2 + \left(\frac{V_5}{5} \right)^2 + \left(\frac{V_7}{7} \right)^2 + \dots \right]^{1/2} = 0.01712V_s$$

From Eq. (8-6), $\text{DF} = 0.01712V_s/(0.45V_s) = 3.804\%$.

(g) The lowest-order harmonic is the third, $V_3 = V_1/3$. From Eq. (8-4), $\text{HF}_3 = V_3/V_1 = 1/3 = 33.33\%$, and from Eq. (8-7), $\text{DF}_3 = (V_3/3^2)/V_1 = 1/27 = 3.704\%$.

8-4 SINGLE-PHASE BRIDGE INVERTERS

A single-phase bridge inverter is shown in Fig. 8-2a. It consists of four choppers. When transistors Q_1 and Q_2 are turned on simultaneously, the input voltage V_s appears across the load. If transistors Q_3 and Q_4 are turned on at the same time, the voltage across the load is reversed and is $-V_s$. The waveform for the output voltage is shown in Fig. 8-2b.

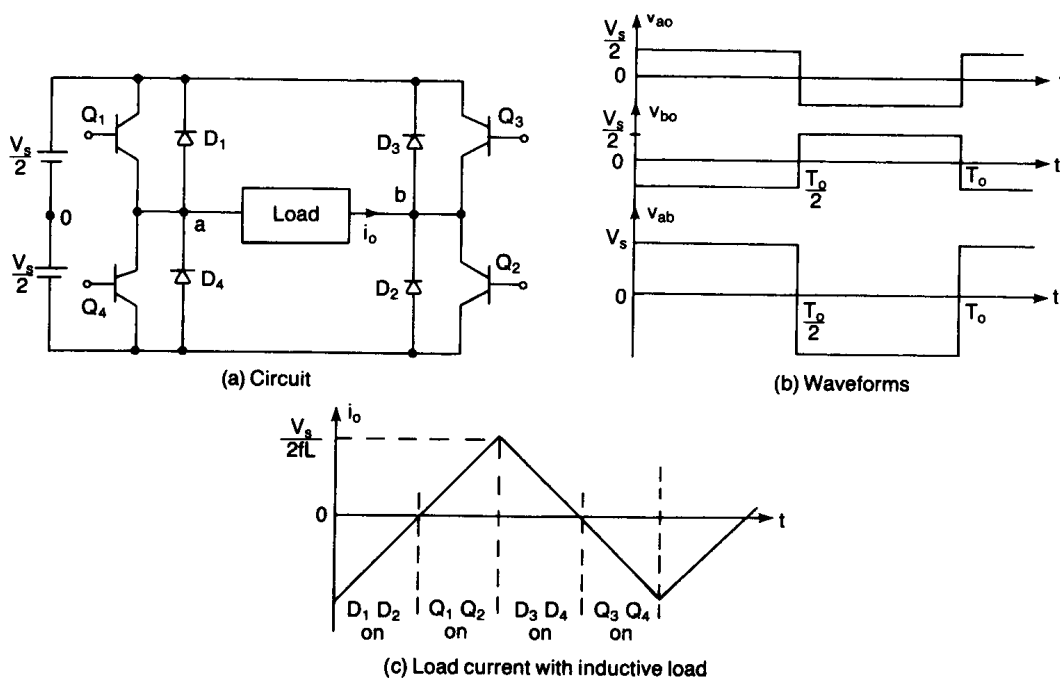


Figure 8-2 Single-phase full-bridge inverter.

The rms output voltage can be found from

$$V_o = \left(\frac{2}{T_0} \int_0^{T_0/2} V_s^2 dt \right)^{1/2} = V_s \quad (8-8)$$

Equation (8-2) can be extended to express the instantaneous output voltage in a Fourier series as

$$v_o = \sum_{n=1,3,5,\dots}^{\infty} \frac{4V_s}{n\pi} \sin n\omega t \quad (8-9)$$

and for $n = 1$, Eq. (8-9) gives the rms value of fundamental component as

$$V_1 = \frac{4V_s}{\sqrt{2}\pi} = 0.90V_s \quad (8-10)$$

When diodes D_1 and D_2 conduct, the energy is fed back to the dc source and they are known as *feedback diodes*. Figure 8-1c shows the waveform of load current for inductive loads.

Example 8-2

Repeat Example 8-1 for a single-phase bridge inverter in Fig. 8-2a.

Solution $V_s = 48$ V and $R = 2.4$ Ω .

(a) From Eq. (8-10), $V_1 = 0.90 \times 48 = 43.2$ V.

(b) From Eq. (8-8), $V_o = V_s = 48$ V. The output power, $P_o = V_s^2/R = 48^2/2.4 = 960$ W.

(c) The peak transistor current, $I_p = 48/2.4 = 20$ A. Since each transistor conducts for a 50% duty cycle, the average current of each transistor is $I_D = 0.5 \times 20 = 10$ A.

(d) The peak reverse blocking voltage, $V_B = 48$ V.

(e) From Eq. (8-10), $V_1 = 0.9V_s$

$$\left(\sum_{n=3,5,7,\dots}^{\infty} V_n^2 \right)^{1/2} = (V_0^2 - V_1^2)^{1/2} = 0.4352V_s$$

From Eq. (8-5), THD = $0.4352V_s/(0.9V_s) = 48.34\%$.

$$(f) \left[\sum_{n=3,5,7,\dots}^{\infty} \left(\frac{V_n}{n^2} \right)^2 \right]^{1/2} = 0.03424V_s$$

From Eq. (8-6), DF = $0.03424V_s/(0.9V_s) = 3.804\%$.

(g) The lowest-order harmonic is the third, $V_3 = V_1/3$. From Eq. (8-4), $HF_3 = V_3/V_1 = 1/3 = 33.33\%$ and from Eq. (8-7), $DF_3 = (V_3/3^2)/V_1 = 1/27 = 3.704\%$.

Note. The peak reverse blocking voltage of each transistor and the quality of output voltage for half-bridge and full-bridge inverters are the same. However, for full-bridge inverters with resistive loads, the output power is four times higher and the fundamental component is twice than that of half-bridge inverters.

Example 8-3

The bridge inverter in Fig. 8-2a has an RLC load with $R = 10$ Ω , $L = 31.5$ mH, and $C = 112$ μ F. The inverter frequency, $f_0 = 60$ Hz and dc input voltage, $V_s = 220$ V. (a) Express the instantaneous load current in Fourier series. Calculate the (b) rms load current at the fundamental frequency, I_1 ; (c) harmonic factor of load current,

HF; (d) power absorbed by the load, P_o ; (e) average current of dc supply; I_s and (f) rms and peak current of each transistor. (g) Draw the waveform of fundamental load current and show the conduction intervals of transistors and diodes. Calculate the conduction time of the (h) transistors, and (i) diodes.

Solution $V_s = 220$ V, $f_o = 60$ Hz, $R = 10$ Ω , $L = 31.5$ mH, $C = 112$ μ F, and $\omega = 2\pi \times 60 = 377$ rad/s. The inductive reactance for the n th harmonic voltage is

$$X_L = 2n\pi \times 60 \times 31.5 \times 10^{-3} = j11.87n \Omega$$

The capacitive reactance for the n th harmonic voltage is

$$X_c = -\frac{10^6}{2n\pi \times 60 \times 112} = \frac{-j23.68}{n} \Omega$$

The impedance for the n th harmonic voltage is

$$Z_n = [10^2 + (11.87n - 23.6/n)^2]^{1/2}$$

and the power factor angle for the n th harmonic voltage is

$$\theta_n = \tan^{-1} \frac{11.87n - 23.6/n}{10} = \tan^{-1} \left(1.187n - \frac{2.346}{n} \right)$$

(a) From Eq. (8-9), the instantaneous output voltage can be expressed as

$$\begin{aligned} v_o(t) = & 280.1 \sin(377t) + 93.4 \sin(3 \times 377t) + 56.02 \sin(5 \times 377t) \\ & + 40.02 \sin(7 \times 377t) + 31.12 \sin(9 \times 377t) + \dots \end{aligned}$$

Dividing the output voltage by the load impedance and considering the appropriate delay due to the power factor angles, we can obtain the instantaneous load current as

$$\begin{aligned} i_o(t) = & 18.1 \sin(377t + 49.72^\circ) + 3.17 \sin(3 \times 377t - 70.17^\circ) \\ & + \sin(5 \times 377t - 79.63^\circ) + 0.5 \sin(7 \times 377t - 82.85^\circ) \\ & + 0.3 \sin(9 \times 377t - 84.52^\circ) + \dots \end{aligned}$$

(b) The rms load current at fundamental frequency, $I_1 = 18.1/\sqrt{2} = 12.8$ A.

(c) Considering up to the ninth harmonic, the peak load current,

$$I_m = (18.1^2 + 3.17^2 + 1.0^2 + 0.5^2 + 0.3^2)^{1/2} = 18.41 \text{ A}$$

The harmonic factor of load current,

$$\text{HF} = \frac{(I_m^2 - I_{m1}^2)^{1/2}}{I_{m1}} = \left[\left(\frac{18.41}{18.1} \right)^2 - 1 \right]^{1/2} = 18.59\%$$

(d) The rms load current, $I_o = 18.41/\sqrt{2} = 13.02$ A, and the load power, $P_o = 13.02^2 \times 10 = 1695$ W.

(e) The average supply current, $I_s = 1695/220 = 7.7$ A.

(f) The peak transistor current, $I_p = 18.41$ A. The rms current of each transistor, $I_R = I_o/\sqrt{2} = I_p/2 = 18.41/2 = 9.2$ A.

(g) The waveform for fundamental load current, $i_1(t)$, is shown in Fig. 8.3.

(h) From Fig. 8-3a, the conduction time of each transistor is found from $t_0 = 180 - 49.72 = 130.28^\circ$ or $t_0 = 130.28 \times \pi/(180 \times 377) = 6031$ μ s.

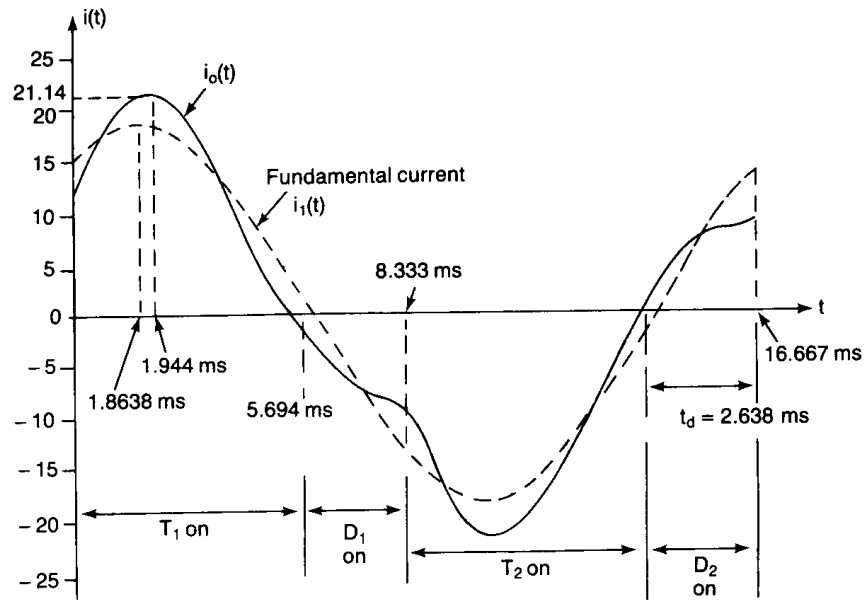


Figure 8-3 Waveforms for Example 8-3.

(i) The conduction time of each diode,

$$t_d = (180 - 130.28) \times \frac{\pi}{180 \times 377} = 2302 \mu\text{s}$$

Note. To calculate the exact values of the peak current, the conduction time of transistors and diodes, the instantaneous load current $i_o(t)$ should be plotted as shown in Fig. 8-3. The conduction time of a transistor must satisfy the condition $i_o(t = t_0) = 0$, and a plot of $i_o(t)$ by a computer program gives $I_p = 21.14$ A, $t_0 = 5694 \mu\text{s}$, and $t_d = 2638 \mu\text{s}$.

8-5 THREE-PHASE INVERTERS

Three-phase inverters are normally used for high-power applications. Three single-phase half (or full)-bridge inverters can be connected in parallel as shown in Fig. 8-4a to form the configuration of a three-phase inverter. The gating signals of single-phase inverters should be advanced or delayed by 120° with respect to each other in order to obtain three-phase balanced (fundamental) voltages. The transformer primary windings must be isolated from each other, while the secondary windings may be connected in wye or delta. The transformer secondary is normally connected in wye to eliminate triplen harmonics ($n = 3, 6, 9, \dots$) appearing on the output voltages and the circuit arrangement is shown in Fig. 8-4b. This arrangement requires three single-phase transformers, 12 transistors (or thyristors), and 12 diodes. If the output voltages of single-phase inverters are not perfectly balanced in magnitudes and phases, the three-phase output voltages will be unbalanced.