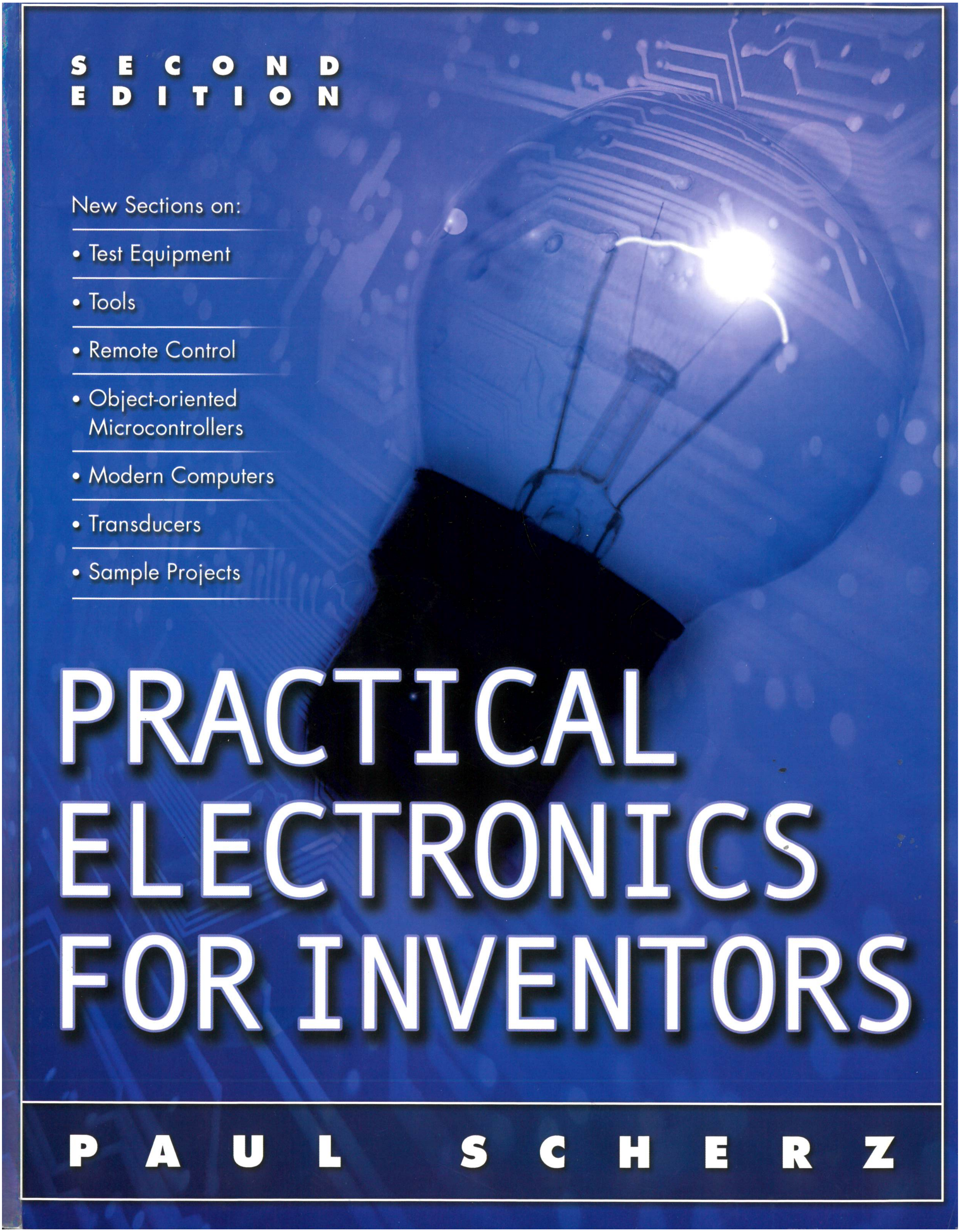


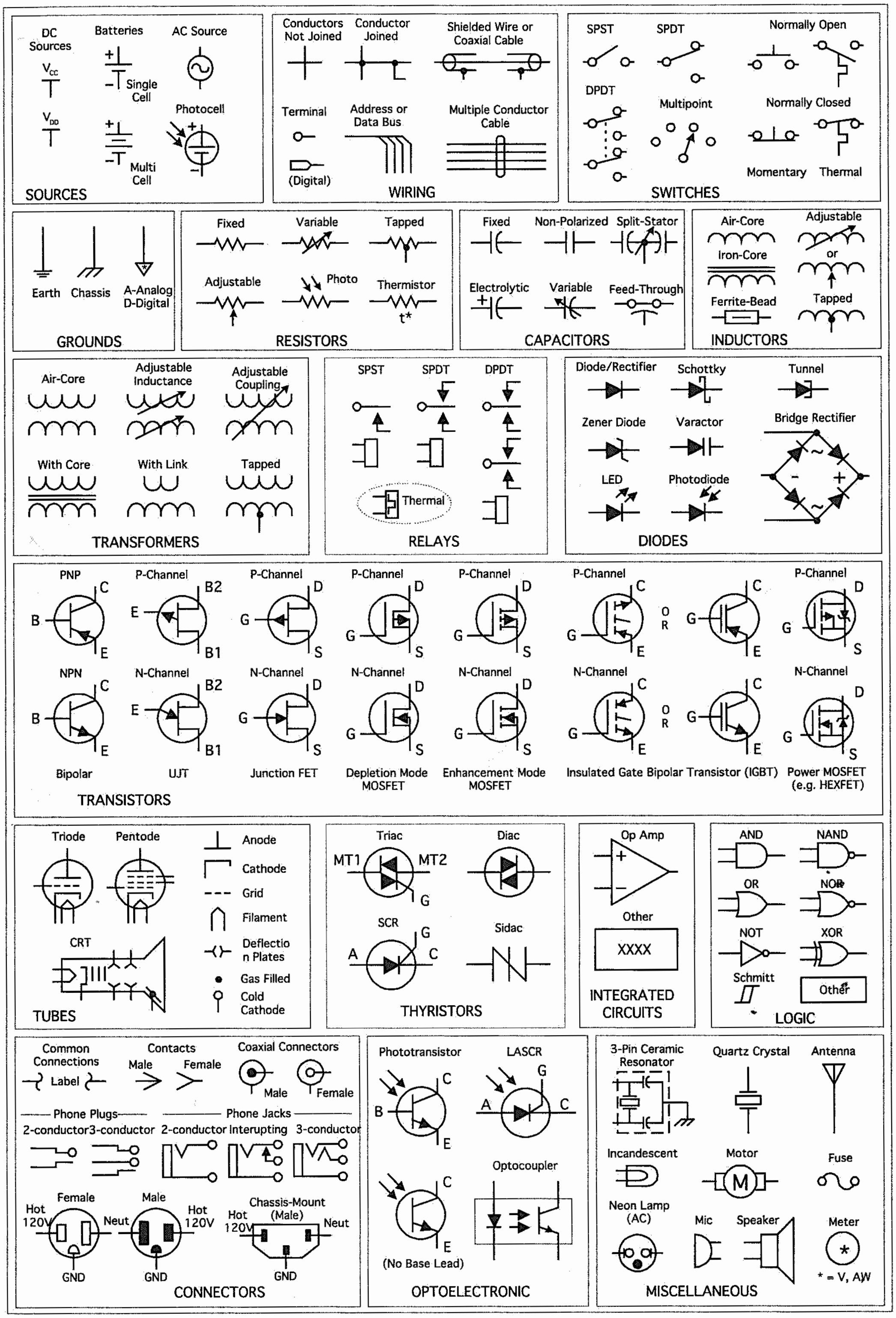
SECOND EDITION

New Sections on:

- Test Equipment
- Tools
- Remote Control
- Object-oriented Microcontrollers
- Modern Computers
- Transducers
- Sample Projects

PRACTICAL ELECTRONICS FOR INVENTORS

PAUL SCHERZ


DC Sources
Batteries
AC Source
Vcc
VDD
Single Cell
Multi Cell
Photocell
SOURCES
Conductors Not Joined
Conductor Joined
Shielded Wire or Coaxial Cable
Terminal
(Digital)
Address or Data Bus
Multiple Conductor Cable
WIRING
SPST
SPDT
DPDT
Multipoint
Normally Open
Normally Closed
Momentary
Thermal
SWITCHES
Earth
Chassis
A-Analog D-Digital
GROUNDS
Fixed
Variable
Tapped
Adjustable
Photo
Thermistor
t*
RESISTORS
Fixed
Non-Polarized
Split-Stator
Electrolytic
Variable
Feed-Through
CAPACITORS
Air-Core
Iron-Core
Ferrite-Bead
Adjustable
or
Tapped
INDUCTORS
Air-Core
Adjustable Inductance
Adjustable Coupling
With Core
With Link
Tapped
TRANSFORMERS
SPST
SPDT
DPDT
Thermal
RELAYS
Diode/Rectifier
Schottky
Tunnel
Zener Diode
Varactor
Bridge Rectifier
LED
Photodiode
DIODES
PNP
NPN
Bipolar
P-Channel
N-Channel
B2
B1
UJT
Junction FET
Depletion Mode MOSFET
Enhancement Mode MOSFET
Insulated Gate Bipolar Transistor (IGBT)
OR
Power MOSFET (e.g. HEXFET)
TRANSISTORS
Triode
Pentode
Anode
Cathode
Grid
Filament
Deflectio n Plates
Gas Filled
Cold Cathode
CRT
TUBES
Triac
MT1
MT2
Diac
SCR
Sidac
THYRISTORS
Op Amp
Other
XXXX
INTEGRATED CIRCUITS
AND
NAND
OR
NOR
NOT
XOR
Schmitt
Other
LOGIC
Common Connections
Label
Contacts
Male
Female
Coaxial Connectors
Phone Plugs
Phone Jacks
2-conductor
3-conductor
2-conductor
Interupting
3-conductor
Hot 120V
Neut
GND
Chassis-Mount (Male)
CONNECTORS
Phototransistor
LASCR
Optocoupler
(No Base Lead)
OPTOELECTRONIC
3-Pin Ceramic Resonator
Quartz Crystal
Antenna
Incandescent
Motor
Fuse
Neon Lamp (AC)
Mic
Speaker
Meter
* = V, A,W
MISCELLANEOUS

Resistor Labels

Conversion Calculator

k = 1,000 ; M = 1,000,000

1MΩ = 1,000,000 Ω = $1 \times 10^6 \Omega$

1kΩ = 1,000 Ω = $1 \times 10^3 \Omega$

Examples:

3.3 kΩ = 3,300 Ω = $3.3 \times 10^3 \Omega$

22 kΩ = 22,000 Ω = $22 \times 10^3 \Omega$

2 MΩ = 2,000,000 Ω = $2 \times 10^6 \Omega$

1.68 MΩ = 1,680,000 Ω = $1.68 \times 10^6 \Omega$

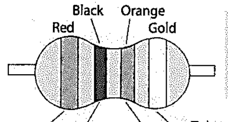
Resistor Color Code

Color	Sig. Fig.	Decimal Multiplier	Tolerance (%)
Black	0	1	-
Brown	1	10	1
Red	2	100	2
Orange	3	1,000	-
Yellow	4	10,000	-
Green	5	100,000	0.5
Blue	6	1,000,000	0.25
Purple	7	10,000,000	0.1
Gray	8	100,000,000	-
White	9	1,000,000,000	-
Gold	-	0.1	5
Silver	-	0.01	10
No Color	-	-	20

Body Color

The body color of a resistor typically doesn't carry meaning, except in some instances where it may specify temperature coefficient. However, if you find resistors within a circuit that are white/gray or blue in color, they may be non-flammable or fusible resistors. Care must be taken when replacing such resistors--don't substitute ordinary resistors in their place.

4-Band Resistor Code (Most Common)

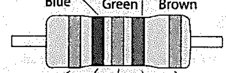


Label Meaning

Red Black Orange Gold

20 x 1,000 = 20k Ω ± 5%

5-Band Resistor Code (3-digit)



Label Meaning

Purple Brown Blue Green Brown

675 x 10 = 6750 Ω ± 1%

5-Band Resistor Code (Reliability)

Label Meaning

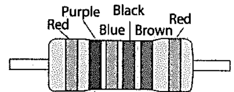
Yellow Purple Green Silver

47 x 100,000 = 4.7 MΩ ± 10%

1% Reliablity/1000 Hr—Brown

Color	Reliability (%/1000 Hr)
Brown	1
Red	0.1
Orange	0.01
Yellow	0.001

6-Band Resistor Code



Label Meaning

Purple Black Red Blue Brown

276 x 1 = 276Ω ± 1%

TC of 50 ppm — Red

Color	Temp. Coeff.
Brown	100 ppm
Red	50 ppm
Orange	15 ppm
Yellow	25 ppm

Surface Mount Resistor Code

3-digit Label

Label Meaning

101	10 and 1 zero = 100 Ω
105	10 and 5 zero = 1,000,000 Ω
224	22 and 4 zeros = 220,000 Ω
1R0	1.0 and no zeros = 1 Ω
22R	22.0 and no zeros = 22 Ω
R10	0.1 and no zeros = 0.1 Ω

The first two digits represent significant figures; the last digit specifies the multiplier. For values under 100 Ω, the letter R is substituted for one of the significant digits and represents a decimal point.

4-digit Label

Label Meaning

1001	100 and 1 zero =1000 Ω
22R0	22.0 and no zeros = 22 Ω

The first three digits represent significant figures; the last digit specifies the multiplier. R represents a decimal point

Tolerance Label

Label Meaning

101F	100 Ω ± 1%
1R0D	1.0 Ω ± 0.5%

Letter	Tolerance
D	±0.5 %
F	±1.0 %
G	±2.0 %
J	±5.0 %

Capacitor Markings

Capacitance Conversion Calculator

1 F = 1 x 10⁶ μ F = 1 x 10⁹ nF = 1 x 10¹² pF

1 μF = 1 x 10⁻⁶ F = 1 x 10³ nF = 1 x 10⁶ pF

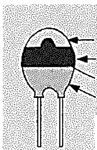
1 nF = 1 x 10⁻⁹ F = 1 x 10⁻³ μF = 1 x 10³ pF

1 pF = 1 x 10⁻¹² F = 1 x 10⁻⁶ μF = 1 x 10⁻³ nF

F = Farad, μ = micro, n = nano, p = pico

1000 μF = 1,000,000 nF = 10 x 10⁸ pF
100 μF = 100,000 nF = 10 x 10⁷ pF
10 μF = 10,000 nF = 10 x 10⁶ pF
1 μF = 1,000 nF = 10 x 10⁵ pF
0.1 μF = 100 nF = 10 x 10⁴ pF
0.01 μF = 10 nF = 10 x 10³ pF
0.001 μF = 1 nF = 10 x 10² pF

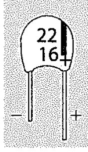
Tantalum



Label meaning 1
- 1st significant figure in μF
- 2nd significant figure in μF
- Multiplier
- Voltage

(See table)

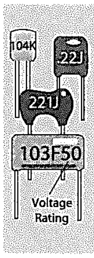
Color	S.F.	Multiplie	Voltage
Black	0	1	10V
Brown	1	10	
Red	2	100	
Orange	3	1000	
Yellow	4		6.3V
Green	5		16V
Blue	6		20V
Violet	7		
Gray	8	0.01	25V
White	9	0.1	3V
Pink			35V



Label meaning 2

Marking	Actual
22	22μF, 16 V

Mylar (Polyester Film)
Polypropylene
Dipped Mica

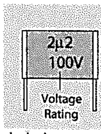


Label meaning

Marking	Actual
.001K*	0.001μF, ± 10%
104K	0.1 μF, ± 10%
.22J *	0.22 μF, ± 5%
472K	0.0047 μF, ± 10%
221J	220 pF, ± 5%
470J	47pF, ± 5%
102J	1000pF, ± 5%
103F	0.01 μF, ± 1%
223F	0.022 μF, ± 1%
104F	0.1 μF, ± 1%

Labels:
Ist digit, 2nd digit, multiplier in pF (or μF if decimal before digits), and tolerance.

Metallized Polyester Film

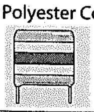


Label meaning

Marking	*Actual*
2μ2	2.2μF
μ22	0.22μF
68n	68 nF
4n7	4.7 nF

Label :
"μ" p lace of decimal in microfarads
"n" place of decimal in nanofarads

Polyester Color Coded



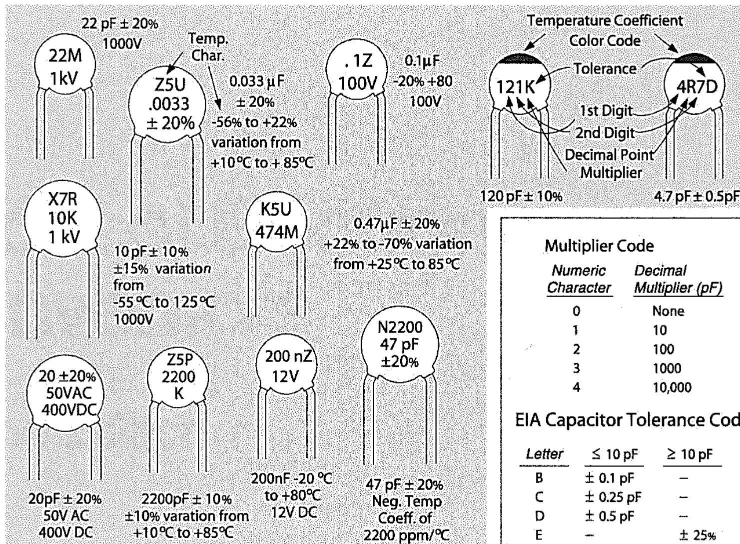
- 1st digit (pF)
- 2nd digit (pF)
- Multiplier
- Tolerance
- Voltage

Standard color code (1st digit, 2nd digit, multiplier)

Tolerance: Black ± 20%, White ± 10%, Green ± 5%

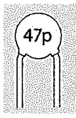
Voltage: Brown 100, Red 250, Yellow 400

Ceramic Disc Capacitors



Label:
Varies widely according to manufacturer. Usually given in pF (see multiplier code table) but may be given in μF when there is a decimal before digits. See other tables for temperature and tolerance markings.

Ceramic Disc (European Markings)



Label Meaning

Marking	*Actual*	*Marking*	*Actual*
p68	0.68 pF	22p	22 pF
1p0	1.0 pF	n10	0.1 nF
4p7	4.7 pF	n27	0.27 nF

Label: p = picofarads, n = nanofarads; location of p or n signifies decimal point.

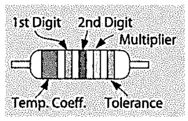
Multiplier Code

Numeric Character	*Decimal Multiplier (pF)*
0	None
1	10
2	100
3	1000
4	10,000

EIA Capacitor Tolerance Codes

Letter	≤ 10 pF	≥ 10 pF
B	± 0.1 pF	–
C	± 0.25 pF	–
D	± 0.5 pF	–
E	–	± 25%
F	± 1 pF	± 1%
G	–	± 2%
H	–	± 2.5%
J	–	± 5%
K	–	± 10%
M	–	± 20%
P	–	-0 + 100%
S	–	-20 + 50%
W	–	-0 + 200%
X	–	-20 + 40%
Z	–	-20 + 80%

Fixed Ceramic Color Code



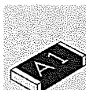
Color	S.F.		Tolerance >10pF	Tolerance <10pF	Temp. Coeff. ppm/°C
Black	0	1	± 20%	2.0 pF	-0
Brown	1	10	± 1%		-30
Red	2	100	± 2%		-80
Orange	3	1000			-150
Yellow	4				-220
Green	5		± 5%	0.5pF	-330
Blue	6				-470
Violet	7				-750
Gray	8	0.01		0.25pF	30
White	9	0.1	± 10%	1.0pF	500

EIA Temperature Characteristic Codes

Minimum temperature		*Maximum temperature*		*Max cap. change over temp. range*	
X	-55° C	2	+45° C	A	± 1.0%
Y	-35° C	4	+65° C	B	± 1.5 %
Z	+10° C	5	+85° C	C	± 2.2%
		6	+105° C	D	± 3.3%
		7	+125° C	E	± 4.7%
				F	± 7.5%
				P	± 10%
				R	± 15%
				S	± 22%
				T	-33%, + 22%
				U	-56%, + 22%
				V	-82%, + 22%

Surface Mount Capacitors

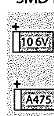
SMD Ceramic



Label meaning

Marking	*Actual*
N1	33 pF
A4	0.01 μF
S6	4.7 μF

SMD Electrolytic



Label meaning 1

Marking	*Actual*
10 6V	10 μF, 6V

Label meaning 2

Marking	*Actual*
A475	4.7 μF, 10V

Significant Figure Code

Char.	*S. F.*	*Char.*	*S. F.*
A	1.0	T	5.1
B	1.1	U	5.6
C	1.2	V	6.2
D	1.3	W	6.8
E	1.5	X	7.5
F	1.6	Y	8.2
G	1.8	Z	9.1
H	2.0	a	2.5
J	2.2	b	3.5
K	2.4	d	4.0
L	2.7	e	4.5
M	3.0	f	5.0
N	3.3	m	6.0
P	3.6	n	7.0
Q	3.9	t	8.0
R	4.3	y	9.0
S	4.7		

Multiplier Code

Numeric Character	*Decimal Multiplier (pF)*
0	1
1	10
2	100
3	1,000
4	10,000
5	100,000
6	1,000,000
7	10,000,000
8	100,000,000
9	0.1

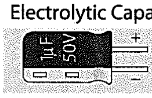
Label 2:
Voltage (see table below), 1st digit, 2nd digit, multiplier (pF).

Char.	*Voltage*
e	2.5
G	4
J	6.3
A	10
C	16
D	20
E	25
V	35
H	50

EIA Temperature Coefficient Color Codes

Color	*Temp. Coeff. Industry*	*EIA*
Black*	NP0	C0G
Brown	N030/N033	S1G
Red	N075/N080	U1G
Orange	N 150	P2G
Yellow	N 220	R2G
Green	N 330	S2H
Blue	N 470	U2J
Violet	N 750	
Gray		
White	P 100	
Red/Violet	P 100	

Electrolytic Capacitors



Label: Usually self-explanatory

Practical Electronics for Inventors

Second Edition

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wave average and calculates the sine wave RMS figure from that. So take care, especially if you're not sure exactly how your meter works.

WAVEFORM	HALF-WAVE AVERAGE	RMS (EFFECTIVE)	PEAK	PEAK-TO-PEAK
Sine wave	1.00	1.11	1.567	3.14
	0.90	1.00	1.414	2.828
	0.637	0.707	1.00	2.00
	0.318	0.354	0.50	1.00
Squarewave	1.00	1.00	1.00	2.00
Triangle or Sawtooth	1.00	1.15	2.00	4.00
	0.87	1.00	1.73	3.46
	0.50	0.578	1.00	2.00
	0.25	0.289	0.50	1.00

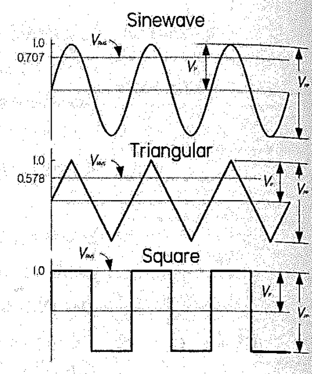


FIGURE 2.89

2.22 Mains Power

In the United States, three wires run from the pole transformers (or underground or surface enclosed transformer) to the main service panel at one's home. One wire is the A-phase wire (usually black in color), another is the B-phase wire (usually black in color), and the third is the neutral wire (white in color). Figure 2.90 shows where these three wires originate from the pole transformer. The voltage between the A-phase and the B-phase wires, or the hot-to-hot voltage, is 240 V, while the voltage between the neutral wire and either the A-phase or the B-phase wire, or the neutral-to-hot voltage, is 120 V. (These voltages are nominal and may vary from region to region, say 117 V instead of 120 V.)

At the home, the three wires from the pole/green box transformer are connected through a wattmeter and then enter a main service panel that is grounded to a long copper rod driven into the ground or to the steel in a home's foundation. The A-phase and B-phase wires that enter the main panel are connected through a main disconnect breaker, while the neutral wire is connected to a terminal referred to as the neutral bar or neutral bus. A ground bar also may be present within the main service panel. The ground bar is connected to the grounding rod or to the foundation's steel supports.

Within the main service panel, the neutral bar and the ground bar are connected together (they act as one). However, within subpanels (service panels that get their power from the main service panel but which are located some distance from the main service panel), the neutral and ground bars are not joined together. Instead, the subpanel's ground bar receives a ground wire from the main services panel. Often the metal conduit that is used to transport the wires from the main service panel to the subpanel is used as the ground wire. However, for certain critical applications (e.g., computer and life-support systems), the ground wire probably will be included within the conduit. Also, if a subpanel is not located in the same building as the main

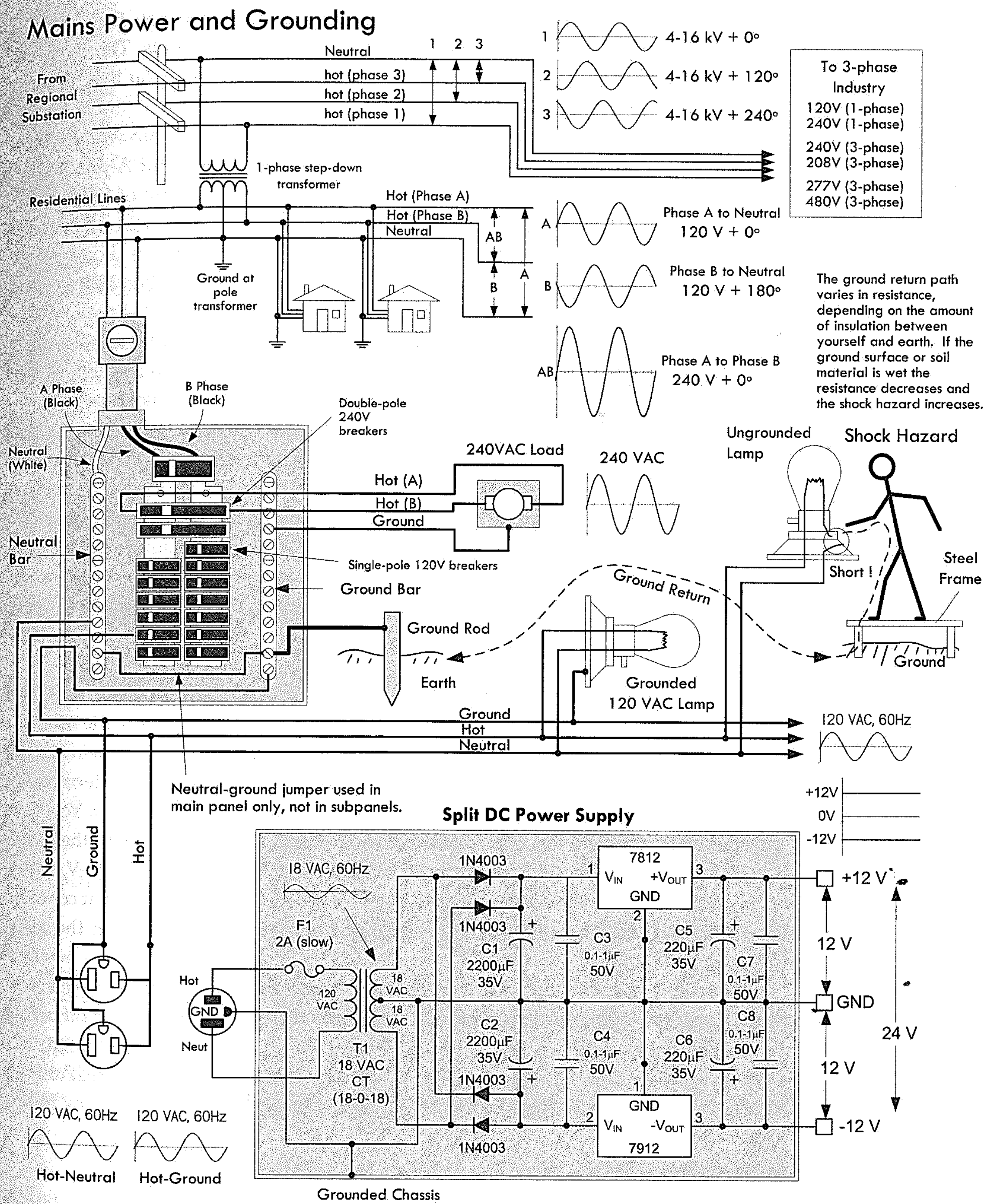

Mains Power and Grounding
From Regional Substation
Neutral
hot (phase 3)
hot (phase 2)
hot (phase 1)
1 2 3
4-16 kV + 0°
4-16 kV + 120°
4-16 kV + 240°
To 3-phase Industry
120V (1-phase)
240V (1-phase)
240V (3-phase)
208V (3-phase)
277V (3-phase)
480V (3-phase)
1-phase step-down transformer
Residential Lines
Hot (Phase A)
Hot (Phase B)
Neutral
AB
A
B
Ground at pole transformer
Phase A to Neutral
120 V + 0°
Phase B to Neutral
120 V + 180°
Phase A to Phase B
240 V + 0°
The ground return path varies in resistance, depending on the amount of insulation between yourself and earth. If the ground surface or soil material is wet the resistance decreases and the shock hazard increases.
A Phase (Black)
B Phase (Black)
Double-pole 240V breakers
Neutral (White)
240VAC Load
240 VAC
Ungrounded Lamp
Shock Hazard
Hot (A)
Hot (B)
Ground
Neutral Bar
Single-pole 120V breakers
Ground Bar
Short !
Steel Frame
Ground Return
Ground Rod
Earth
Ground
Grounded 120 VAC Lamp
Ground
Hot
Neutral
120 VAC, 60Hz
Neutral-ground jumper used in main panel only, not in subpanels.
Split DC Power Supply
+12V
0V
-12V
Neutral
Ground
Hot
18 VAC, 60Hz
F1
2A (slow)
Hot
GND
Neut
120 VAC
18 VAC
18 VAC
T1
18 VAC
CT
(18-0-18)
1N4003
1N4003
C1
2200µF
35V
C2
2200µF
35V
1N4003
1N4003
C3
0.1-1µF
50V
C4
0.1-1µF
50V
7812
VIN +VOUT
GND
GND
VIN -VOUT
7912
C5
220µF
35V
C6
220µF
35V
C7
0.1-1µF
50V
C8
0.1-1µF
50V
+12 V
12 V
GND
24 V
12 V
-12 V
120 VAC, 60Hz
Hot-Neutral
120 VAC, 60Hz
Hot-Ground
Grounded Chassis

FIGURE 2.90

panel, a new ground rod typically is used to ground the subpanel. Note that different regions within the United States may use different wiring protocols. Therefore, do not assume that what I am telling you is standard practice where you live. Contact your local electrical inspector.

Within the main service panel, there are typically two bus bars into which circuit breaker modules are inserted. One of these bus bars is connected to the A-phase wire; the other bus bar is connected to the B-phase wire. To power a group of 120-V loads (e.g., upstairs lights and 120-V outlets), you throw the main breaker to the off position and then insert a single-pole breaker into one of the bus bars. (You can choose either the A-phase bus bar or the B-phase bus bar. The choice of which bus bar you use becomes important only when it comes to balancing the overall load—more on that in a moment.) Next, you take a 120-V three-wire cable and connect the cable's black (hot) wire to the breaker, connect the cable's white (neutral) wire to the neutral bar, and connect the cable's ground wire (green or bare) to the ground bar. You then run the cable to where the 120-V loads are located, connect the hot and neutral wires across the load, and fasten the ground wire to the case of the load (typically a ground screw is supplied on an outlet mounting or light figure for this purpose). To power other 120-V loads that use their own breakers, you basically do the same thing you did in the last setup. However, to maximize the capacity of the main panel (or subpanel) to supply as much current as possible without overloading the main circuit breaker in the process, it is important to balance the number of loads connected to the A-phase breakers with the number of loads connected to the B-phase breakers. This is referred to as "balancing the load."

Now, if you want to supply power to 240-V appliances (ovens, washers, etc.), you insert a double-pole breaker between the A-phase and B-phase bus bars in the main (or subpanel). Next, you take a 240-V three-wire cable and attach one of its hot wires to the A-phase terminal of the breaker and attach its other hot wire to the B-phase terminal of the breaker. The ground wire (green or bare) is connected to the ground bar. You then run the cable to where the 240-V loads are located and attach the wires to the corresponding terminals of the load (typically within a 240-V outlet). Also, 120-V/240-V appliances are wired in a similar manner, except you use a four-wire cable that contains an additional neutral (white) wire that is joined at the neutral bar within the main panel (or subpanel).

As a note of caution, do not attempt home wiring unless you are sure of your abilities. If you feel that you are capable, just make sure to flip the main breaker off before you start work within the main service panel. When working on light fixtures, switches, and outlets that are connected to an individual breaker, tag the breaker with tape so that you do not mistakenly flip the wrong breaker when you go back to test your connections.

2.23 Capacitors

If you take two oppositely charged parallel conducting plates separated a small distance apart by an insulator—such as air or a dielectric such as ceramic—you have created what's called a capacitor. Now, if you apply a voltage across the plates of the capacitor using a battery, as shown in Fig. 2.91, an interesting thing occurs. Electrons are pumped out the negative battery terminal and collect on the lower plate, while

CHAPTER 3

Basic Electronic Circuit Components

3.1 Wires, Cables, and Connectors

Wires and cables provide low-resistance pathways for electric currents. Most electrical wires are made from copper or silver and typically are protected by an insulating coating of plastic, rubber, or lacquer. Cables consist of a number of individually insulated wires bound together to form a multiconductor transmission line. Connectors, such as plugs, jacks, and adapters, are used as mating fasteners to join wires and cable with other electrical devices.

3.1.1 Wires

A wire's diameter is expressed in terms of a *gauge number.* The gauge system, as it turns out, goes against common sense. In the gauge system, as a wire's diameter increases, the gauge number decreases. At the same time, the resistance of the wire decreases. When currents are expected to be large, smaller-gauge wires (large-diameter wires) should be used. If too much current is sent through a large-gauge wire (small-diameter wire), the wire could become hot enough to melt. Table 3.1 shows various characteristics for B&S-gauged insulated copper wire at 20°C. For rubber-insulated wire, the allowable current should be reduced by 30 percent.

Wire comes in solid core, stranded, or braided forms.

Solid Core

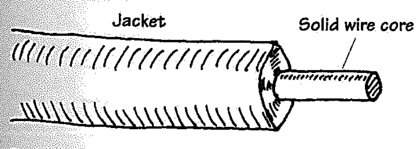
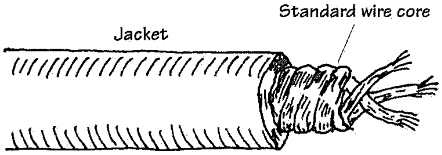


FIGURE 3.1

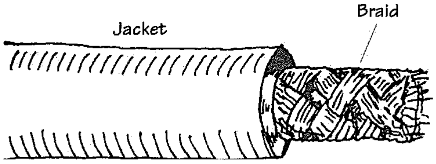
This wire is useful for wiring breadboards; the solid-core ends slip easily into breadboard sockets and will not fray in the process. These wires have the tendency to snap after a number of flexes.

Stranded Wire



The main conductor is comprised of a number of individual strands of copper. Stranded wire tends to be a better conductor than solid-core wire because the individual wires together comprise a greater surface area. Stranded wire will not break easily when flexed.

Braided Wire



A braided wire is made up of a number of individual strands of wire braided together. Like stranded wires, these wires are better conductors than solid-core wires, and they will not break easily when flexed. Braided wires are frequently used as an electromagnetic shield in noise-reduction cables and also may act as a wire conductor within the cable (e.g., coaxial cable).

FIGURE 3.1 (*Continued*)

TABLE 3.1 Copper Wire Specifications (Bare and Enamel-Coated Wire)

WIRE SIZE (AWG)	DIAMETER (MILS)*	AREA† (CIRCULAR MIL)	FEET PER POUND (BARE)	OHMS PER 1000 FT	CURRENT-CARRYING CAPACITY (A)	NEAREST BRITISH SWG NO.
1	289.3	83,694	3.948	0.1239	119.564	1
2	257.6	66,357	4.978	0.1563	94.797	2
3	229.4	52,624	6.277	0.1971	75.178	4
4	204.3	41,738	7.918	0.2485	59.626	5
5	181.9	33,087	9.98	0.3134	47.268	6
6	162.0	26,244	12.59	0.3952	37.491	7
7	144.3	20,822	15.87	0.4981	29.746	8
8	128.5	16,512	20.01	0.6281	23.589	9
9	114.4	13,087	25.54	0.7925	18.696	11
10	101.9	8226	31.82	0.9987	14.834	12
11	90.7	8226	40.16	1.2610	11.752	13
12	80.8	6528	50.61	1.5880	9.327	13
13	72.0	5184	63.73	2.0010	7.406	15
14	64.1	4108	80.39	2.5240	5.870	15
15	57.1	3260	101.32	3.1810	4.658	16
16	50.8	2580	128	4.0180	3.687	17
17	45.3	2052	161	5.0540	2.932	18
18	40.3	1624	203.5	6.3860	2.320	19
19	35.9	1288	256.4	8.0460	1.841	20
20	32.0	1024	322.7	10.1280	1.463	21
21	28.5	812	406.7	12.770	1.160	22
22	25.3	640	516.3	16.2000	0.914	22
23	22.6	510	646.8	20.300	0.730	24
24	20.1	404	817.7	25.6700	0.577	24
25	17.9	320	1031	32.3700	0.458	26
26	15.9	252	1307	41.0200	0.361	27
27	14.2	201	1639	51.4400	0.288	28

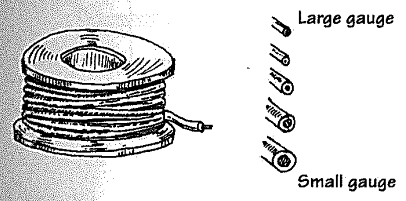
TABLE 3.1 Copper Wire Specifications (Bare and Enamel-Coated Wire) (*Continued*)

WIRE SIZE (AWG)	DIAMETER (MILS)*	AREA† (CIRCULAR MIL)	FEET PER POUND (BARE)	OHMS PER 1000 FT	CURRENT-CARRYING CAPACITY (A)	NEAREST BRITISH SWG NO.
28	12.6	158	2081	65.3100	0.227	29
29	11.3	127	2587	81.2100	0.182	31
30	10.0	100	3306	103.7100	0.143	33
31	8.9	79	4170	130.9000	0.113	34
32	8.0	64	5163	162.0000	0.091	35
33	7.1	50	6553	205.7000	0.072	36
34	6.3	39	8326	261.3000	0.057	37
35	5.6	31	10,537	330.7000	0.045	38
36	5.0	25	13,212	414.8000	0.036	39
37	4.5	20	16,319	512.1000	0.029	40

* 1 Mil = 2.54×10^{-5} m
† 1 Circular Mil = 5.067×10^{-10} m^2

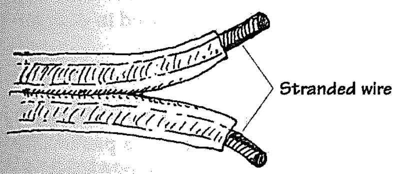
Kinds of Wires

Pretinned Solid Bus Wire



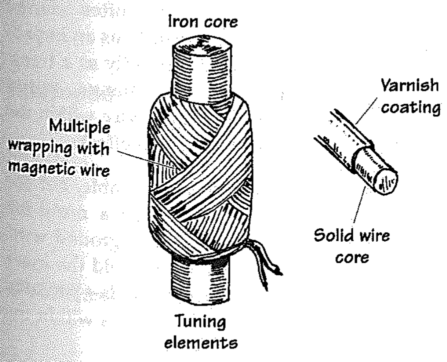
This wire is often referred to as *hookup wire.* It includes a tin-lead alloy to enhance solderability and is usually insulated with polyvinyl chloride (PVC), polyethylene, or Teflon. Used for hobby projects, preparing printed circuit boards, and other applications where small bare-ended wires are needed.

Speaker Wire



This wire is stranded to increase surface area for current flow. It has a high copper content for better conduction.

Magnetic Wire



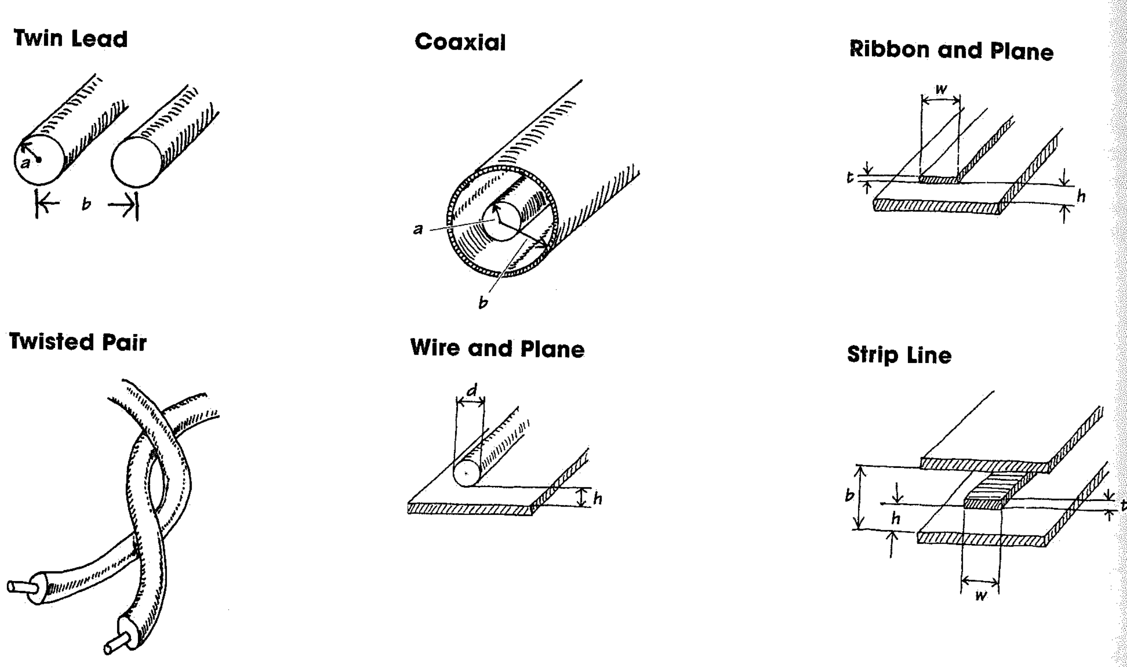
This wire is used for building coils and electromagnets or anything that requires a large number of loops, say, a tuning element in a radio receiver. It is built of solid-core wire and insulated by a varnish coating. Typical wire sizes run from 22 to 30 gauge.

FIGURE 3.2

3.1.2 Cables

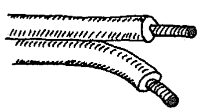
A cable consists of a multiple number of independent conductive wires. The wires within cables may be solid core, stranded, braided, or some combination in between. Typical wire configurations within cables include the following:

FIGURE 3.3



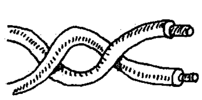
Kinds of Cables

Paired Cable



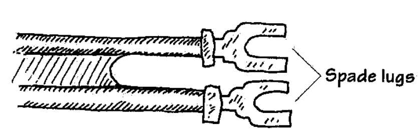
This cable is made from two individually insulated conductors. Often it is used in dc or low-frequency ac applications.

Twisted Pair



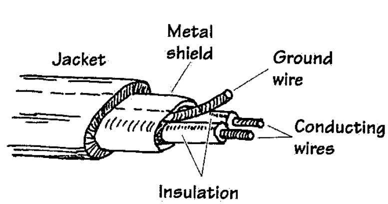
This cable is composed of two interwound insulated wires. It is similar to a paired cable, but the wires are held together by a twist.

Twin Lead



This cable is a flat two-wire line, often referred to as 300-Ω line. The line maintains an impedance of 300 Ω. It is used primarily as a transmission line between an antenna and a receiver (e.g., TV, radio). Each wire within the cable is stranded to reduce skin effects.

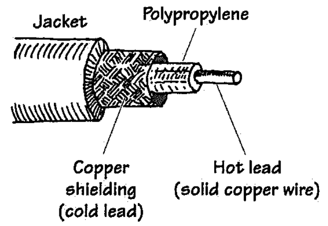
Shielded Twin Lead



This cable is similar to paired cable, but the inner wires are surrounded by a metal-foil wrapping that's connected to a ground wire. The metal foil is designed to shield the inner wires from external magnetic fields—potential forces that can create noisy signals within the inner wires.

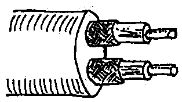
FIGURE 3.4

Unbalanced Coaxial



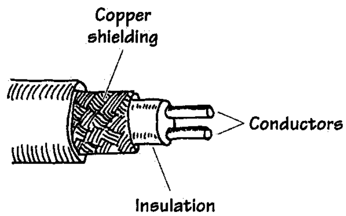
This cable typically is used to transport high-frequency signals (e.g., radio frequencies). The cable's geometry limits inductive and capacitive effects and also limits external magnetic interference. The center wire is made of solid-core copper wire and acts as the hot lead. An insulative material, such as polyethylene, surrounds the center wire and acts to separate the center wire from a surrounding braided wire. The braided wire, or copper shielding, acts as the cold lead or ground lead. Coaxial cables are perhaps the most reliable and popular cables for transmitting information. Characteristic impedances range from about 50 to 100 Ω.

Dual Coaxial



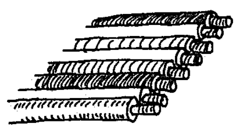
This cable consists of two unbalanced coaxial cables in one. It is used when two signals must be transferred independently.

Balanced Coaxial



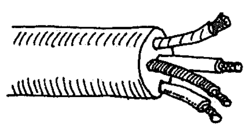
This cable consists of two solid wires insulated from one another by a plastic insulator. Like unbalanced coaxial cable, it too has a copper shielding to prevent noise pickup. Unlike unbalanced coaxial cable, the shielding does not act as one of the conductive paths; it only acts as a shield against external magnetic interference.

Ribbon



This type of cable is used in applications where many wires are needed. It tends to flex easily. It is designed to handle low-level voltages and often is found in digital systems, such as computers, to transmit parallel bits of information from one digital device to another.

Multiple Conductor



This type of cable consists of a number of individually wrapped, color-coded wires. It is used when a number of signals must be sent through one cable.

Fiberoptic

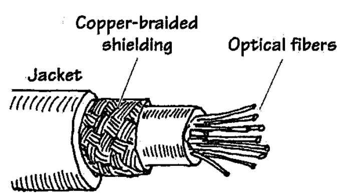


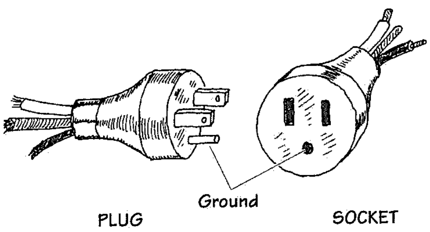
FIGURE 3.4 *(Continued)*

Fiberoptic cable is used in the transport of electromagnetic signals, such as light. The conducting-core medium is made from a glass material surrounded by a fiberoptic cladding (a glass material with a higher index of refraction than the core). An electromagnetic signal propagates down the cable by multiple total internal reflections. It is used in direct transmission of images and illumination and as waveguides for modulated signals used in telecommunications. One cable typically consists of a number of individual fibers.

3.1.3 Connectors

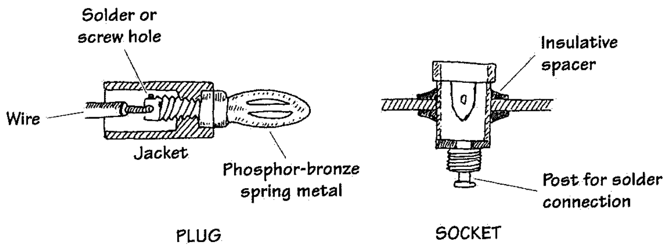
The following is a list of common plug and jack combinations used to fasten wires and cables to electrical devices. Connectors consist of plugs (male-ended) and jacks (female-ended). To join dissimilar connectors together, an adapter can be used.

117-Volt



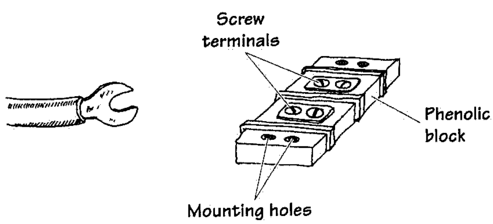
This is a typical home appliance connector. It comes in unpolarized and polarized forms. Both forms may come with or without a ground wire.

Banana



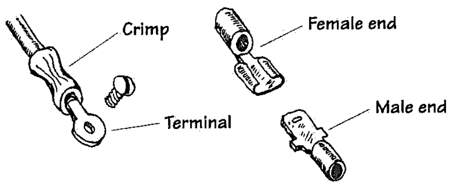
This is used for connecting single wires to electrical equipment. It is frequently used with testing equipment. The plug is made from a four-leafed spring tip that snaps into the jack.

Spade Lug/Barrier Strip



This is a simple connector that uses a screw to fasten a metal spade to a terminal. A barrier strip often acts as the receiver of the spade lugs.

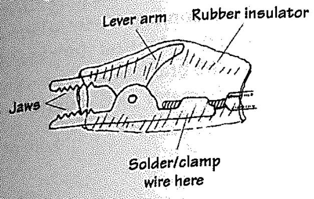
Crimp



Crimp connectors are color-coded according to the wire size they can accommodate. They are useful as quick, friction-type connections in dc applications where connections are broken repeatedly. A crimping tool is used to fasten the wire to the connector.

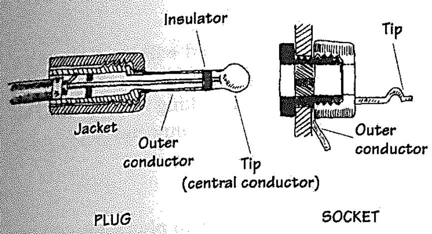
FIGURE 3.5

Alligator



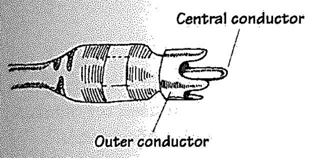
Alligator connectors are used primarily as temporary test leads.

Phone



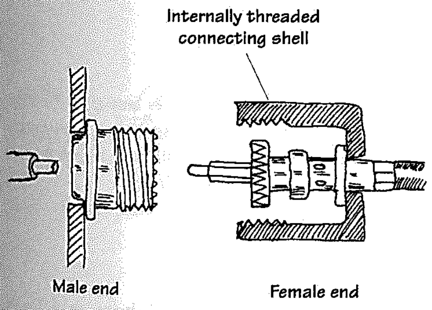
These connectors accept shielded braid, but they are larger in size. They come in two- or three-element types and have a barrel that is 1¼ in (31.8 mm) long. They are used as connectors in microphone cables and for other low-voltage, low-current applications.

Phono



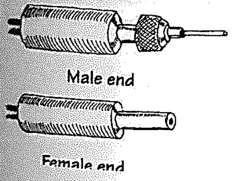
Phono connectors are often referred to as RCA plugs or pin plugs. They are used primarily in audio connections.

F-Type



F-type connectors are used with a variety of unbalanced coaxial cables. They are commonly used to interconnect video components. F-type connectors are either threaded or friction-fit together.

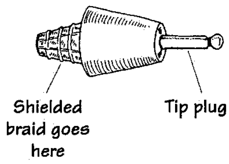
Tip



Here, the plug consists of a solid metallic tip that slides into the jack section. The two are held together by friction. Wires are either soldered or screwed into place under the plastic collar.

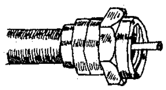
FIGURE 3.5 (*Continued*)

Mini



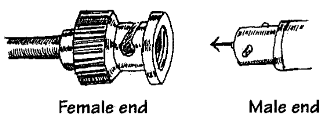
These connectors are used to join wires with shielded braid cables. The tip of the plug makes contact with the center conductor wire, whereas the cylindrical metal extension (or barrel) makes contact with the braid. Such connectors are identified by diameter and number of threads per inch.

PL-259



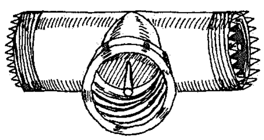
These are often referred to as UHF plugs. They are used with RG-59/U coaxial cable. Such connectors may be threaded or friction-fit together.

BNC



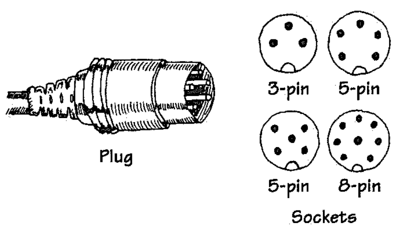
BNC connectors are used with coaxial cables. Unlike the F-type plug, BNC connectors use a twist-on bayonet-like locking mechanism. This feature allows for quick connections

T-Connector



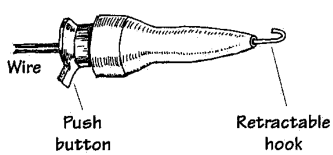
T-connectors consist of two plug ends and one central jack end. They are used when a connection must be made somewhere along a coaxial cable.

DIN Connector



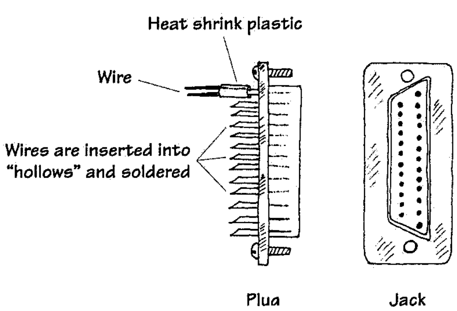
These connectors are used with multiple conductor wires. They are often used for interconnecting audio and computer accessories.

Meat Hook



These connectors are used as test probes. The spring-loaded hook opens and closes with the push of a button. The hook can be clamped onto wires and component leads.

D-Connector



D-connectors are used with ribbon cable. Each connector may have as many as 50 contacts. The connection of each individual wire to each individual plug pin or jack socket is made by sliding the wire in a hollow metal collar at the backside of each connector. The wire is then soldered into place.

FIGURE 3.5 (*Continued*)

3.1.4 Wiring and Connector Symbols

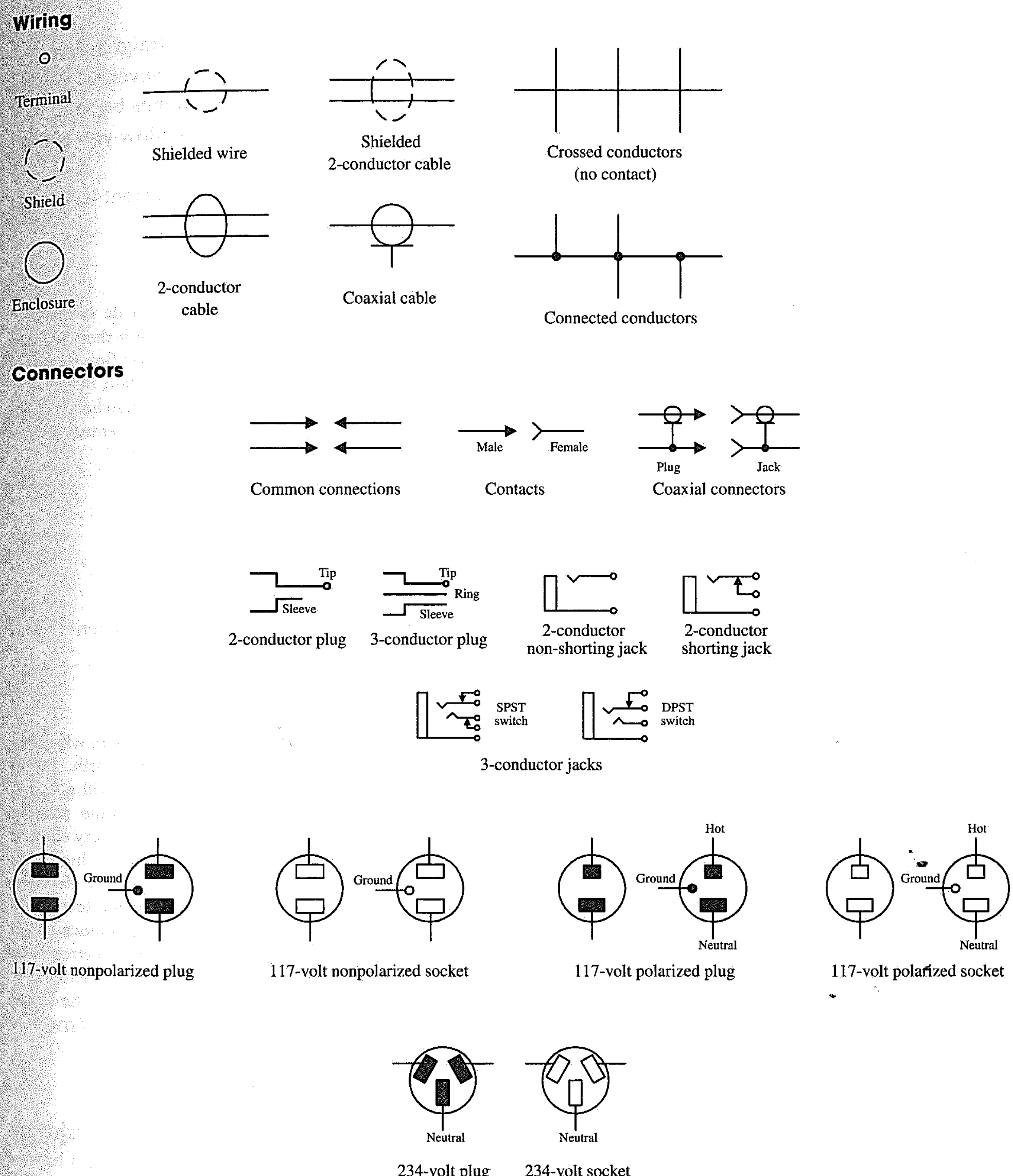


FIGURE 3.6

3.1.5 High-Frequency Effects Within Wires and Cables

Weird Behavior in Wires (Skin Effect)

When dealing with simple dc hobby projects, wires and cables are straightforward—they act as simple conductors with essentially zero resistance. However, when you replace dc currents with very high-frequency ac currents, weird things begin to take place within wires. As you will see, these "weird things" will not allow you to treat wires as perfect conductors.

First, let's take a look at what is going on in a wire when a dc current is flowing through it.

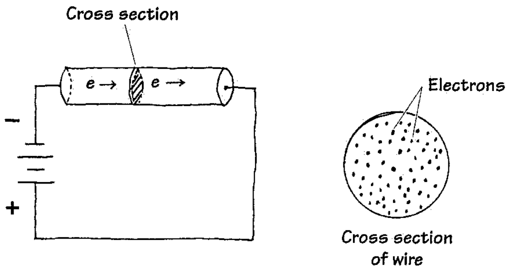


FIGURE 3.7

A wire that is connected to a dc source will cause electrons to flow through the wire in a manner similar to the way water flows through a pipe. This means that the path of any one electron essentially can be anywhere within the volume of the wire (e.g., center, middle radius, surface).

Now, let's take a look at what happens when a high-frequency ac current is sent through a wire.

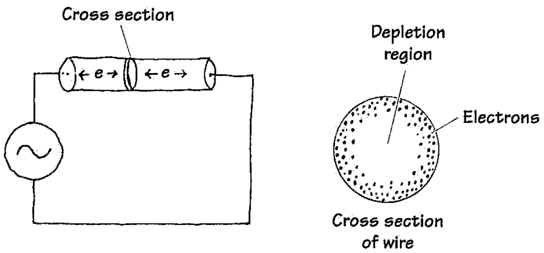


FIGURE 3.8

An ac voltage applied across a wire will cause electrons to vibrate back and forth. In the vibrating process, the electrons will generate magnetic fields. By applying some physical principles (finding the forces on every electron that result from summing up the individual magnetic forces produced by each electron), you find that electrons are pushed toward the surface of the wire. As the frequency of the applied signal increases, the electrons are pushed further away from the center and toward the surface. In the process, the center region of the wire becomes devoid of conducting electrons.

The movement of electrons toward the surface of a wire under high-frequency conditions is called the *skin effect.* At low frequencies, the skin effect does not have a large effect on the conductivity (or resistance) of the wire. However, as the frequency increases, the resistance of the wire may become an influential factor. Table 3.2 shows just how influential skin effect can be as the frequency of the signal increases (the table uses the ratio of ac resistance to dc resistance as a function of frequency).

One thing that can be done to reduce the resistance caused by skin effects is to use stranded wire—the combined surface area of all the individual wires within the conductor is greater than the surface area for a solid-core wire of the same diameter.

TABLE 3.2 AC/DC Resistance Ratio as a Function of Frequency

WIRE GAUGE	R_{AC}/R_{DC}			
	10^6 Hz	10^7 Hz	10^8 Hz	10^9 Hz
22	6.9	21.7	68.6	217
18	10.9	34.5	109	345
14	17.6	55.7	176	557
10	27.6	87.3	276	873

Weird Behavior in Cables (Lecture on Transmission Lines)

Like wires, cables also exhibit skin effects. In addition, cables exhibit inductive and capacitive effects that result from the existence of magnetic and electrical fields within the cable. A magnetic field produced by the current through one wire will induce a current in another. Likewise, if two wires within a cable have a net difference in charge between them, an electrical field will exist, thus giving rise to a capacitive effect.

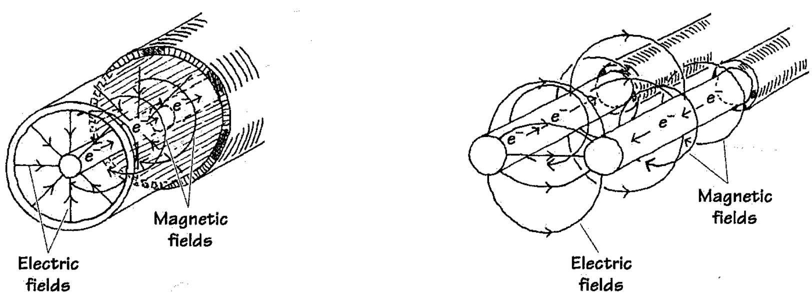


FIGURE 3.9 Illustration of the electrical and magnetic fields within a coaxial and paired cable.

Taking note of both inductive and capacitive effects, it is possible to treat a cable as if it were made from a number of small inductors and capacitors connected together. An equivalent inductor-capacitor network used to model a cable is shown in Fig. 3.10.

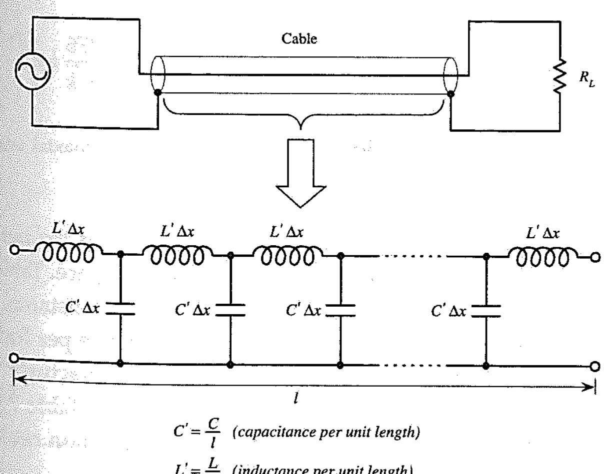


FIGURE 3.10

The impedance of a cable can be modeled by treating it as a network of inductors and capacitors.

To simplify this circuit, we apply a reduction trick; we treat the line as an infinite ladder and then assume that adding one "run" to the ladder (one inductor-capacitor section to the system) will not change the overall impedance Z of the cable. What this means—mathematically speaking—is we can set up an equation such that Z = Z + (*LC* section). This equation can then be solved for Z. After that, we find the limit as Δx goes to zero. The mathematical trick and the simplified circuit are shown below.

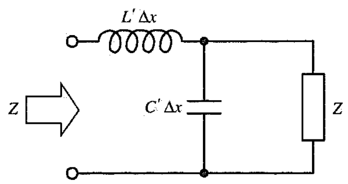


FIGURE 3.11

$$Z = j\omega L'\Delta x + \frac{Z/j\omega C'\Delta x}{Z + 1/j\omega C'\Delta x} = j\omega L'\Delta x + \frac{Z}{1 + j\omega C' Z \Delta x}$$

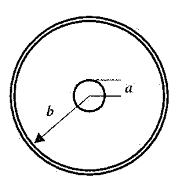
When $\Delta x \rightarrow$ small,

$$Z = \sqrt{L'/C'} = \sqrt{\frac{L/l}{C/l}} = \sqrt{L/C}$$

By convention, the impedance of a cable is called the *characteristic impedance* (symbolized Z_0). Notice that the characteristic impedance Z_0 is a real number. This means that the line behaves like a resistor despite the fact that we assumed the cable had only inductance and capacitance built in.

The question remains, however, what are *L* and *C*? Well, figuring out what *L* and *C* should be depends on the particular geometry of the wires within a cable and on the type of dielectrics used to insulate the wires. You could find *L* and *C* by applying some physics principles, but instead, let's cheat and look at the answers. The following are the expressions for *L* and *C* and Z_0 for both a coaxial and parallel-wire cable:

Coaxial



	L (H/m)	C (F/m)	$Z_0 = \sqrt{L/C}$ (Ω)
Coaxial	$\frac{\mu_0 \ln(b/a)}{2\pi}$	$\frac{2\pi\varepsilon_0 k}{\ln(b/a)}$	$\frac{138}{\sqrt{k}} \log \frac{b}{a}$
Parallel Wire	$\frac{\mu_0 \ln(D/a)}{\pi}$	$\frac{\pi\varepsilon_0 k}{\ln(D/a)}$	$\frac{276}{\sqrt{k}} \log \frac{D}{a}$

Parallel Wire

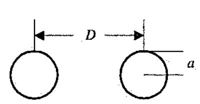


FIGURE 3.12 Inductance, capacitance, and characteristic impedance formulas for coaxial and parallel wires.

Here, *k* is the dielectric constant of the insulator, $\mu_0 = 1.256 \times 10^{-6}$ H/m is the permeability of free space, and $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m is the permitivity of free space. Table 3.3 provides some common dielectric materials with their corresponding constants.

Often, cable manufacturers supply capacitance per foot and inductance per foot values for their cables. In this case, you can simply plug the given manufacturer's values into $Z = \sqrt{L/C}$ to find the characteristic impedance of the cable. Table 3.4 shows capacitance per foot and inductance per foot values for some common cable types.

TABLE 3.3 Common Dielectrics and Their Constants

MATERIAL	DIELECTRIC CONSTANT (*k*)
Air	1.0
Bakelite	4.4–5.4
Cellulose acetate	3.3–3.9
Pyrex glass	4.8
Mica	5.4
Paper	3.0
Polyethylene	2.3
Polystyrene	5.1–5.9
Quartz	3.8
Teflon	2.1

TABLE 3.4 Capacitance and Inductance per Foot for Some Common Transmission-Line Types

CABLE TYPE	CAPACITANCE/FT (pF)	INDUCTANCE/FT (μH)
RG-8A/U	29.5	0.083
RG-11A/U	20.5	0.115
RG-59A/U	21.0	0.112
214-023	20.0	0.107
214-076	3.9	0.351

Sample Problems (Finding the Characteristic Impedance of a Cable)

EXAMPLE 1

An RG-11AU cable has a capacitance of 21.0 pF/ft and an inductance of 0.112 μH/ft. What is the characteristic impedance of the cable?

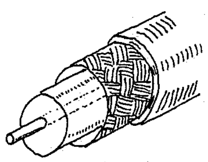


FIGURE 3.13

You are given the capacitance and inductance per unit length: $C' = C/\text{ft}$, $L' = L/\text{ft}$. Using $Z_0 = \sqrt{L/C}$ and substituting C and L into it, you get

$$Z_0 = \sqrt{L/C}$$

$$Z_0 = \sqrt{\frac{0.112 \times 10^{-6}}{21.0 \times 10^{-12}}} = 73\Omega$$

EXAMPLE 2

What is the characteristic impedance of the RG-58/U coaxial cable with polyethylene dielectric ($k = 2.3$) shown below?

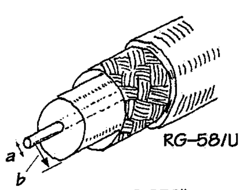


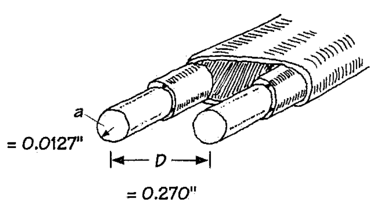
FIGURE 3.14

$$Z_0 = \frac{138}{\sqrt{k}} \log \frac{b}{a}$$

$$Z_0 = \frac{138}{\sqrt{2.3}} \log\left(\frac{0.116}{0.032}\right) = 91 \times 0.056 = 51\Omega$$

EXAMPLE 3

Find the characteristic impedance of the parallel-wire cable insulated with polyethylene ($k = 2.3$) shown below.



$$Z_0 = \frac{276}{\sqrt{k}} \log \frac{D}{a}$$

$$Z_0 = \frac{276}{\sqrt{2.3}} \log \frac{0.270}{0.0127} = 242\Omega$$

FIGURE 3.15

Impedance Matching

Since a transmission line has impedance built in, the natural question to ask is, How does the impedance affect signals that are relayed through a transmission line from one device to another? The answer to this question ultimately depends on the impedances of the devices to which the transmission line is attached. If the impedance of the transmission line is not the same as the impedance of, say, a load connected to it, the signals propagating through the line will only be partially absorbed by the load. The rest of the signal will be reflected back in the direction it came. Reflected signals are generally bad things in electronics. They represent an inefficient power transfer between two electrical devices. How do you get rid of the reflections? You apply a technique called *impedance matching*. The goal of impedance matching is to make the impedances of two devices—that are to be joined—equal. The impedance-matching techniques make use of special matching networks that are inserted between the devices.

Before looking at the specific methods used to match impedances, let's first take a look at an analogy that should shed some light on why unmatched impedances result in reflected signals and inefficient power transfers. In this analogy, pretend that the transmission line is a rope that has a density that is analogous to the transmission line's characteristic impedance Z_0. Pretend also that the load is a rope that has a density that is analogous to the load's impedance Z_L. The rest of the analogy is carried out below.

Unmatched Impedances ($Z_0 < Z_L$)

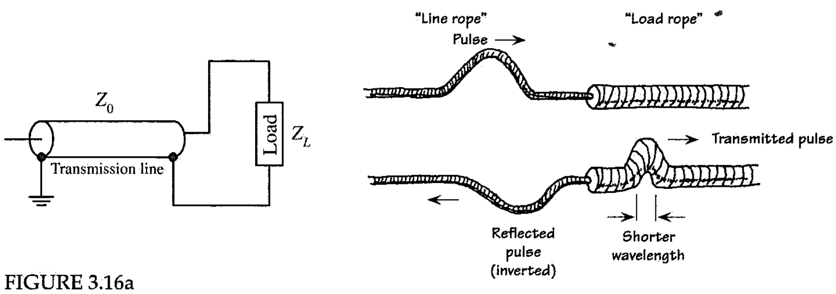


FIGURE 3.16a

A low-impedance transmission line that is connected to a high-impedance load is analogous to a low-density rope connected to a high-density rope. In the rope analogy, if you impart a pulse at the left end of the low-density rope (analogous to sending an electrical signal through a line to a load), the pulse will travel along without problems until it reaches the high-density rope (load). According to the laws of physics, when the wave reaches the high-density rope, it will do two things. First, it will induce a smaller-wavelength pulse within the high-density rope, and second, it will induce a similar-wavelength but inverted and diminished pulse that rebounds back toward the left end of the low-density rope. From the analogy, notice that only part of the signal energy from the low-density rope is transmitted to the high-density rope. From this analogy, you can infer that in the electrical case similar effects will occur—only now you are dealing with voltage and currents and transmission lines and loads.

Unmatched Impedances ($Z_0 > Z_L$)

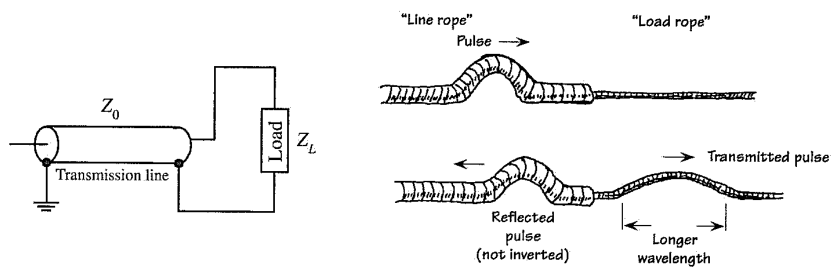


FIGURE 3.16b

A high-impedance transmission line that is connected to a low-impedance load is analogous to a high-density rope connected to a low-density rope. If you impart a pulse at the left end of the high-density rope (analogous to sending an electrical signal through a line to a load), the pulse will travel along the rope without problems until it reaches the low-density rope (load). At that time, the pulse will induce a longer-wavelength pulse within the low-density rope and will induce a similar-wavelength but inverted and diminished pulse that rebounds back toward the left end of the high-density rope. From this analogy, again you can see that only part of the signal energy from the high-density rope is transmitted to the low-density rope.

Matched Impedances ($Z_0 = Z_L$)

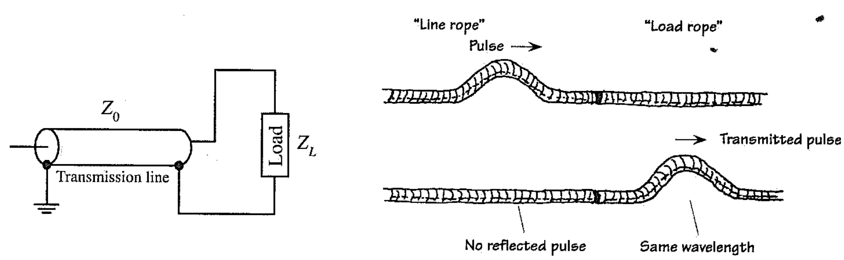


FIGURE 3.16c

Connecting a transmission line and load of equal impedances together is analogous to connecting two ropes of similar densities together. When you impart a pulse in the "transmission line" rope, the pulse will travel along without problems. However, unlike the first two analogies, when the pulse meets the load rope, it will continue on through the load rope. In the process, there will be no reflection, wavelength change, or amplitude change. From this analogy, you can infer that if the impedance of a transmission line matches the impedance of the load, power transfer will be smooth and efficient.

Standing Waves

Let's now consider what happens to an improperly matched line and load when the signal source is producing a continuous series of sine waves. You can, of course, expect reflections as before, but you also will notice that a superimposed standing-wave pattern is created within the line. The standing-wave pattern results from the interaction of forward-going and reflected signals. Figure 3.17 shows a typical resulting standing-wave pattern for an improperly matched transmission line attached between a sinusoidal transmitter and a load. The standing-wave pattern is graphed in terms amplitude (expressed in terms of V_{rms}) versus position along the transmission line.

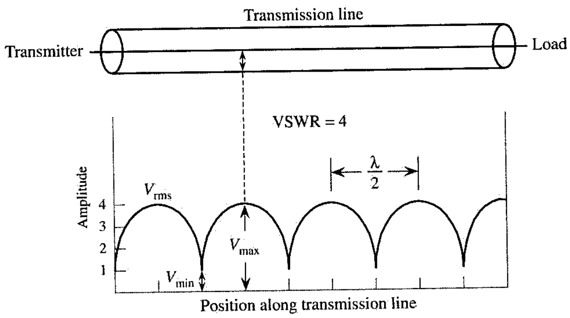


FIGURE 3.17 Standing waves on an improperly terminated transmission line. The VSWR is equal to V_{max}/V_{min}.

A term used to describe the standing-wave pattern is the *voltage standing-wave ratio* (VSWR). The VSWR is the ratio between the maximum and minimum rms voltages along a transmission line and is expressed as

$$\text{VSWR} = \frac{V_{rms,max}}{V_{rms,min}}$$

The standing-wave pattern shown in Fig. 3.17 has VSWR of 4/1, or 4.

Assuming that the standing waves are due entirely to a mismatch between load impedance and characteristic impedance of the line, the VSWR is simply given by either

$$\text{VSWR} = \frac{Z_0}{R_L} \quad \text{or} \quad \text{VSWR} = \frac{R_L}{Z_0}$$

whichever produces a result that is greater than 1.

A VSWR equal to 1 means that the line is properly terminated, and there will be no reflected waves. However, if the VSWR is large, this means that the line is not properly terminated (e.g., a line with little or no impedance attached to either a short or open circuit), and hence there will be major reflections.

The VSWR also can be expressed in terms of forward and reflected waves by the following formula:

$$\text{VSWR} = \frac{V_F + V_R}{V_F - V_R}$$

To make this expression meaningful, you can convert it into an expression in terms of forward and reflected power. In the conversion, you use $P = IV = V^2/R$. Taking P to be proportional to V^2, you can rewrite the VSWR in terms of forward and reflected power as follows:

$$\text{VSWR} = \frac{\sqrt{P_F} + \sqrt{P_R}}{\sqrt{P_F} - \sqrt{P_R}}$$

Rearranging this equation, you get the percentage of reflected power and percentage of absorbed power in terms of VSWR:

$$\%\ \text{reflected power} = \left[\frac{\text{VSWR} - 1}{\text{VSWR} + 1}\right]^2 \times 100\%$$

$$\%\ \text{absorbed power} = 100\% - \%\ \text{reflected power}$$

EXAMPLE (VSWR)

Find the standing-wave ratio (VSWR) of a 50-Ω line used to feed a 200-Ω load. Also find the percentage of power that is reflected at the load and the percentage of power absorbed by the load.

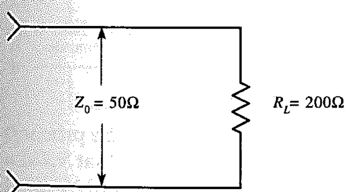


FIGURE 3.18

$$\text{VSWR} = \frac{Z_0}{R_L} = \frac{200}{50} = 4$$

VSWR is 4:1

$$\%\ \text{reflected power} = \frac{\text{VSWR} - 1^2}{\text{VSWR} + 1} \times 100\%$$

$$= \frac{4 - 1^2}{4 + 1} \times 100\% = 36\%$$

$$\%\ \text{absorbed power} = 100\% - \%\ \text{reflected power} = 64\%$$

Techniques for Matching Impedances

This section looks at a few impedance-matching techniques. As a rule of thumb, with most low-frequency applications where the signal's wavelength is much larger than the cable length, there is no need to match line impedances. Matching impedances is usually reserved for high-frequency applications. Moreover, most electrical equipment, such as oscilloscopes, video equipment, etc., has input and output impedances that match the characteristic impedances of coaxial cables (typically 50 Ω). Other devices, such as television antenna inputs, have characteristic input impedances that match the characteristic impedance of twin-lead cables (300 Ω). In such cases, the impedance matching is already taken care of.

IMPEDANCE-MATCHING NETWORK

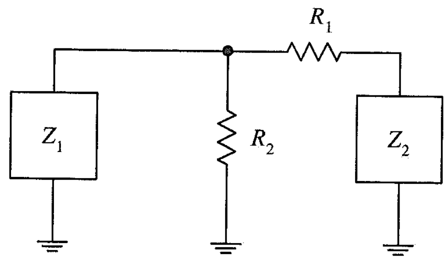


FIGURE 3.19

A general method used to match impedance makes use of the impedance-matching network shown here. To match impedances, choose

$$R_1 = \sqrt{Z_2(Z_2 - Z_1)}$$

$$R_2 = Z_1 \sqrt{Z_2/(Z_2 - Z_1)}$$

The attenuation seen from the Z_1 end will be $A_1 = R_1/Z_2 + 1$. The attenuation seen from the Z_2 end will be $A_2 = R_1/R_2 + R_1/Z_1 + 1$.

For example, if $Z_1 = 50$ W, and $Z_2 = 125$ W, then R_1, R_2, A_1, and A_2 are

$$R_1 = \sqrt{Z_2(Z_2 - Z_1)} = \sqrt{125(125 - 50)} = 97\Omega$$

$$R_2 = Z_1 \sqrt{\frac{Z_2}{Z_2 - Z_1}} = 50 \sqrt{\frac{125}{125 - 50}} = 65\Omega$$

$$A_1 = \frac{R_1}{Z_2} + 1 = \frac{96.8}{125} + 1 = 1.77$$

$$A_2 = \frac{R_1}{R_2} + \frac{R_1}{Z_1} + 1 = \frac{96.8}{64.6} + \frac{96.8}{50} + 1 = 4.43$$

IMPEDANCE TRANSFORMER

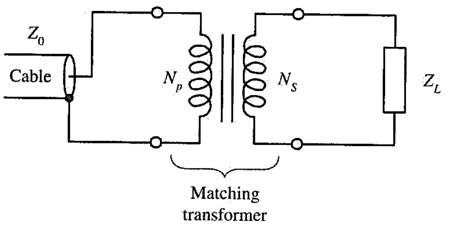


FIGURE 3.20

Here, a transformer is used to match the characteristic impedance of a cable with the impedance of a load. By using the formula

$$N_P/N_S = \sqrt{Z_0/Z_L}$$

you can match impedances by choosing appropriate values for N_P and N_S so that the ratio N_P/N_S is equal to $\sqrt{Z_0/Z_L}$.

For example, if you wish to match an 800-Ω impedance line with an 8-Ω load, you first calculate

$$\sqrt{Z_0/Z_L} = \sqrt{800/8} = 10$$

To match impedances, you select N_P (number of coils in the primary) and N_S (number of coils in the secondary) in such a way that $N_P/N_S = 10$. One way of doing this would be to set N_P equal to 10 and N_S equal to 1. You also could choose N_P equal to 20 and N_S equal to 2 and you would get the same result.

BROADBAND TRANSMISSION-LINE TRANSFORMER

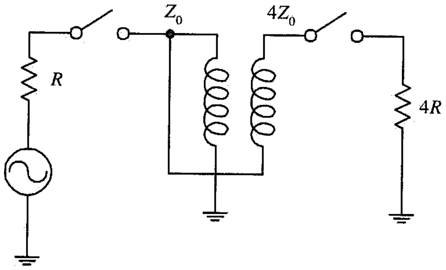


FIGURE 3.21

A broadband transmission-line transformer is a simple device that consists of a few turns of miniature coaxial cable or twisted-pair cable wound about a ferrite core. Unlike conventional transformers, this device can more readily handle high-frequency matching (its geometry eliminates capacitive and inductive resonance behavior). These devices can handle various impedance transformations and can do so with incredibly good broadband performance (less than 1 dB loss from 0.1 to 500 MHz).

QUARTER-WAVE SECTION

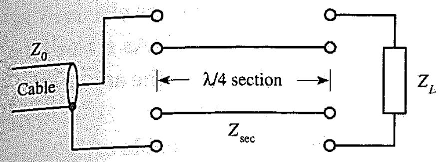


FIGURE 3.22

A transmission line with characteristic impedance Z_0 can be matched with a load with impedance Z_L by inserting a wire segment that has a length equal to one quarter of the transmitted signal's wavelength ($\lambda/4$) and which has an impedance equal to

$$Z_{sec} = \sqrt{Z_0 Z_L}$$

To calculate the segment's length, you must use the formula $\lambda = v/f$, where v is the velocity of propagation of a signal along the cable and f is the frequency of the signal. To find v, use

$$v = c/\sqrt{k}$$

where $c = 3.0 \times 10^8$ m/s, and k is the dielectric constant of the cable's insulation.

For example, say you wish to match a 50-Ω cable that has a dielectric constant of 1 with a 200-Ω load. If you assume the signal's frequency is 100 MHz, the wavelength then becomes

$$\lambda = \frac{v}{f} = \frac{c/\sqrt{k}}{f} = \frac{3 \times 10^8/1}{100 \times 10^6} = 3 \text{ m}$$

To find the segment length, you plug λ into $\lambda/4$. Hence the segment should be 0.75 m long. The wire segment also must have an impedance equal to

$$Z_{sec} = \sqrt{(50)(200)} = 100\ \Omega$$

STUBS

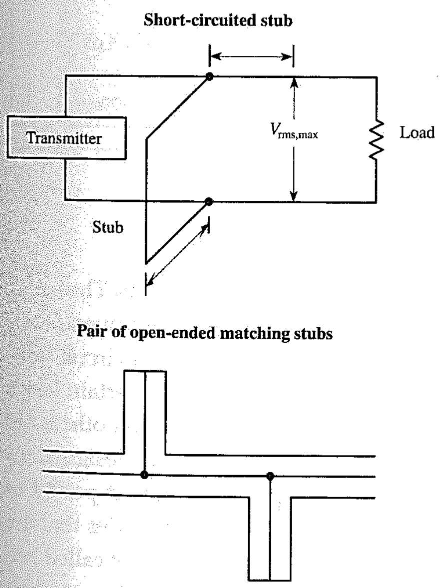


FIGURE 3.23

A short length of transmission line that is open ended or short-circuit terminated possesses the property of having an impedance that is reactive. By properly choosing a segment of open-circuit or short-circuit line and placing it in shunt with the original transmission line at an appropriate position along the line, standing waves can be eliminated. The short segment of wire is referred to as a *stub*. Stubs are made from the same type of cable found in the transmission line. Figuring out the length of a stub and where it should be placed is fairly tricky. In practice, graphs and a few formulas are required. A detailed handbook on electronics is the best place to learn more about using stubs.

3.2 Batteries

A battery is made up of a number of *cells*. Each cell contains a positive terminal, or *cathode*, and a negative terminal, or *anode*. (Note that most other devices treat *anodes* as positive terminals and *cathodes* as negative terminals.)

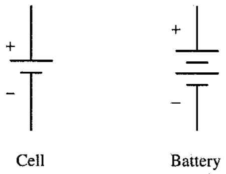


FIGURE 3.24

When a load is placed between a cell's terminals, a conductive bridge is formed that initiates chemical reactions within the cell. These reactions produce electrons in the anode material and remove electrons from the cathode material. As a result, a potential is created across the terminals of the cell, and electrons from the anode flow through the load (doing work in the process) and into the cathode.

A typical cell maintains about 1.5 V across its terminals and is capable of delivering a specific amount of current that depends on the size and chemical makeup of the cell. If more voltage or power is needed, a number of cells can be added together in either series or parallel configurations. By adding cells in series, a larger-voltage battery can be made, whereas adding cells in parallel results in a battery with a higher current-output capacity. Figure 3.25 shows a few cell arrangements.

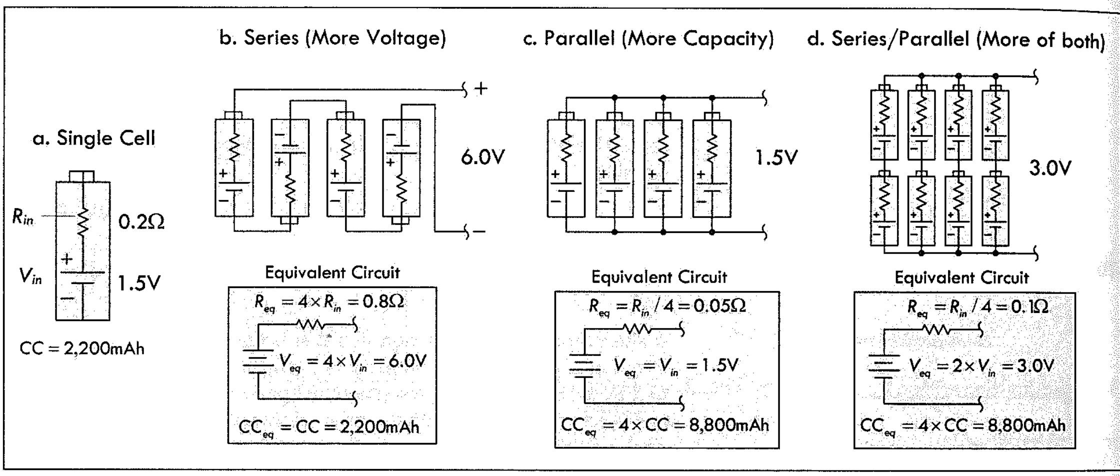


FIGURE 3.25

Battery cells are made from a number of different chemical ingredients. The use of a particular set of ingredients has practical consequences on the battery's overall performance. For example, some cells are designed to provide high open-circuit voltages, whereas others are designed to provide large current capacities. Certain kinds of cells are designed for light-current, intermittent applications, whereas others are designed for heavy-current, continuous-use applications. Some cells are designed for pulsing applications, where a large burst of current is needed for a short period of time. Some cells have good shelf lives; other have poor shelf lives. Batteries that are designed for one-time use, such as carbon-zinc and alkaline batteries, are called *primary batteries.* Batteries that can be recharged a number of times, such as nickel-cadmium and lead-acid batteries, are referred to as *secondary batteries.*

3.2.1 How a Cell Works

A cell converts chemical energy into electrical energy by going through what are called *oxidation-reduction reactions* (reactions that involve the exchange of electrons).

The three fundamental ingredients of a cell used to initiate these reactions include two chemically dissimilar metals (positive and negative electrodes) and an electrolyte (typically a liquid or pastelike material that contains freely floating ions). The following is a little lecture on how a simple lead-acid battery works.

For a lead-acid cell, one of the electrodes is made from pure lead (Pb); the other electrode is made from lead oxide (PbO_2); and the electrolyte is made from a sulfuric acid solution ($H_2O + H_2SO_4 \rightarrow 3H^+ + SO_4^{2-} + OH^-$).

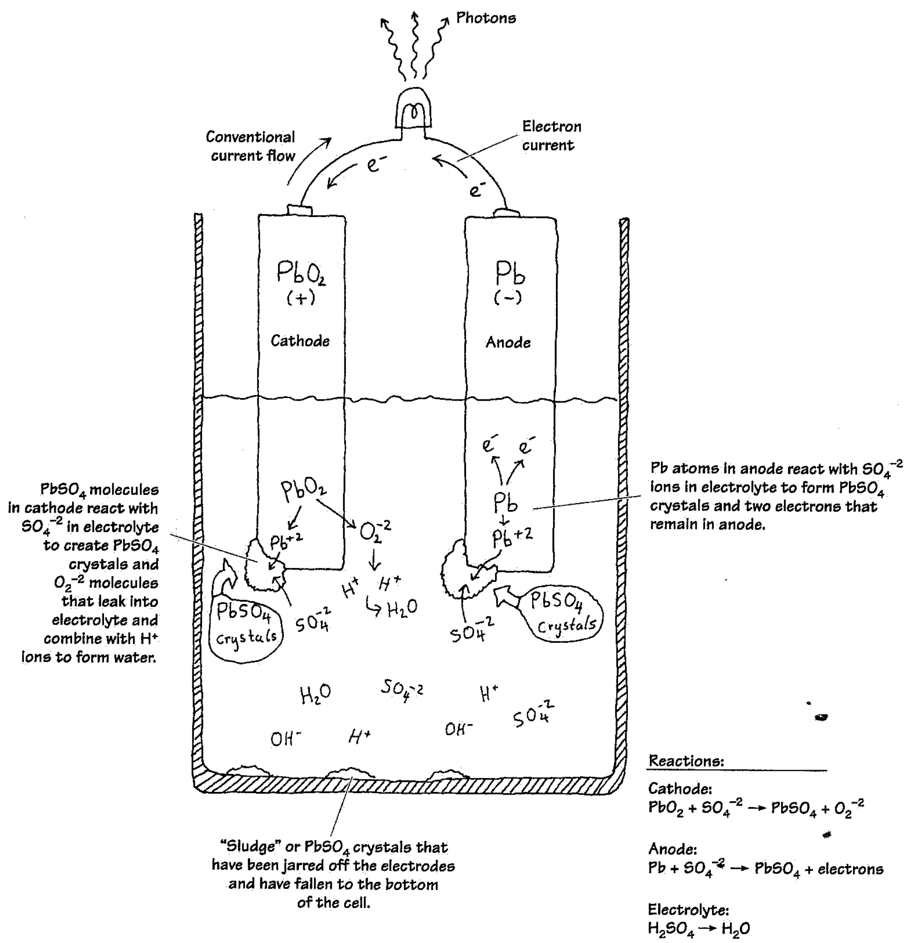


FIGURE 3.26

When the two chemically dissimilar electrodes are placed in the sulfuric acid solution, the electrodes react with the acid (SO_4^{-2}, H^+ ions), causing the pure lead electrode to slowly transform into $PbSO_4$ crystals. During this transformation reaction, two electrons are liberated within the lead electrode. Now, if you examine the lead oxide electrode, you also will see that it too is converted into $PbSO_4$ crystals. However, instead of releasing electrons during its transformation, it releases O_2^{2-} ions. These ions leak out into the electrolyte solution and combine with the hydrogen ions to form H_2O (water). By placing a load element, say, a lightbulb, across the electrodes, electrons will flow from the electron-abundant lead electrode, through the bulb's filament, and into the electron-deficient lead oxide electrode.

As time passes, the ingredients for the chemical reactions run out (the battery is drained). To get energy back into the cell, a reverse voltage can be applied across the cell's terminals, thus forcing the reactions backward. In theory, a lead-acid battery can be drained and recharged indefinitely. However, over time, chunks of crystals will break off from the electrodes and fall to the bottom of the container, where they are not recoverable. Other problems arise from loss of electrolyte due to gasing during electrolysis (a result of overcharging) and due to evaporation.

3.2.2 Primary Batteries

Primary batteries are one-shot deals—once they are drained, it is all over. Common primary batteries include carbon-zinc batteries, alkaline batteries, mercury batteries, silver oxide batteries, zinc-air batteries, and silver-zinc batteries. Here are some common battery packages:

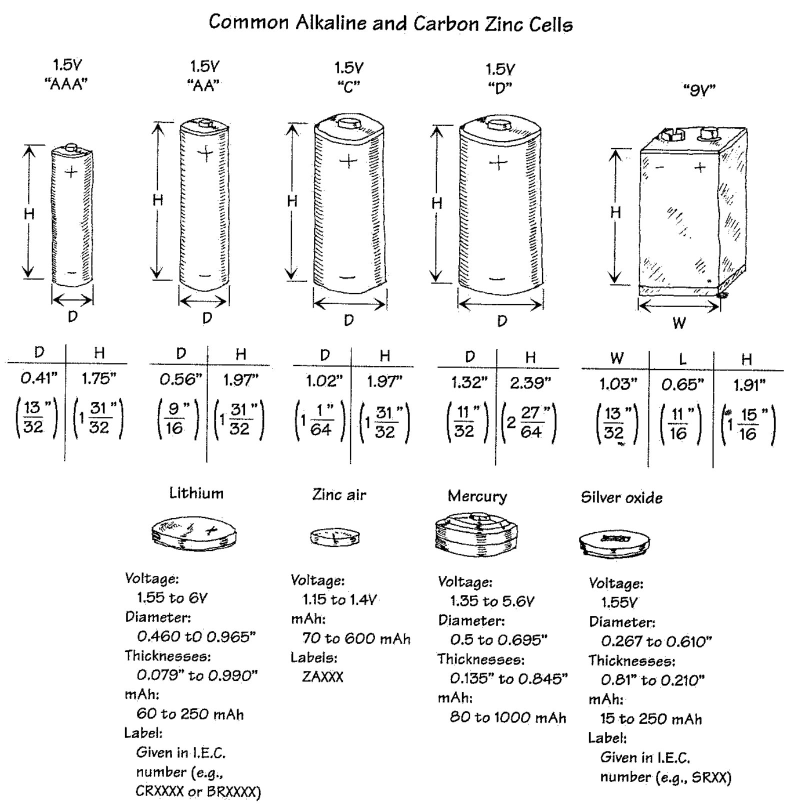


FIGURE 3.27

3.2.3 Comparing Primary Batteries

Carbon-Zinc Batteries

Carbon-zinc batteries ("standard-duty") are general-purpose primary-type batteries that were popular back in the 1970s, but have become obsolete with the advent of alkaline batteries. These batteries are not suitable for continuous use (only for intermittent use) and are susceptible to leakage. The nominal voltage of a carbon-zinc cell is about 1.5 V, but this value gradually drops during service. Shelf life also tends to be poor, especially at elevated temperatures. The only really positive aspect of these batteries is their low cost and wide size range. They are best suited to low-power applications with intermittent use, such as in radios, toys, and general-purpose low-cost devices. Don't use these cells in expensive equipment or leave them in equipment for long periods of time—there is a good chance they will leak. Standby applications and applications that require a wide temperature range should also be avoided. In all, these batteries are to be avoided, if you can even find them.

Zinc-Chloride Batteries

Zinc-chloride batteries ("heavy-duty") are a heavy-duty version of the carbon-zinc battery, designed to deliver more current and provide about 50 percent more capacity. Like the carbon-zinc battery, zinc-chloride batteries are essentially obsolete as compared to alkaline batteries. The terminal voltage of a zinc-chloride cell is initially about 1.5 V, but drops as chemicals are consumed. Unlike carbon-zinc batteries, zinc-chloride batteries perform better at low temperatures, and slightly better at higher temperatures, too. The shelf life is also longer. They tend to have lower internal resistance and higher capacities than carbon-zinc, allowing higher currents to be drawn for longer periods. These batteries are suited to moderate, intermittent use. However, an alkaline battery will provide better performance in similar applications.

Alkaline Batteries

Alkaline batteries are the most common type of household battery you can buy—they have practically replaced the carbon-zinc and zinc-chloride batteries. They are relatively powerful and inexpensive. The nominal voltage of an alkaline cell is again 1.5 V, but doesn't drop as much during discharge as the previous two battery types. The internal resistance is also considerably lower, and remains so until near the end of the battery's life cycle. They have very long shelf lives and better high- and low-temperature performance, too. General-purpose alkaline batteries don't work particularly well on high-drain devices like digital cameras, since the internal resistance limits output current flow. They will still work in your device, but the battery life will be greatly reduced. They are well suited to most general-purpose applications, such as toys, flashlights, portable audio equipment, flashes, digital cameras, and so on. Note that there is a rechargeable version of an alkaline battery, as well.

Lithium Batteries

Lithium batteries use a lithium anode, one of a number of different kinds of cathodes, and an organic electrolyte. They have a nominal voltage of 3.0 V—twice that of most other primary cells—that remains almost flat during the discharge cycle. They also have a very low self-discharge rate, giving them an excellent shelf life—as much as 10 years. The internal resistance is also quite low, and remains so during discharge. It performs well in both low and high temperatures, and advanced versions of this battery are used on satellites, on space vehicles, and in military applications. They are ideal for low-drain applications such as smoke detectors, data-retention devices, pacemakers, watches, and calculators.

Lithium-Iron Disulfide Batteries

Unlike other lithium cells that have chemistries geared to obtaining the greatest capacity in a given package, lithium-iron disulfide cells are a compromise. To match existing equipment and circuits, their chemistry has been tailored to the standard nominal 1.5-V output (whereas other lithium technologies produce double that). These cells are consequently sometimes termed *voltage-compatible lithium* batteries. Unlike other lithium technologies, lithium-iron disulfide cells are not rechargeable. Internally, the lithium-iron disulfide cell is a sandwich of a lithium anode, a separator, and an iron disulfide cathode with an aluminum cathode collector. The cells are sealed but vented. Compared to the alkaline cells—with which they are meant to compete—lithium-iron disulfide cells are lighter (weighing about 66 percent of same-size alkaline cells) and higher in capacity, and they have a much longer shelf life—even after 10 years on the shelf, lithium disulfide cells still retain most of their capacity. Lithium iron-disulfide cells operate best under heavier loads. In high-current applications, they can supply power for a duration exceeding 260 percent the time that a similar-sized alkaline cell can supply. This advantage diminishes at lower loads, however, and at very light loads may disappear or even reverse. For example, under a 20-mA load, a certain manufacturer rates its AA-size lithium-disulfide cells to provide power for about 122 hours while its alkaline cells will last for 135 hours. However, under a heavy load of 1 A, the lithium disulfide cell overshadows the alkaline counterpart by lasting 2.1 hours versus only 0.8 hours for the alkaline battery.

Mercury Cells

Zinc-mercuric oxide, or "mercury," cells take advantage of the high electrode potential of mercury to offer a very high energy density combined with a very flat discharge curve. Mercuric oxide forms the positive electrode, sometimes mixed with manganese dioxide. The nominal terminal voltage of a mercury cell is 1.35 V, and this remains almost constant over the life of the cell. They have an internal resistance that is fairly constant. Although made only in small button sizes, mercury cells are capable of reasonably high-pulsed discharge current and are thus suitable for applications such as quartz analog watches and hearing aids as well as voltage references in instruments, and the like.

Silver Oxide Batteries

The silver oxide battery is the predominate miniature battery found on the market today. Silver oxide cells are made only in small button sizes of modest capacity but have good pulsed discharge capability. They are typically used in watches, calculators, hearing aids, and electronic instruments. This battery's general characteristics include higher voltage than comparable mercury batteries, flatter discharge curve than alkaline batteries, good low-temperature performance, good resistance to shock and vibration, essentially constant internal resistance, excellent service maintenance, and long shelf life—exceeding 90 percent charge after storage for five years. The nominal terminal voltage of a silver oxide cell is slightly over 1.5 V and remains almost flat over the life of the cell. Batteries built from cells range from 1.5 V to 6.0 V and come in a variety of sizes. Silver oxide hearing aid batteries are designed to produce greater volumetric energy density at higher discharge rates than silver oxide watch or photographic batteries. Silver oxide photo batteries are designed to provide constant voltage or periodic high-drain pulses with or without a low drain background current. Silver oxide watch batteries, using a sodium hydroxide (NaOH) electrolyte system are designed primarily for low-drain continuous use over long periods of time—typically five years. Silver oxide watch batteries using potassium hydroxide (KOH) electrolyte systems are designed primarily for continuous low drains with periodic high-drain pulse demands, over a period of about two years.

Zinc Air Batteries

Zinc air cells offer very high energy density and a flat discharge curve, but have relatively short working lives. The negative electrode is formed of powdered zinc, mixed with the potassium hydroxide electrolyte to form a paste. This is retained inside a small metal can by a separator membrane that is porous to ions, and on the other side of the membrane is simply air to provide the oxygen (which acts as the positive electrode). The air/oxygen is inside an outer can of nickel-plated steel that also forms the cell's positive connection, lined with another membrane to distribute the oxygen over the largest area. Actually there is no oxygen or air in the zinc-oxygen cell when it's made. Instead, the outer can has a small entry hole with a covering seal, which is removed to admit air and activate the cell. The zinc is consumed as the cell supplies energy, which is typically for around 60 days. The nominal terminal voltage of a zinc-oxygen cell is 1.45 V, and the discharge curve is relatively flat. The internal resistance is only moderately low, and they are not suitable for heavy or pulsed discharging. They are found mainly in button and pill packages, and are commonly used in hearing aids and pagers. Miniature zinc air batteries are designed primarily to provide power to hearing aids. In most hearing aid applications, zinc air batteries can be directly substituted for silver oxide or mercuric oxide batteries and will typically give the longest hearing aid service of any common battery system. Notable characteristics include high capacity-to-volume ratio for a miniature battery, more stable voltage at high currents when compared to mercury or silver oxide batteries, and essentially constant internal resistance. They are activated by removing the covering (adhesive tab) from the air access hole, and they are most effective in applications that consume battery capacity in a few weeks.

TABLE 3.5 Primary Battery Comparison Chart

TYPE (CHEMISTRY)	COMMON NAME(S)	NOMINAL CELL VOLTS	INTERNAL RESISTANCE	MAXIMUM DISCHARGE RATE	COST	PROS AND CONS	TYPICAL APPLICATIONS
Carbon-zinc	Standard-duty	1.5	Medium	Medium	Low	Low cost, various sizes, but terminal voltage drops steadily during cell life	Radios, toys, and general-purpose electrical equipment
Zinc-chloride	Heavy-duty	1.5	Low	Medium to high	Low to medium	Low cost at higher discharge rates and at lower temperature; terminal voltage still drops	Motor-driven portable devices, clocks, remote controls
Alkaline zinc-manganese dioxide	Alkaline	1.5	Very low	High	Medium to high	Better for high continuous or pulsed loads and at low temperatures, but terminal voltage drops	Photoflash units, battery shavers, digital cameras, handheld transceivers, portable CD players, etc.
Lithium-manganese dioxide	Lithium	1.5	Low	Medium to high	High	High energy density, very low self-discharge rate (excellent shelf-life), good temperature tolerance	Watches, calculators, cameras (digital and film), DMMs, and other test instruments
Zinc-mercuric oxide	Mercury cell	1.35	Low	Low	High	High energy density (compact), very flat discharge curve, good at higher temperatures	Calculators, pagers, hearing aids, watches, test instruments
Zinc-silver oxide	Silver oxide cell	1.5	Low	Low	High	Very high energy density (very compact), very flat discharge curve, reasonable at lower temperatures	Calculators, pagers, hearing aids, watches, test instruments
Zinc-oxygen	Zinc-air cell	1.45	Medium	Low	Medium	High energy density, very lightweight, flat discharge curve, but must have access to air	Hearing aids and pagers

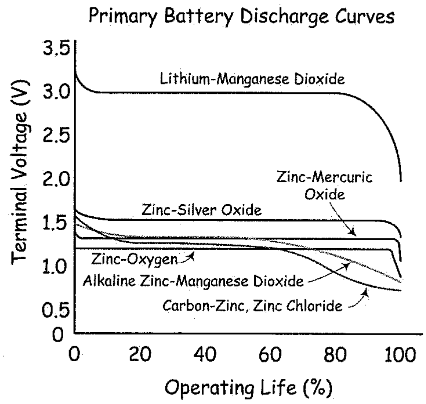


FIGURE 3.28

3.2.4 *Secondary Batteries*

Secondary batteries, unlike primary batteries, are rechargeable by nature. The actual discharge characteristics for secondary batteries are similar to those of primary batteries, but in terms of design, secondary batteries are made for long-term, high-power-level discharges, whereas primary batteries are designed for short discharges at low power levels. Most secondary batteries come in packages similar to those of primary batteries, with the exception of, say, lead-acid batteries and special-purpose batteries. Secondary batteries are used to power such devices as laptop computers, portable power tools, electric vehicles, emergency lighting systems, and engine starting systems.

Here are some common packages for secondary batteries:

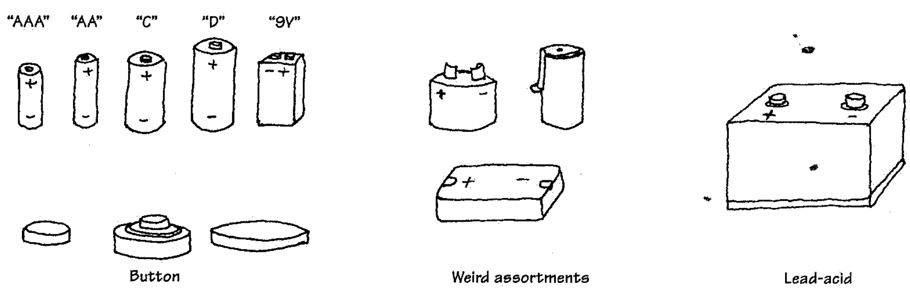


FIGURE 3.29

Comparing Secondary (Rechargeable) Batteries

LEAD-ACID BATTERIES

Lead-acid batteries are typically used for high-power applications, such as motorized vehicle power and battery backup applications. There are basically three types of lead-acid batteries: flooded lead-acid, valve-regulated lead-acid (VRLA), and sealed lead-acid (SLA). The flooded types must be stood upright and tend to lose electrolytes while producing gas over time. The SLA and VRLA are designed for a low overvoltage potential to prohibit the battery from reaching its gas-generating potential during discharge. However, SLA and VRLA can never be charged to their full potential. VRLA is generally used for stationary applications, while the SLA can be used in various positions. Lead-acid batteries typically come in 2-V, 4-V, 6-V, 8-V, and 12-V versions, with capacities ranging from 1 to several thousand amp-hours. The flooded lead-acid battery is used in automobiles, forklifts, wheelchairs, and UPS devices.

An SLA battery uses a gel-type electrolyte rather than a liquid to allow it to be used in any position. However, to prevent gas generation, it must be operated at a lower potential—meaning it's never fully charged. This means that it has a relatively poor energy density—the lowest for all sealed secondary batteries. However, they're the cheapest secondary, making them best suited for applications where low-cost, stationary power storage is the main concern. SLA batteries have the lowest self-discharge rate of any of the secondary batteries (about 5 percent per month). They do not suffer from memory effect (as displayed in NiCad batteries), and they perform well with shallow cycling; in fact, they tend to prefer it to deep cycling, although they perform well with intermittent heavy current demands, too. SLA batteries aren't designed for fast charging—typically 8 to 16 hours for full recharge. They must also always be stored in a charged state. Leaving them in a discharged state can lead to sulfation, a condition that makes the batteries difficult, if not impossible, to recharge. Also, SLA batteries have an environmentally unfriendly electrolyte.

The basic technique for recharging lead-acid batteries, be they flooded, sealed, or valve-regulated, is to read the technical directions that come with them. If you don't know what you're doing—say, trying to make your own battery recharger—you may run into a serious problem, such as blowing up batteries with too much pressure, melting them, or destroying the chemistry. (The procedure for charging lead-acid batteries is different from that for NiCad and NiMH batteries in that voltage limiting is used instead of current limiting.)

NICKEL-CADMIUM (NiCad) BATTERIES

Nickel-cadmium batteries are made using nickel hydroxide as the positive electrode and cadmium hydroxide as the negative electrode, with potassium hydroxide as the electrolyte. Nickel-cadmium batteries have been a very popular rechargeable battery over the years; however, with the introduction of NiMH batteries, they have seen a decline in use. In practical terms, NiCad batteries don't last very long before needing a recharge. They put out less voltage (per cell) than a standard alkaline (1.2 V versus 1.5 V for alkaline). This means that applications that require four or more alkaline batteries might not work at all with comparable-sized NiCad batteries. During discharge, the average voltage of a sealed NiCad cell is about 1.2 V per cell. At nominal discharge rates, the characteristic is very nearly flat until the cell approaches full discharge. The battery provides most of its energy above 1.0 V per cell. The self-discharge rate of a NiCad is not great, either—around two to three months. However, like SLAs, sealed NiCads can be used in virtually any position. NiCads have a higher energy density than SLAs (about twice as much), and with a relatively low cost, they are popular for powering compact portable equipment: cordless power tools, model boats and cars, and appliances such as flashlights and vacuum cleaners. NiCads suffer from memory effect and are therefore not really suitable for applications that involve shallow cycling or spending most of their time on a float charger. They perform best in situations where they're deeply cycled. They have a high number of charge/discharge cycles—around 1000.

Use a recommended charger—a constant current–type charger with due regard for heat dissipation and wattage rating. Improper charging can cause heat damage or even high-pressure rupture. Observe proper charging polarity. The safe charge rate for sealed NiCad cells for extended charge periods is 10 hours, or C/10 rate.

NICKEL METAL HYDRIDE (NiMH) BATTERIES

NiMH batteries are very popular secondary batteries, replacing NiCad batteries in many applications. NiMH batteries use a nickel/nickel hydroxide positive electrode, a hydrogen-storage alloy (such as lanthanum-nickel or zirconium-nickel) as a negative electrode, and potassium hydroxide as the electrolyte. They have a higher energy density than standard NiCad batteries (about 30 to 40 percent higher) and don't require special disposal requirements, either. They are about 20 percent more expensive than NiCad batteries. The nominal voltage of a NiMH battery is 1.2 V per cell, which must be taken into consideration when substituting them into devices that use standard 1.5-V cells such as alkaline cells. They self-discharge in about two to three months and do display some memory effect, but not as bad as NiCad batteries. They are not as happy with a deep discharge cycle as a NiCad battery, and they tend to have a shorter work life. Best results are achieved with load currents of 0.2-C to 0.5-C (one-fifth to one-half of the rated capacity). Typical applications include mobile and cordless phones, portable camcorders, and laptop computers. They are also popular in the power tool market.

Recharging NiMH batteries is a bit complex due to significant heat generation; the charge uses a special algorithm that requires trickle charging and temperature sensing. The batteries require regular full discharge to prevent crystalline formation.

Li-ION BATTERIES

Lithium is the lightest of all metals and has the highest electrochemical potential, giving it the possibility of an extremely high energy density. However, the metal itself is highly reactive. While this isn't a problem with primary cells, it poses an explosion risk with rechargeable batteries. For these to be made safe, lithium-ion technology had to be developed; the technology uses lithium ions from chemicals such as lithium-cobalt dioxide, instead of the metal itself. Typical Li-ion batteries have a negative electrode of aluminum coated with a lithium compound such as lithium-cobalt dioxide, lithium-nickel dioxide, or lithium-manganese dioxide. The positive electrode is generally of copper, coated with carbon (generally either graphite or coke), while the electrolyte is a lithium salt such as lithium-phosphorous hexafluoride, dissolved in an organic solvent such as a mixture of ethylene carbonate and dimethyl carbonate. Li-ion batteries have roughly twice the energy density of NiCads, making them the most compact rechargeable yet in terms of energy storage. Unlike NiCad or NiMH batteries, they are not subject to memory effect, and have a relatively low self-discharge rate—about 6 percent per month, less than half that of NiCads. They are also capable of moderately deep discharging, although not as deep as NiCads, as they have a higher internal resistance. On the other hand, Li-ion batteries cannot be charged as rapidly as NiCads, and they cannot be trickle or float charged, either. They also are significantly more costly than either NiCads or NiMH batteries, making them the most expensive rechargeables of all. Part of this is that they must be provided with built-in protection against both excessive discharging and overcharging (both of which pose a safety risk). Most Li-ion batteries are therefore supplied in self-contained battery packs, complete with "smart" protective circuitry. They are subject to aging, even if not used, and have moderate discharge currents. The main applications for Li-ion batteries are in places where as much energy as possible needs to be stored in the smallest possible space, and with as little weight as possible. They are found in laptop computers, PDAs, camcorders, and cell phones.

Li-ion batteries require special voltage-limiting recharging devices. Commercial Li-ion battery packs contain a protection circuit that prevents the cell voltage from going too high while charging. The typical safety threshold is set to 4.30 V/cell. In addition, temperature sensing disconnects the charging device if the internal temperature approaches 90°C (194°F). Most cells feature a mechanical pressure switch that permanently interrupts the current path if a safe pressure threshold is exceeded. The charge time of all Li-ion batteries, when charged at a 1-C initial current, is about three hours. The battery remains cool during charge. Full charge is attained after the voltage has reached the upper voltage threshold and the current has dropped and leveled off at about 3 percent of the nominal charge current. Increasing the charge current on a Li-ion charger does not shorten the charge time by much. Although the voltage peak is reached more quickly with higher current, the topping charge will take longer.

LITHIUM POLYMER (Li-POLYMER) BATTERIES

The lithium polymer batteries are a potentially lower-cost version of the Li-ion batteries. Their chemistry is similar to that of the Li-ion in terms of energy density, but uses a dry solid polymer electrolyte only. This electrolyte resembles a plastic-like film that does not conduct electricity but allows an exchange of ions (electrically charged atoms or groups of atoms). The dry polymer is more cost effective during fabrication, and the overall design is rugged, safe, and thin. With a cell thickness measuring as little as 1 mm, it is possible to use this battery in thin compact devices where space is an issue. It is possible to create designs which form part of a protective housing, are in the shape of a mat that can be rolled up, or are even embedded into a carrying case or piece of clothing. Such innovative batteries are still a few years away, especially for the commercial market.

Unfortunately, the dry Li-polymer suffers from poor ion conductivity, due to high internal resistance; it cannot deliver the current bursts needed for modern communication devices. However, it tends to increase in conductivity as the temperature rises, a characteristic suitable for hot climates. To make a small Li-polymer battery more conductive, some gelled electrolyte may be added. Most of the commercial Li-polymer batteries used today for mobile phones are hybrids and contain gelled electrolytes.

The charge process of a Li-polymer battery is similar to that of the Li-ion battery. The typical charge time is around three to five hours. Li-polymer batteries with gelled electrolyte, on the other hand, are almost identical to Li-ion batteries. In fact, the same charge algorithm can be applied.

NICKEL-ZINC (NiZn) BATTERIES

Nickel-zinc batteries are commonly used in light electric vehicles. They are considered the next generation of batteries used for high-drain applications, and are expected to replace sealed lead-acid batteries due to their higher energy densities (up to 70 percent lighter for the same power). They are also relatively cheap compared to NiCad batteries.

NiZn batteries are chemically very similar to NiCad batteries; both use an alkaline electrolyte and a nickel electrode, but they differ significantly in their voltage. The NiZn cell delivers more than 0.4 V of additional voltage both at open circuit and under load. With the additional 0.4 V per cell, multicell batteries can be constructed in smaller packages. For example, a 19.2-V pack can replace a 14.4-V NiCad pack, representing a 25 percent lower cell space and delivering higher power and a 45 percent lower impedance. They are also less expensive than most rechargeables. They are safe (abuse-tolerant). The cycle life is a bit better than for NiCad batteries for typical applications. They have superior shelf life when compared to lead-acid. Also, they are considered environmentally green—both nickel and zinc are nontoxic and easily recycled.

In terms of recharge times, it takes less than two hours to achieve full recharge; there is an 80 percent charge in one hour. This feature makes them useful in cordless power tools. Their high energy density and high discharge rate make them suitable for applications that demand large amounts of power in small, lightweight packages. They are found in cordless power tools, UPS systems, electric scooters, high-intensity dc lighting and the like.

NICKEL-IRON (NiFe) BATTERIES

Nickel-iron batteries, also called nickel alkaline or NiFe batteries, were introduced in 1900 by Thomas Edison. These are very robust batteries that are tolerant of abuse and can have very long life spans (30 years or more). The open-circuit voltage of these cells is 1.4 V, and the discharge voltage is about 1.2 V. They withstand overcharge and over-discharge. They accept high depth of discharge (deep cycling) and can remain discharged for long periods without damage, unlike lead-acid batteries that need to be stored in a charged state. They are, however, very heavy and bulky. Also, the low reactivity of the active components limits high-discharge performance. The cells take a charge slowly, give it up slowly, and have a steep voltage dropoff with state of charge. Furthermore, they have a low energy density compared to other secondary batteries, and a high self-discharge rate. NiFe batteries are used in applications similar to those for lead-acid batteries, but oriented toward a necessity of longevity. (A typical lead-acid battery will last around five years, compared to around 30 to 80 years for a NiFe battery.)

TABLE 3.6 Rechargeable Battery Comparison Chart

TYPE (CHEMISTRY)	NOMINAL CELL VOLTS (APPROX.)	ENERGY DENSITY (Wh/Kg)	CYCLE LIFE	CHARGE TIME	MAX. DISCHARGE RATE	COST	PROS AND CONS	TYPICAL APPLICATIONS
Sealed lead-acid	2.0	Low (30)	Long (shallow cycles)	8–16 h	Medium (0.2 C)	Low	Low cost, low self-discharge, happy float charging, but prefers shallow charging	Emergency lighting, GPSs, solar power systems, wheelchairs, etc.
RAM	1.1	High (75 initial)	Short to medium	2–6 h (pulsed)	Medium (0.3 C)	Low	Low cost, low self-discharge, prefer shallow cycling, no memory effect but short cycle life	Portable emergency lighting, toys, portable radios, CD players, test instruments, etc.
NiCad	1.2	Medium (40–60)	Long (deep cycles)	14–16 h (0.1 C) or <2 h with care (1 C)	High (>2 C)	Medium	Prefer deep cycling, good pulse capacity, but have memory effect, fairly high self-discharge rate, environmentally unfriendly	Portable tools and appliances, model cars and boats, data loggers, camcorders, portable transceivers, and test equipment
NiMH	1.2	High (60–80)	Medium	2–4 h	Medium (0.2–0.5 C)	Higher	Very compact energy source, but have some memory effect, high self-discharge rate	Cell phones and cordless phones, compact camcorders, laptop computers, PDAs, personal DVD and CD players, power tools
NiZn	1.65	High (>170)	Medium to high	1–2 h	—	Medium	Low cost, environmentally green, twice energy density of Ni-Cad	Exceptional performance, no memory, long shelf-life
NiFe	1.4	High (>200)	Extremely long	Long	—	Low	High cycle life, incredibly long life up to 80 years, environmentally friendly	Forklifts and other, similar SLA-like applications, but where longevity is important
Li-ion	3.6	Very high (>100)	Medium	3–4 h (1 C–0.03 C)	Med/high (<1 C)	Very high	Very compact, low maintenance, low self-discharge, but needs great care with charging	Compact cell phones and notebook PCs, digital cameras, and similar very small portable device

RECHARGEABLE ALKALINE-MANGANESE (RAM) BATTERIES

Rechargeable alkaline-manganese, or RAM, batteries are the rechargeable version of primary alkaline batteries. Like the primary technology, they use a manganese dioxide positive electrode and potassium hydroxide electrode, but the negative electrode is now a special porous zinc gel designed to absorb hydrogen during the charging process. The separator is also laminated to prevent it being pierced by zinc dendrites. These are often considered a poor substitute for a rechargeable, as compared to a NiCad or NiMH battery. RAM batteries have a tendency to plummet in capacity over few recharge cycles. It is feasible for a RAM battery to lose 50 percent of its capacity after only eight cycles. On the positive side, they are inexpensive and readily available, and they can be used as a direct replacement for non-rechargeable batteries, except in high-drain devices like digital cameras. They have a low self-discharge rate and can be stored on standby for up to 10 years. Also, they are environmentally friendly (no toxic metals are used) and maintenance-free; there is no need for cycling or worrying about memory effect. On the short side, they have limited current-handling capability and are limited to light-duty applications such as flashlights and other low-cost portable electronic devices that require shallow cycling. Recharging a RAM battery requires a special recharger; if you charge them in a standard charger, they may explode.

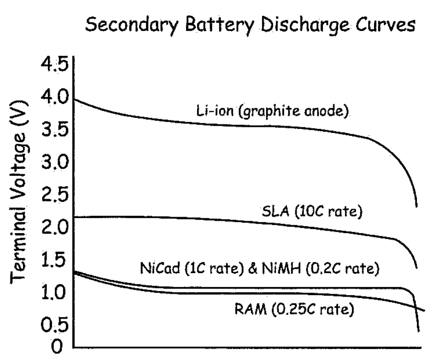


FIGURE 3.30

The Supercapacitor

The supercapacitor isn't really a battery but a cross between a capacitor and a battery. It resembles a regular capacitor, but uses special electrodes and some electrolytes. There are three kinds of electrode material found in a supercapacitor: high-surface-area-activated carbons, metal oxide, and conducting polymers. The one using high-surface-area-activated carbons is the most economical to manufacture. This system is also called double layer capacitor (DLC) because the energy is stored in the double layer formed near the carbon electrode surface. The electrolyte may be aqueous or organic. The aqueous electrolyte offers low internal resistance but limits the voltage to 1 V. In contrast, the organic electrolyte allows 2 and 3 V of charge, but the internal resistance is higher.

To make the supercapacitor practical for use in electronic circuits, higher voltages are needed. Connecting the cells in series accomplishes this task. If more than three or four capacitors are connected in series, voltage balancing must be used to prevent any cell from reaching overvoltage.

Supercapacitors are rated in units of 1 F and higher. They have higher energy storage capacity than electrolytic capacitors, but a lower capacity than a battery (approximately 1⁄10 that of a NiMH battery). Unlike electrochemical batteries that deliver a fairly steady voltage, the voltage of a supercapacitor drops from full voltage to zero volts without the customary flat voltage curve characteristic of most batteries. For this reason, supercapacitors are unable to deliver the full charge. The percentage of charge that is available depends on the voltage requirements of the applications. For example, a 6-V battery is allowed to discharge to 4.5 V before the equipment cuts off; the supercapacitor reaches that threshold with the first quarter of the discharge. The remaining energy slips into an unusable voltage range.

The self-discharge of the supercapacitor is substantially higher than that of the electrochemical battery. Typically, the voltage of the supercapacitor with an organic electrolyte drops from full charge to the 30 percent level in as little as 10 hours. Other supercapacitors can retain the charged energy longer. With these designs, the capacity drops from full charge to 85 percent in 10 days. In 30 days, the voltage drops to roughly 65 percent percent, and to 40 percent percent after 60 days.

The most common supercapacitor applications are memory backup and standby power. Only in special applications can the supercapacitor be used as a direct replacement for a chemical battery. Often the supercapacitor is used in tandem with a battery (placed across its terminals, with a provision in place to limit high influx of current when equipment is turned on) to improve the current handling of the battery: during low load current the battery charges the supercapacitor; the stored energy of the supercapacitor kicks in when a high load current is requested. In this way the supercapacitor acts to filter and smooth pulsed load currents. This enhances the battery's performance, prolongs the runtime, and even extends the longevity of the battery.

Limitations include an inability to use the full energy spectrum—depending on the application, not all energy is available. A supercapacitor has low energy density, typically holding 1⁄5 to 1⁄10 the energy of an electrochemical battery. Cells have low voltages—serial connections are needed to obtain higher voltages. Voltage balancing is required if more than three capacitors are connected in series. Furthermore, the self-discharge is considerably higher than that of an electrochemical battery.

Advantages include a virtually unlimited cycle life—supercapacitors are not subject to the wear and aging experienced by electrochemical batteries. Also, low impedance can enhance pulsed current demands on a battery when placed in parallel with the battery. Supercapacitors experience rapid charging—with low-impedance versions reaching full charge within seconds. The charge method is simple—the voltage-limiting circuit compensates for self-discharge.

Selecting the Right Battery (Comparison Chart)

- ● Yes, or common
- ● Yes, but not the best choice
- O Borderline
- No

	Carbon Zinc	Zinc Chloride	Alkaline	Lithium	Zinc-air	Silver Oxide	Mercury	RAM	Lead Acid (SLA)	NiCd	NiMH	Lithium Ion	Lithium Polymer	NiZn	Supercapacitor
Characteristics of single cell															
Obsolete (not recommended)	●	●						●							
Rechargeable								●	●	●	●	●	●	●	●
Stable voltage				●	●	●	●				●	●	●	●	
High energy density (Wh/kg)		O	●	●	●	●	●	●			O	●	●	●	
High capacity rating (mAh)														●	
High peak load-current rating	O	●	●	●				●	●	●	●	O	O	●	d
High pulsed discharge current		●	●	●		●	●		●	●		●	●	●	●
Low self-discharge rate			●	●				●	●	O		●	●	●	
Good at high temperatures		O	●	●			●								
Good at low temperatures		●	●	●		●									
High cycle life									●	●	●	●	●	●	●
Miniature				●	●	●	●							●	
Memory effect										●	O				
Expensive (cost)				●	●	●	●			●	●	●	●	O	
Environmentally unfriendly									●	●					
Applications															
Very small portable devices				●	●	●	●					●	●		
Pagers, hearing aids (h), watches (w)				●	h	w	●								
Radios, toys, general purpose	●	●	●					●							
Small motorized items		●	●					O			●				
Camcorders, digital cameras, test equipment			●							●	●				
Remotes, clocks, calculators		●	●	●				●							
Cellphones, mobile phones, laptops			O							O	●	●	●		
Low-self discharge (smoke detectors, data loggers)				●			●								
Power tools, model cars, electric toothbrush, etc.										●	●			●	
Motorized vehicles (electric bike, scooters, trolling motors, power tools, mower)									●	●	●			●	
High-power battery backup (emergency lighting, solar power storage, UPS)									●						
Power backup for short-term primary power outages (e.g. CMOS RAM, motor start, etc.)			●	●											●
Standard cell and battery packages															
AAA	●	●	●	●				●		●	●				
AA	●	●	●	●				●		●	●				
C	●	●	●	●				●		●	●				
D	●	●	●	●				●		●	●				
9V	●	●	●	●						●	●				
6V Lantern	●	●	●												
Button (coin)			●	●	●	●	●								●
Special battery pack			●	●					●	●	●	●	●	●	
Plastic Box									●					●	
PCB mount				●											●

FIGURE 3.31

3.2.5 Battery Capacity

Batteries are given a capacity rating that indicates how much electrical energy they are capable of delivering over a period of time. The capacity rating is specified in terms of ampere-hours (Ah) and millampere-hours (mAh). Knowing the battery capacity, it is possible to estimate how long the battery will last before being considered dead. The following example illustrates this.

Example: A battery with a capacity of 1800 mAh is to be used in a device that draws 120 mAh continuously. Ignoring possible loss in capacity as a result of load current magnitude, how long should the battery be able to deliver power?

Answer: Ideally, this would be:

$$t = \frac{1800 \text{ mAh}}{120 \text{ mAh}} = 15 \text{ h}$$

Note: In reality, you must consult the battery manufacturer's data sheets and analyze their discharge graphs (voltage as a function of time and of load current) to get an accurate determination of actual discharge time. As the load current increases, there is an apparent loss in battery capacity caused by internal resistance.

Typical capacity ratings for AAA, AA, C, D, and 9-V NiMH batteries are 1000 mAh (AAA), 2300 mAh (AA), 5000 mAh (C), 8500 mAh (D), 250 mAh (9).

C Rating

The charge and discharge currents of a battery are measured in capacity rating or C rating. The capacity represents the efficiency of a battery to store energy and its ability to transfer this energy to a load. Most portable batteries, with the exception of lead-acid, are rated at 1 C. A discharge rate of 1 C draws a current equal to the rated capacity that takes one hour (h). For example, a battery rated at 1000 mAh provides 1000 mA for 1 hour if discharged at 1 C rate. The same discharge at 0.5 C provides 500 mA for 2 hours. At 2 C, the same battery delivers 2000 mA for 30 minutes. 1 C is often referred to as a 1-hour discharge; 0.5 C would be 2 hours, and 0.1C would be a 10-hour discharge. The discrepancy in C rates between different batteries is largely dependent on the internal resistance.

Example: Determine the discharge time and average current output of a battery with a capacity rating of 1000 mAh if it is discharged at 1 C. How long would it take to discharge at 5 C, 2 C, 0.5 C, 0.2 C, and 0.05 C?

Answer: At 1 C, the battery is attached to a load drawing 1000 mA (rated capacity/hour), so the discharge time is:

$$t = 1 \text{ hC/C rating} = 1 \text{ hC}/1 \text{ C} = 1 \text{ h}$$

At 5 C, the battery is attached to a load drawing 5000 mA (five times rated capacity/hour), so the discharge time is:

$$t = 1 \text{ hC/C rating} = 1 \text{ hC}/5 \text{ C} = 0.2 \text{ h}$$

At 2 C, the battery is attached to a load drawing 2000 mA (two times rated capacity/hour), so the discharge time is:

$$t = 1 \text{ hC/C rating} = 1 \text{ hC}/2 \text{ C} = 0.5 \text{ h}$$

At 0.5 C, the battery is attached to a load drawing 500 mA (half the rated capacity/hour), so the discharge time is:

$$t = 1 \text{ hC/C rating} = 1 \text{ hC}/0.5 \text{ C} = 2 \text{ h}$$

At 0.2 C, the battery is attached to a load drawing 200 mA (20 percent rated capacity/hour) so the discharge time is:

$$t = 1 \text{ hC/C rating} = 1 \text{ hC}/0.2 \text{ C} = 5 \text{ h}$$

At 0.05 C, the battery is attached to a load drawing 50 mA (5 percent rated capacity/hour) so the discharge time is:

$$t = 1 \text{ hC/C rating} = 1 \text{ hC}/0.05 \text{ C} = 20 \text{ h}$$

Again, note that these values are estimates. When load currents increase (especially when C values get large), the capacity level drops below nominal values—due to nonideal internal characteristics such as internal resistance—and must be determined using manufacturer's discharge curves and Peurkert's equation. Do a search of the Internet, using "Peurkert's equation" as a keyword, to learn more.

3.2.6 Note on Internal Voltage Drop of a Battery

Batteries have an internal resistance that is a result of the imperfect conducting elements that make up the battery (resistance in electrodes and electrolytes). Though the internal resistance may appear low (around 0.1 Ω for an AA alkaline battery, or 1 to 2 Ω for a 9-V alkaline battery), it can cause a noticeable drop in output voltage if a low-resistance (high-current) load is attached to it. Without a load, we can measure the open-circuit voltage of a battery, as shown in Fig. 3.32a. This voltage is essentially equal to the battery's rated nominal voltage—the voltmeter has such a high input resistance that it draws practically no current, so there is no appreciable voltage drop. However, if we attach a load to the battery, as shown in Fig. 3.29, the output terminal voltage of the battery drops. By treating the internal resistance R_{in} and the load resistance R_{load} as a voltage divider, you can calculate the true output voltage present across the load—see the equation in Fig. 3.29b.

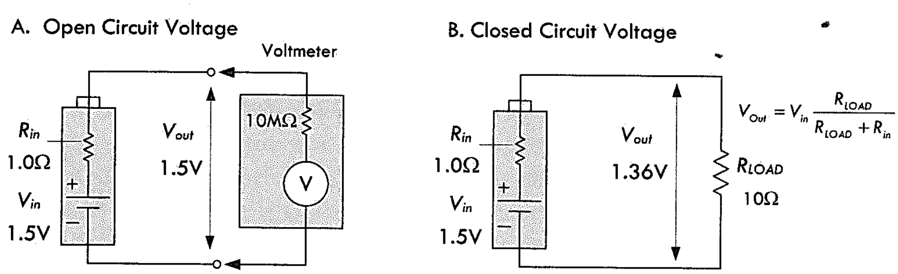


FIGURE 3.32

Batteries with large internal resistances show poor performance in supplying high current pulses. (Consult the battery comparison section and tables to determine which batteries are best suited for high-current, high-pulse applications.) Internal resistance also increases as the battery discharges. For example, a typical alkaline AA battery may start out with an internal resistance of 0.15 Ω when fresh, but may increase to 0.75 Ω when 90 percent discharged. The following list shows typical internal resistance for various batteries found in catalogs. The values listed should not be assumed to be universal—you must check the specs for your particular batteries.

9-V zinc carbon	35 Ω
9-V lithium	16 to 18 Ω
9-V alkaline	1 to 2 Ω
AA alkaline	0.15 Ω (0.30 Ω at 50 percent discharge)
AA NiMH	0.02 ΩW (0.04 Ω at 50 percent discharge)
D Alkaline	0.1 Ω
D NiCad	0.009 Ω
D SLA	0.006 Ω
AC13 zinc-air	5 Ω
76 silver	10 Ω
675 mercury	10 Ω

Battery OK / LOW Indicator

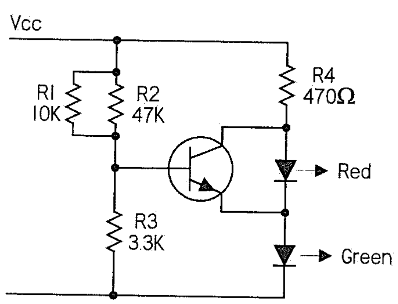


FIGURE 3.33

Here a green LED is used to indicate that the battery is okay. This stays on all the time to indicate that the battery is live, and the red LED comes on when the battery voltage falls below the set threshold. A green LED has around 2.0 V on when it is illuminated. This value varies a bit with different manufacturers, but is pretty well matched within any batch. Add the base emitter voltage, and you need 2.6V on the base of the right transistor (i.e., across the 3k3) to turn on the transistor. 2.6 V across 3k3 needs 9.1 across the supply rail. Below this threshold voltage, the transistor is off and the red LED is on. Above this voltage, the red LED is off. By adjusting the values of the three resistors, you can alter the threshold level. We'll discuss transistors and LEDs later on in this book.

3.3 Switches

A *switch* is a mechanical device that interrupts or diverts electric current flow within a circuit.

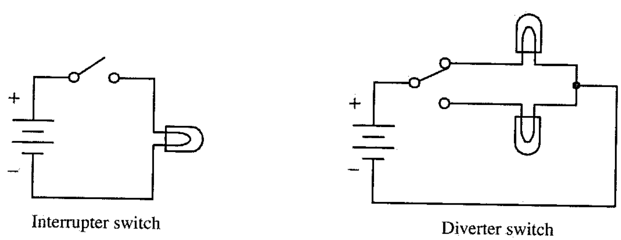


FIGURE 3.34

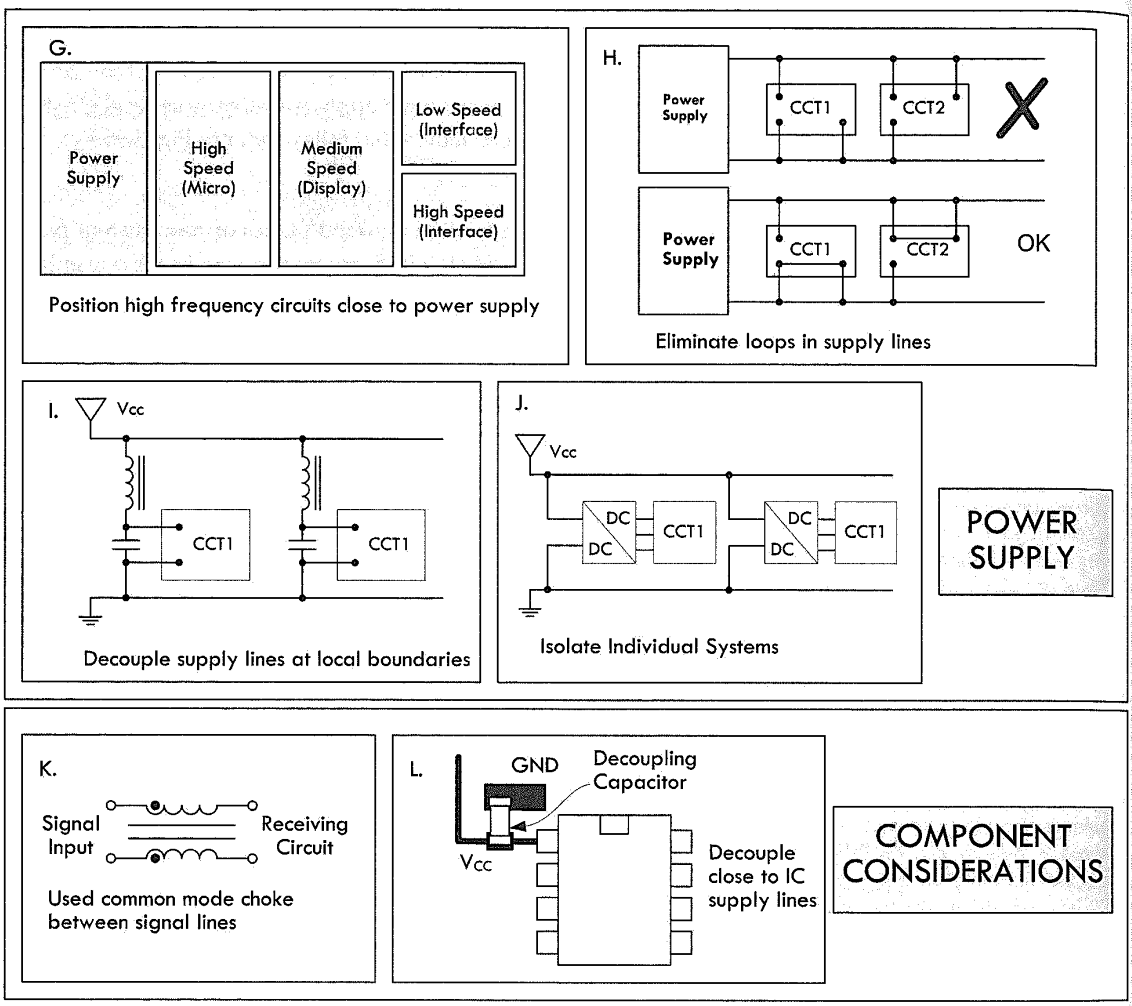


FIGURE 3.95 *(Continued)*

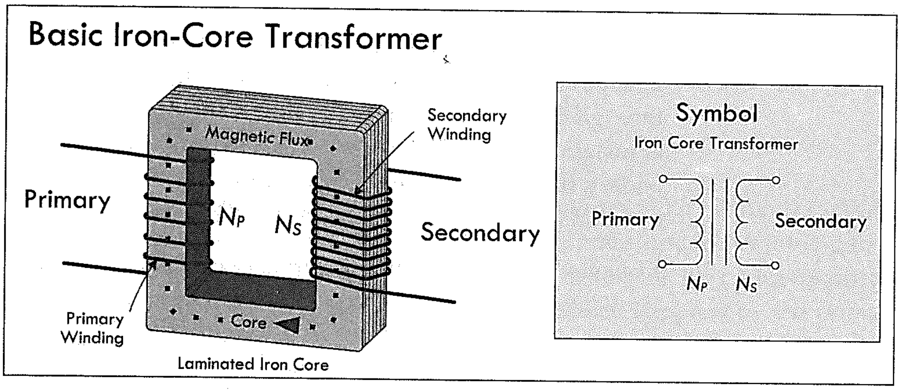
These tips where adapted from an Engineering Note, "Electro-Magnetic Interference and Electro-Magnetic Compatibility (EMI/EMC)" written by David B. Fancher, Inductive Products Division, Vishay Dale.

3.8 Transformers

3.8.1 Basic Operations

A basic transformer is a two-port (four-terminal) device capable of transforming an ac input voltage into a higher or lower ac output voltage. Transformers are not designed to raise or lower dc voltages, however, since the conversion mechanism relies on a changing magnetic field generated by a changing current. A typical transformer consists of two or more insulated wire coils that share a common laminated iron core. One of the coils is called the primary (containing N_P turns), while the other coil is called the secondary (containing N_S turns). A simplistic representation of a transformer is shown in Fig. 3.96, along with its schematic symbol.

IGURE 3.96



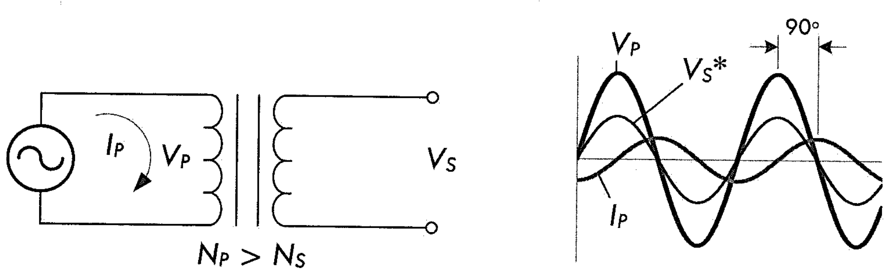
When an ac voltage is applied across the primary coil of the transformer, an alternating magnetic flux $\Phi_M = \int(V_{IN}/N_P)dt$ emanates from the primary, propagates through the iron-laminated core, and passes through the secondary coil. (The iron core increases the inductance, and the laminations decrease power-consuming eddy currents.) According to Faraday's law of induction, the changing magnetic flux induces a voltage of $V_S = N_S d\Phi_M/dt$, assuming there is perfect magnetic flux coupling (coefficient of coupling $k = 1$). Combining the primary flux equation with the secondary induced voltage equation results in the following useful expression:

$$V_S = V_P\left(\frac{N_S}{N_P}\right) \quad \text{(3.1) Transformer voltage ratio}$$

This equation says that if the number of turns in the primary coil is larger than the number of turns in the secondary coil, the secondary voltage will be smaller than the primary voltage. Conversely, if the number of turns in the primary coil is less than the number of turns in the secondary, the secondary voltage will be larger than the primary.

When a source voltage is applied across a transformer's primary terminals while the secondary terminals are open-circuited (see Fig. 3.97), the source treats the transformer as if it were a simple inductor with an impedance of $Z_P = j\omega L_P = \omega L \angle 90°$, where L_P represents the inductance of the primary coil. This means that the primary current will lag the voltage (source voltage) by 90°, and the primary current will be equal to V_P/Z_P, according to Ohm's law. At the same time, a voltage of $(N_S/N_P)V_P$ will be present across the secondary and will be in phase with the primary voltage or 180° out of phase, depending on the secondary coil winding direction or depending on which secondary coil end you choose as a reference (more on this in a moment).

URE 3.97



* In phase with V_P or 180° out of phase, depending on winding arrangement and ground reference.

When there is no load attached to the secondary of a transformer, the current within the primary is called the magnetizing current of the transformer. An ideal transformer, with no internal losses, would consume no power, since the current through the primary inductor would be 90° out of phase with the voltage (in $P = IV$, I is imaginary and the "power" is imaginary or reactive). With no load in the secondary, the only losses in the transformer are associated with those losses in the iron core and losses within the primary coil wire itself.

Example 1: A transformer has a primary of 200 turns and a secondary of 1200 turns. If a 120 VAC is applied to the primary, what voltage appears across the secondary?

Answer: Rearranging Eq. 3.1,

$$V_S = V_P\left(\frac{N_S}{N_P}\right) = 120\text{ VAC}\left(\frac{1200\text{ turns}}{200\text{ turns}}\right) = 720\text{ VAC}$$

This is an example of a step-up transformer, since the secondary voltage is higher than the primary voltage.

Example 2: Using the same transformer from Example 1, flip it around so the secondary now acts as the primary. What will be the new secondary voltage?

Answer:

$$V_S = V_P\left(\frac{N_S}{N_P}\right) = 120\text{ VAC}\left(\frac{200\text{ turns}}{1200\text{ turns}}\right) = 20\text{ VAC}$$

This is an example of a step-down transformer, since the secondary voltage is lower than the primary voltage.

As you can see from the previous example, either winding of a transformer can be used as the primary, provided the windings have enough turns (enough inductance) to induce a voltage equal to the applied voltage without requiring an excessive current. The windings must also have insulation with a voltage rating sufficient for the voltage present.

Now let's take a look at what happens when you attach a load to the secondary, as shown in Fig. 3.98.

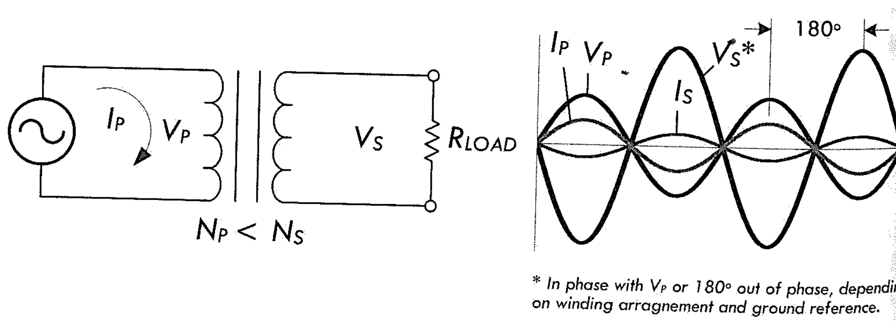


FIGURE 3.98

When a load is attached to the secondary, the secondary current sets up a magnetic field that opposes the field set up by the primary current. For the induced voltage in the primary to equal the applied voltage, the original field must be maintained. The primary must draw enough additional current to set up a field exactly equal and opposite to the field set up by the secondary current. At this point, for practical purposes, we assume that the entire primary current is a result of the secondary load. (This is close to true, since the magnetizing current will be very small in comparison with the primary load current at rated power output.)

Current Ratio

To figure out the relationship between the primary and secondary currents, consider that an ideal transformer is 100 percent efficient (real transformers are around 65 to 99 percent efficient, depending on make), and then infer that all the power dissipated by the load in the secondary will be equal to the power supplied by the primary source. With the help of the generalized power law, we get:

$$P_P = P_S$$
$$I_P V_P = I_S V_S$$

Plugging our transformer voltage equation (3.1) into the V_S term, we get:

$$I_P V_P = I_S\left(V_P \frac{N_S}{N_P}\right)$$

Eliminating the V_P from both sides, we get the following useful current relation:

$$I_P = I_S\left(\frac{N_S}{N_P}\right) \quad \text{(3.2) Ideal transformer current ratio}$$

Example 3: A transformer with a primary of 180 turns and a secondary with 1260 turns is delivering 0.10 A to a load. What is the primary current?

Answer: Rearranging Eq. 3.2 and solving for the primary current:

$$I_P = I_S\left(\frac{N_S}{N_P}\right) = 0.10\ \text{A}\left(\frac{1260\ \text{turns}}{180\ \text{turns}}\right) = 0.7\ \text{A}$$

Notice from the previous example that even though the secondary voltage is larger than the primary voltage, the secondary current is smaller than the primary current. The secondary current in an ideal transformer is 180° out of phase with the primary current, since the field in the secondary just offsets the field in the primary. The phase relationship between the currents in the windings holds true no matter what the phase difference between the current and the voltage of the secondary. In fact, the phase difference, if any, between voltage and current in the secondary will be reflected back to the primary as an identical phase difference. Note that phase, however, can be selected according to how you pull the secondary out—see the following note.

NOTE ABOUT PHASE

By now you may be a bit annoyed with the notion of phase. For example, to say that that the primary voltage is out of phase with the secondary by 180° is smack in the phase to relativity. Couldn't you simply wind the secondary winding in a different direction or, more easily, simply reverse the secondary leads to get an output that is within phase? The answer is yes. It is a relativity game with the transformer pins. Figure 3.99 shows two transformers that are identical in every way except for the winding direction of the secondary. The

(continued)

winding A arrangement, when tested with a common ground and oscilloscope, yields in-phase voltages, while the winding in B yields voltage and currents that are 180° out of phase with the primary. To avoid confusion, a convention is used to keep track of the relative polarity between the leads. This convention makes use of what are called phase dots, which are a pair of dots: one placed on the primary side; the other placed on the secondary side. The similar placement of these dots next to the top ends of the primary and secondary windings tells you that whatever instantaneous voltage polarity is seen across the primary winding will be the same as that across the secondary winding. In other words, the phase shift from primary to secondary will be zero degrees. On the other hand, if dots on each winding of the transformer do not match up, the phase shift is 180° between primary and secondary. Of course, the dot convention only tells you which end of each winding is which, relative to the other winding(s). If you want to reverse the phase relationship, all you have to do is swap the winding connections.

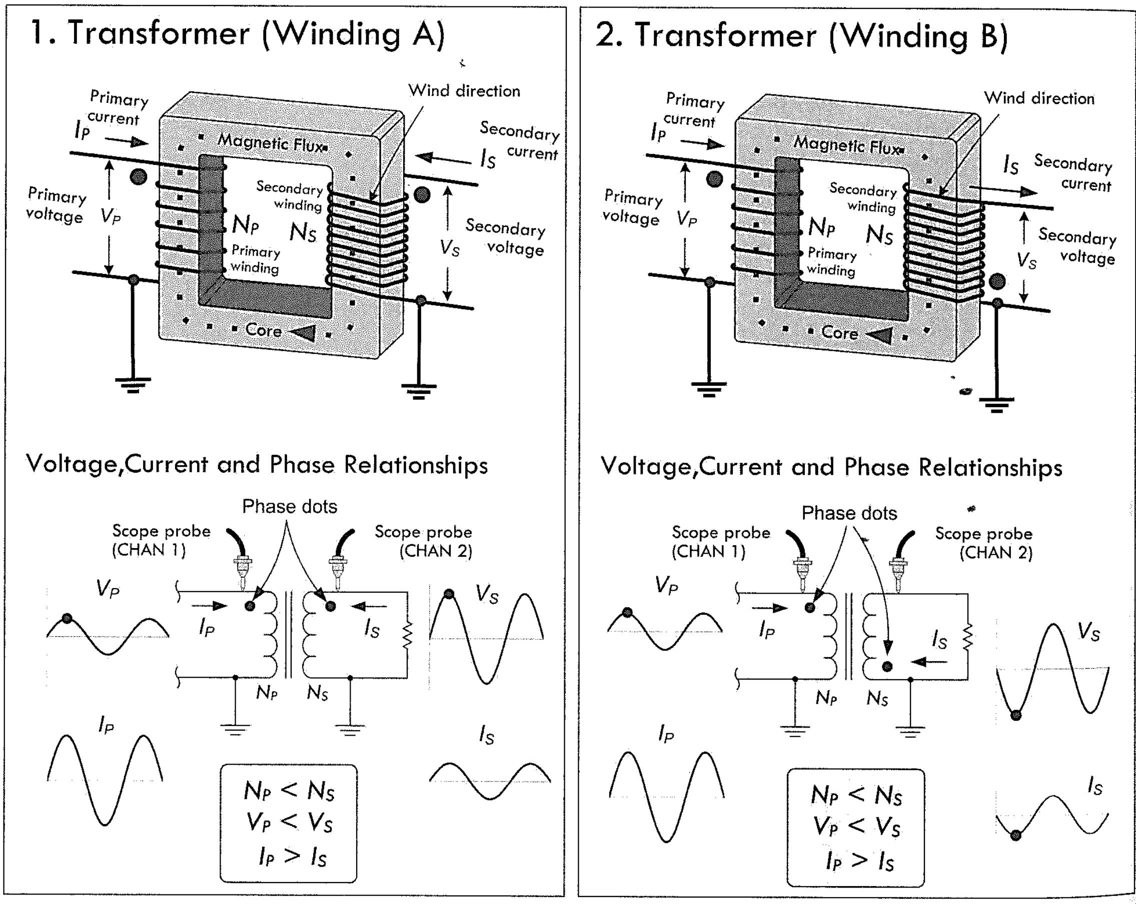


FIGURE 3.99

Power Ratio

A moment ago, when deriving the transformer current equation, we assumed that the transfer of power from primary to secondary was 100 percent efficient. However, it is important to realize that there is always some power loss in the resistance of the coils and in the iron core of the transformer. This means that the power taken from the source is greater than the power used in the secondary. This can be stated by the following expression:

$$P_S = n \times P_P \qquad \text{(3.3) Efficiency factor}$$

where P_S is the power output from the secondary, P_P is the power input to primary, and n is the efficiency factor. The efficiency n is always less than 1. It is usually expressed as a percentage—for example, 0.75 represents an efficiency of 75 percent.

Example 4: What is the power input to the primary if a transformer has an efficiency of 75 percent and its full load output at the secondary is 100 W?

Answer: Rearranging Eq. 3.3,

$$P_P = \frac{P_S}{n} = \frac{100\text{ W}}{0.75} = 133\text{ W}$$

Transformers are typically designed to have highest efficiency at the manufacturer's rated outputs. Above or below the rated output, the efficiency drops. The amount of power a transformer can handle depends on its own losses (heating of wire and core, etc.). Exceeding the rated power of a transformer can lead to wire meltdown or insulation breakdown. Even when the load is purely reactive, the transformer will still be generating heat loss due to internal resistance of the coils and losses in the core. For this reason, manufacturers also specify a maximum volt-amp rating, or VA-rating, that should not be exceeded.

Impedance Ratio

Using ac Ohm's law, $I_P = V_P/Z_P$, and assuming an ideal transformer, where power from the primary is 100 percent transferred to secondary, we can come up with an equation relating the primary and secondary impedances:

$$P_P = P_S$$

$$I_P V_P = I_S V_S$$

$$\frac{V_P^2}{Z_P} = \frac{V_S^2}{Z_S} \rightarrow \text{(plug in } V_S = V_P(N_S/N_P)) \rightarrow \frac{V_P^2}{Z_P} = \frac{V_P^2(N_S/N_P)^2}{Z_S}$$

Canceling the primary voltage terms, you get the following useful expression:

$$Z_P = Z_S\left(\frac{N_P}{N_S}\right)^2 \qquad \text{(3.4) Transformer impedance ratio}$$

where Z_P is the impedance looking into the primary terminal from the power source, and Z_S is the impedance of the load connected to the secondary. Figure 3.100 shows an equivalent circuit.

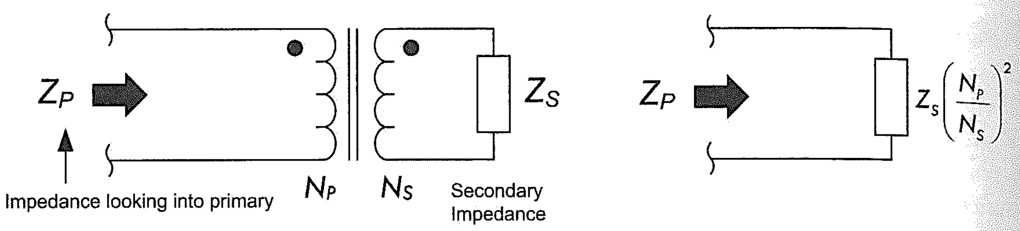


FIGURE 3.100

If the load impedance in the secondary increases, the impedance looking into the primary (from the source's point of view) will also increase in a manner that is proportional to the ratio of the turns squared.

Example 5: A transformer has a primary with 500 turns and a secondary with 1000 turns. What is the primary impedance if a 2000-Ω load impedance is attached to the secondary?

Answer: Using Eq. 3.4:

$$Z_P = 2000\ \Omega\left(\frac{500\text{ turns}}{1000\text{ turns}}\right)^2 = 2000\ \Omega(0.5)^2 = 500\ \Omega$$

As you can see, by selecting the proper turns ratio, the impedance of a fixed load can be transformed to any desired value (ideally). If transformer losses can be neglected, the transformed (reflected) impedance has the same phase angle as the actual load impedance. Hence, if the load is purely resistive, the load presented by the primary to the power source will also be pure resistance. If the load impedance is complex (e.g., inductance and capacitance are thrown in so that load current and voltage are out of phase with each other), then the primary voltage and current will show the same phase angle.

In electronics, there are many instances where circuits require a specific load resistance (or impedance) for optimum performance. The impedance of the actual load dissipating power may differ widely from the impedance of the source. In this case, a transformer can be used to change the actual load into an impedance of desired value. This is referred to as *impedance matching*. We can rearrange Eq. 3.4 and get:

$$\frac{N_P}{N_S} = \sqrt{\frac{Z_P}{Z_S}} \tag{3.5}$$

where N_P/N_S is the required turns ratio—primary to secondary, Z_P is the primary impedance required, and Z_S is the impedance of the load connected to the secondary.

Example 6: An amplifier circuit requires a 500-Ω load for optimum performance, but is to be connected to an 8.0-Ω speaker. What turns ratio, primary to secondary, is required in the coupling transformer?

Answer:

$$\frac{N_P}{N_S} = \sqrt{\frac{Z_P}{Z_S}} = \sqrt{\frac{500\ \Omega}{8\ \Omega}} = 8$$

Hence, the primary must have eight times as many turns as the secondary.

Knowing what to set the primary count at depends on low internal losses and leakage current and making sure that the primary has enough inductance to operate with low magnetizing current at the voltage applied to the primary.

Example 7: What are the load impedances "seen" by the voltage sources in Fig. 3.101?

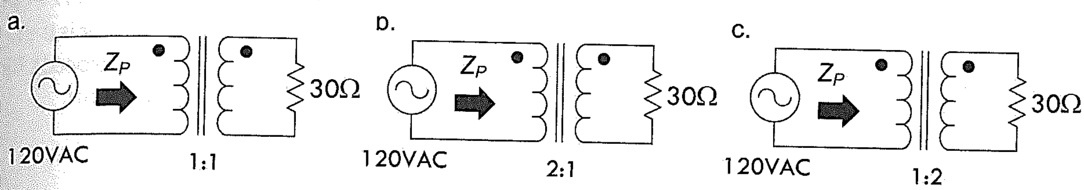


FIGURE 3.101

Answer: (a) 30 Ω, (b) 120 Ω, (c) 8 Ω.

Example 9: If a step-up transformer has a turns ratio of 1:3, what are the voltage ratio, current ratio, and impedance ratio? Assume ratios are given in the form "primary: secondary."

Answer: Voltage ratio is 1:3, current ratio is 3:1, impedance ratio is 1:9.

Transformer Gear Analogy

It is often helpful to think of transformers as gearboxes. For example, in the gearbox analogy in Fig. 3.101, the primary winding is analogous to the input shaft (where the motor is

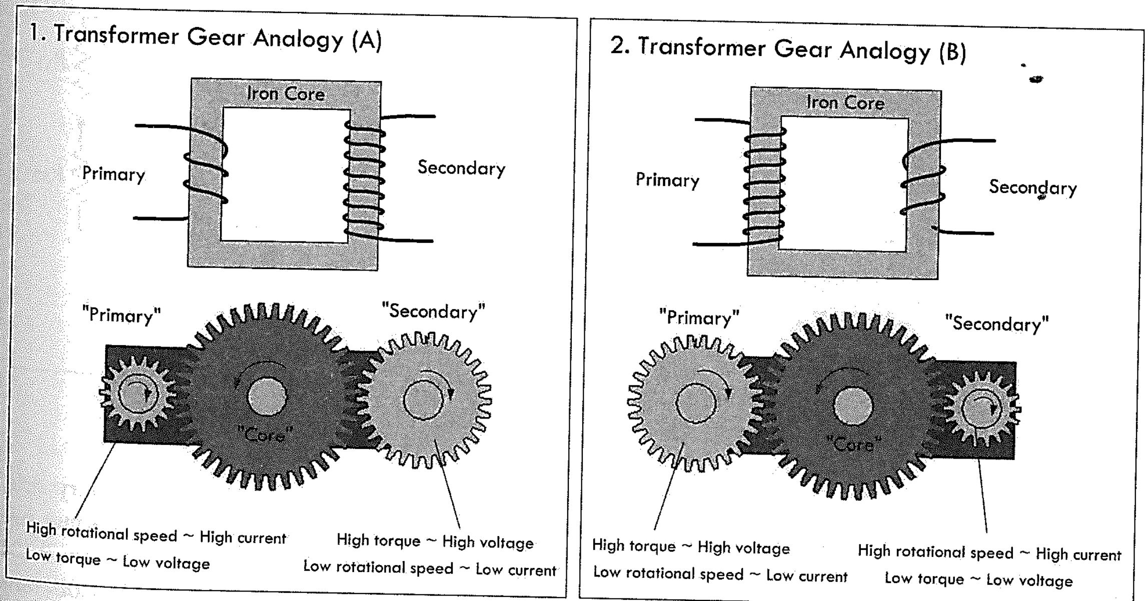


FIGURE 3.102

attached) and the secondary winding is analogous to the output shaft. Current is equivalent to shaft speed (rmp) and voltage is equivalent to torque. In a gearbox, mechanical power (speed multiplied by torque) is constant (neglecting losses) and is equivalent to electrical power (voltage times current), which is also constant. The gear ratio is equivalent to the transformer step-up or step-down ratio. A step-up transformer acts like a reduction gear (in which mechanical power is transferred from a small, rapidly rotating gear to a large, slowly rotating gear): it trades current (speed) for voltage (torque), by transferring power from a primary coil to a secondary coil having more turns. A step-down transformer acts similarly to a multiplier gear (in which mechanical power is transferred from a large gear to a small gear): it trades voltage (torque) for current (speed), by transferring power from a primary coil to a secondary coil having fewer turns.

Center-Tap Transformers

Rarely do you see transformers in the real world with just four leads—two for the primary and two for the secondary. Many commercial transformers employ center taps. A center tap is simply an electrical connection that is made somewhere between the two ends of a transformer winding. By using a center tap, it is possible to utilize only a fraction of the winding voltage. For example, in Fig. 3.103, a transformer's secondary is center-tapped midway between its winding, yielding two output voltages V_{S1} and V_{S2}. If we place a ground reference on the center tap (it is treated now as a common), we see the voltages in terms of phase, as shown in the example circuit in Fig. 3.103. In this case, the two secondary voltages are equal because we assumed that the number of turns on either end of the center tap were the same. In general, the secondary voltages are determined by the turns ratio.

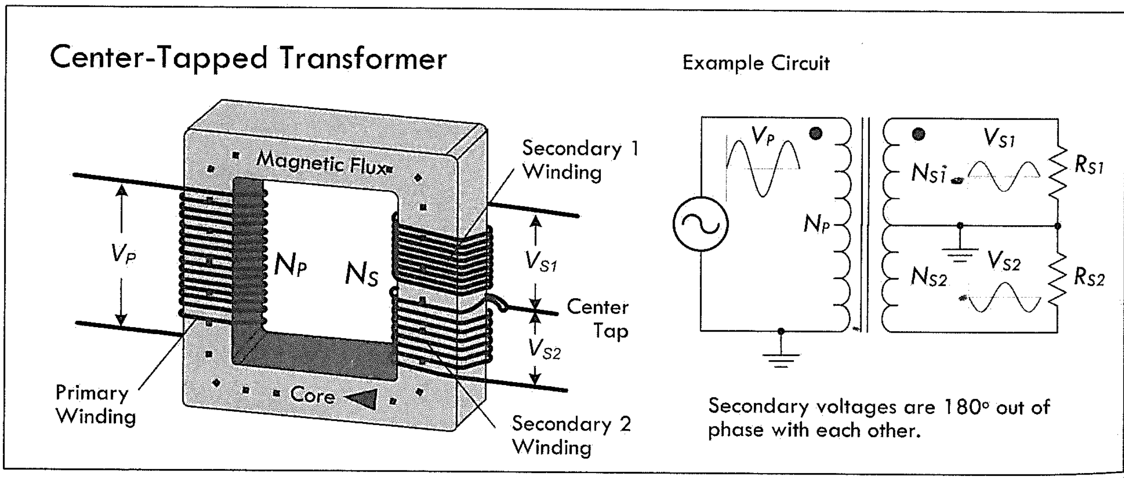


FIGURE 3.103

Center taps can be placed on both the primary side and the secondary side, with multiple taps on either side. For example, a typical power transformer has several secondary windings, each providing a different voltage. Figure 3.104 shows a schematic of a typical power supply transformer. It is possible to join pins with a jumper to get the desired voltage ratios across other pins. Manufacturers will provide you with the voltages between the various tap points, usually specifying CT as the center-tap voltage. Center taps provide flexibility in design and allow varying outputs, which you implement by incorporating switches, for example. We'll see how a center-tap transformer is used to split incoming 240 VAC for the main into two 120-VAC legs within the circuit breaker of your house, and we'll also discover how full-wave center-tap rectifier circuits are used in building dc power supplies.

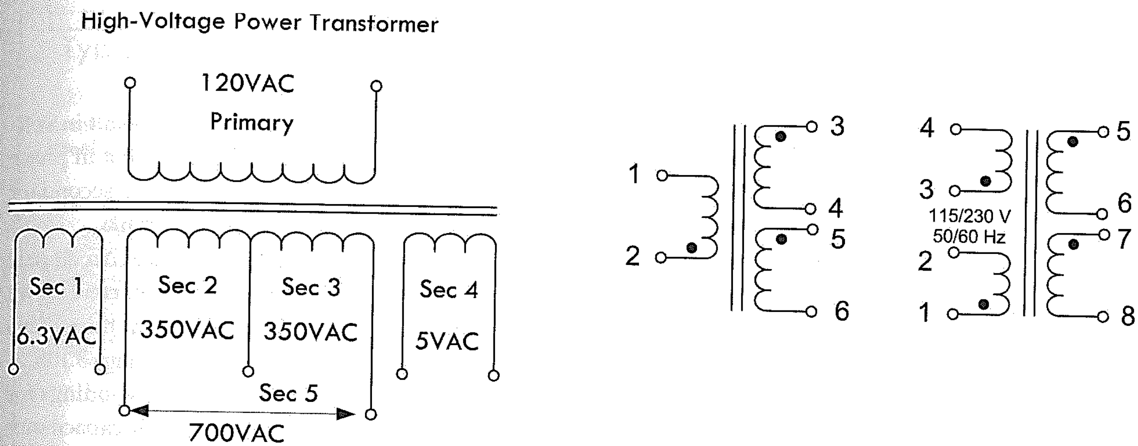


FIGURE 3.104

Real Transformer Characteristics

A perfect or ideal transformer has a primary-to-secondary coupling coefficient of 1. This means that both coils link with all the magnetic flux lines, so that the voltage induced per turn is the same for both coils. This also means that the induced voltage per turn is the same for both primary and secondary coils. Iron core transformers operating at low frequencies come close to being ideal. However, due to various imperfections, such as eddy current, hysteresis losses, internal coil resistance, and skin effects at higher frequencies, this isn't quite true.

In real transformers, not all of the magnetic flux is common to both windings. Flux not associated with linkage is referred to as *leakage flux* and is responsible for a voltage of self-induction. There are small amounts of leakage inductance associated with both windings of a transformer. Leakage inductance acts in exactly the same manner as an equivalent amount of ordinary inductance inserted in series with the circuit. The reactance associated with leakage inductance is referred to as *leakage reactance*, which varies with transformer build and frequency. Figure 3.105 shows a real-life model of a transformer including leakage reactances for both primary and secondary coils, namely, X_{L1} and X_{L2}. When current flows through a leakage reactance, there is an associated voltage drop. The voltage drop becomes greater with increasing current and increases as more power is taken from the secondary.

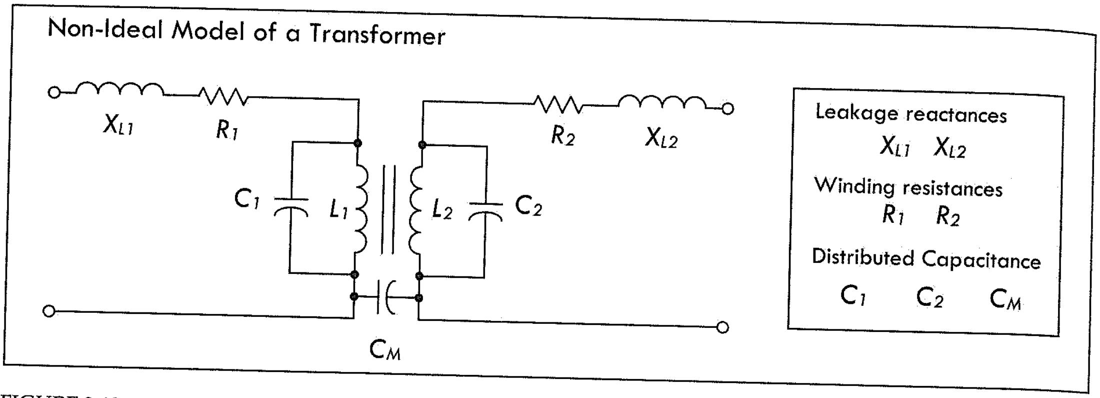


FIGURE 3.105

The internal resistances of a transformer's windings R_1 and R_2 also result in voltage drop when there is current flow. Although these voltage drops are not in phase with those caused by leakage reactance, together they result in a lower secondary voltage under load than is indicated by the transformer turns ratio formula.

Another nonideal characteristic of transformers is stray capacitance. An electric field exists between any two points having a different voltage. When current flows through a coil, each turn has a slightly different voltage than its adjacent turns. This results in capacitance between turns and is modeled by C_1 and C_2 in Fig. 3.105. A mutual capacitance C_M also exists between the primary and secondary windings for the same reason. It is also possible for transformer windings to exhibit capacitance relative to nearby metal, such as a chassis, shield, or even the core itself.

Stray capacitance tends to have little influence in power and audio transformers, but becomes influential as the frequencies increase. In RF applications where transformers are used, the stray capacitance can resonate with either the leakage reactance or, at lower frequencies, the winding reactances, especially under very light or zero-ohm loads. In the frequency region around resonance, transformers do not exhibit behavior as described by the previous transformer equations.

Iron core transformers also experience losses with hysteresis and eddy current, as was discussed in Chap. 2.24. These losses, which add to the required magnetizing current, are equivalent to adding a resistance in parallel to R_1 in Fig. 3.105.

TRANSFORMER PRECAUTIONS

There are three basic rules to observe when using a transformer. First, never apply a voltage that is greatly in excess of the transformer winding ratings. Second, never allow a significant direct current to flow through any winding not designed to handle it. Third, don't operate the transformer at a frequency outside the range specified by the manufacturer. Applying a voltage of, say, 120 VAC to a secondary in hopes of achieving 1200 VAC at the primary is a bad idea—expect smoke and combustion, accompanied by insulation failure. Similar results can be expected with excessive dc current through the primary. In terms of frequency, a 60-Hz transformer driven at 20 Hz will draw too much magnetizing current and will run dangerously hot.

3.8.2 Transformer Construction

Cores

Transformers used for power and audio frequencies have cores made of many thin laminations of silicon steel. The laminations reduce eddy currents, as discussed in Sec. 2.24. A typical laminated core is made from E-shaped and I-shaped pieces, sandwiched together, as shown in Fig. 3.106. Transformers made from these cores are therefore often referred to as EI transformers.

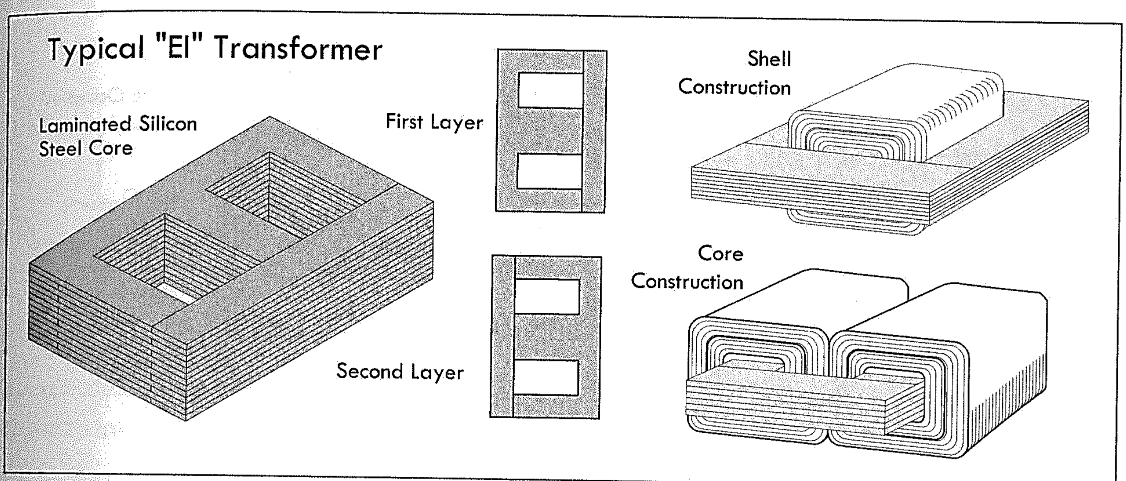


FIGURE 3.106

Two common core shapes in use are shown in Fig. 3.106. In the shell construction, both the primary and the secondary windings are wound around the same inner leg, while in the core construction, primary and secondary windings are wound on separate legs. The core construction is often implemented to minimize capacitive effects between primary and secondary windings, or when one winding is to be operated at very high voltage. The size, shape, and type of core material, as well as the frequency range, influence the required number of turns in each winding. In most transformers, the coils are wound in layers, with a sheet of special paper insulation placed between each layer. A thicker insulation is used between adjacent coils and between the core and the first coil.

Powdered iron cores, with their low eddy current characteristics, are used in transformers that operate above mains frequencies (60 Hz) up to several kilohertz. These cores have a very high permeability and thus provide decent stepping capability for their size. Transformers that are used in even higher-frequency applications, such as RF, often contain cores made from nonconductive magnetic ceramic materials or ferrites.

A common core shape for powdered iron and ferrite core transformers is the toroid, as shown in Fig. 3.107a. The closed ring shape of the toroid eliminates air gaps inherent in the construction of an EI core. The primary and secondary coils are often wound concentrically to cover the entire surface of the core. Ferrite cores are used at higher frequencies, typically between a few tens of kilohertz to a megahertz. In general, toroidal transformers are more efficient (around 95 percent) than cheaper laminated EI transformers; they are more compact (about half the size), weigh less (about half), have less mechanical hum (making them superior in audio applications), and have lower off-load losses (making them more efficient in standby circuits).

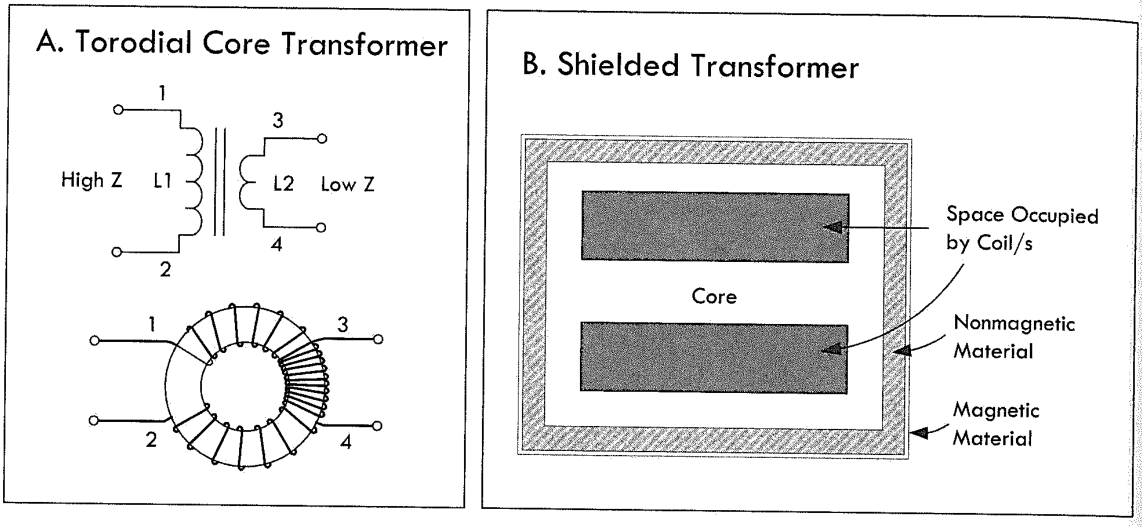


FIGURE 3.107

Shielding

To eliminate mutual capacitance between windings within a transformer, an electrostatic shield is often placed between the windings. Some transformers may incorporate a magnetic shield, as shown in Fig. 3.107b. The magnetic shield helps prevent outside magnetic fields (interference) from inducing currents within the inner windings. The shield also helps prevent the transformer from becoming an interference radiator itself.

Windings

For small-power and signal transformers, the windings are made from solid wire copper, insulated typically with enamel; sometimes additional insulation is used for safety. Larger-power transformers may be wound with copper or aluminum wire, or even strip conductors for very heavy current; in some cases multistrand conductors are used to reduce skin effect losses. High-frequency transformers operating in the kilohertz range often have windings made of Litz wire to minimize skin effects. For signal transformers, the windings may be arranged in a way to minimize leakage inductance and stray capacitance in order to improve high-frequency response.

3.8.3 Autotransformers and Variable Transformers

An autotransformer is similar to a standard transformer; however, it uses only one single coil and a center tap (or taps) to make primary and secondary connections. See

Fig. 3.108. As with standard transformers, autotransformers can be used to step up or step down voltages, as well as match impedances; however, they will not provide electrical isolation like a standard transformer, since their primary and secondary are on the same coil—there is no electrical isolation between the two coils.

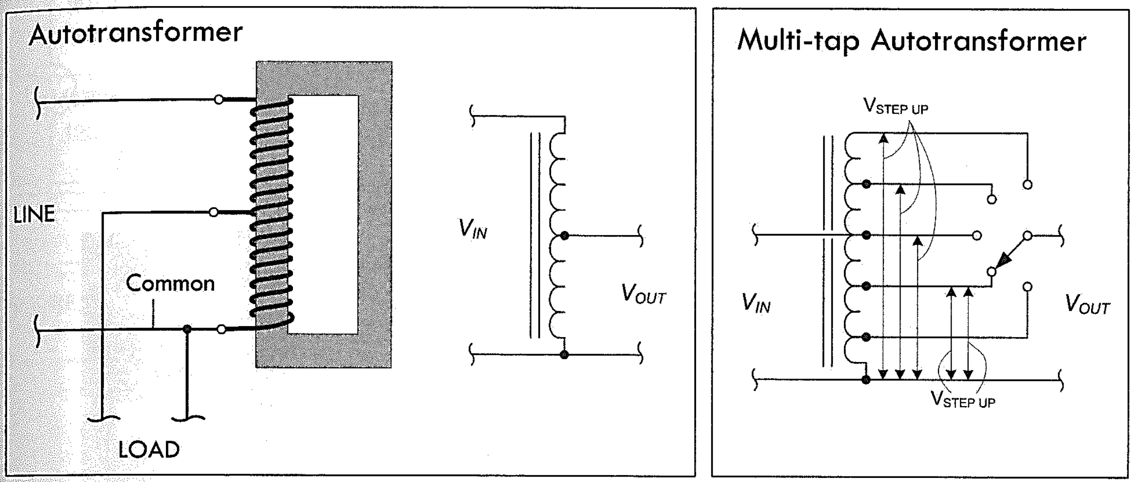


FIGURE 3.108

Although an autotransformer has only one winding, the laws of induction that were used with a standard transformer to step up and step down voltage can be applied just as well. This also applies to principles of current and impedance as a function of the number of winding turns. In Fig. 3.108, the current in the common winding is the difference between the line current (primary current) and the load current (secondary current), since these currents are out of phase. Hence, if the line and load currents are nearly equal, the common section of the winding may be wound with comparatively small wire. The line and load currents will be equal only when the primary (line) and secondary (load) voltages are close in magnitude.

Autotransformers are often used in impedance-matching applications. They are also frequently used for boosting or reducing the power-line voltage by relatively small amounts. Figure 3.108 shows a switch-stepped autotransformer whose output voltage can be set to any number of values determined by the switch contact position.

A variable transformer or Variac (commercial name) is similar to the switch-stepped autotransformer in Fig. 3.108; however, it has a continuous wiper action along a circular coil, as shown in Fig. 3.109. A Variac acts like an adjustable ac voltage source. Its primary is connected to the hot and neutral of the 120-V line voltage, while the secondary leads consist of the neutral and an adjustable wiper that moves along the single core winding.

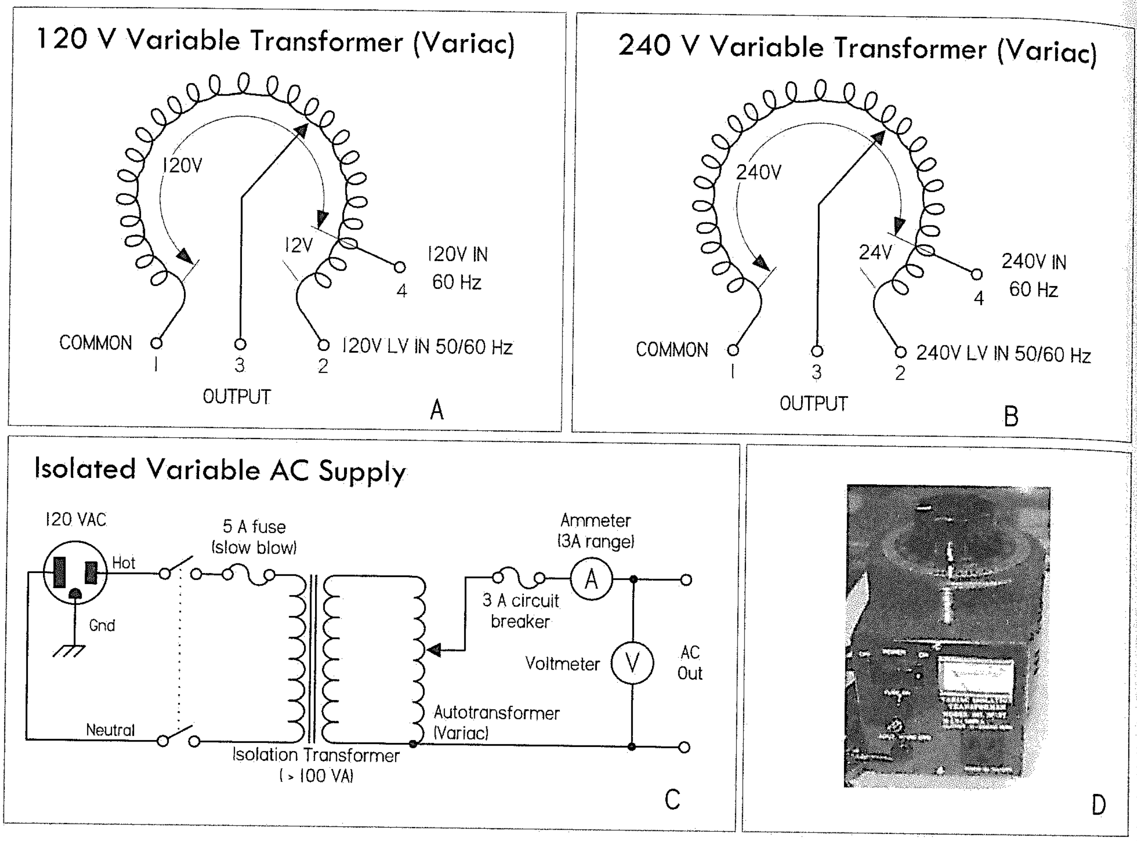


FIGURE 3.109 (a) Nonisolated 120-V Variac whose output voltage is varied by rotating a wiper. (b) Nonisolated 240-V Variac. (c) A homemade variable ac supply with isolation protection provided by means of an isolation transformer. (d) ac power supply that houses an isolation transformer, Variac, switch, fuse, ac outlet, and meter.

Being able to adjust the line voltage is a very useful trick when troubleshooting line-power equipment, where the fuse instantly blows at normal line voltage. Even without a fuse blowing, troubleshooting at around 85 V may reduce the fault current.

It is important to note that a Variac by itself does not provide isolation protection like a standard transformer, since the primary and secondary shared a common winding. It is therefore important, if you plan to work on ungrounded, "hot chassis" equipment, that you place an isolation transformer before the Variac—never after it. If you don't, shock hazards await. Figure 3.109c shows a schematic of such an arrangement. It includes a switch and fuse protection, as well as current and voltage meters, all of which create an adjustable, fully isolated ac power source.

To avoid the hassle of cascading a Variac and isolation transformer together, simply get an ac power supply that houses both elements together in one package—see Fig. 3.109d.

Boosting and Bucking

We just saw how autotransformers are used in applications requiring a slight boost or reduction in voltage to a load. It is possible to accomplish the same effect by using a normal (isolated) transformer with just the right primary/secondary turns ratio.

There is still another alternative—use a step-down configuration with secondary winding connected in a series-aiding ("boosting") or series-opposing ("bucking") configuration, as shown in Fig. 3.110.

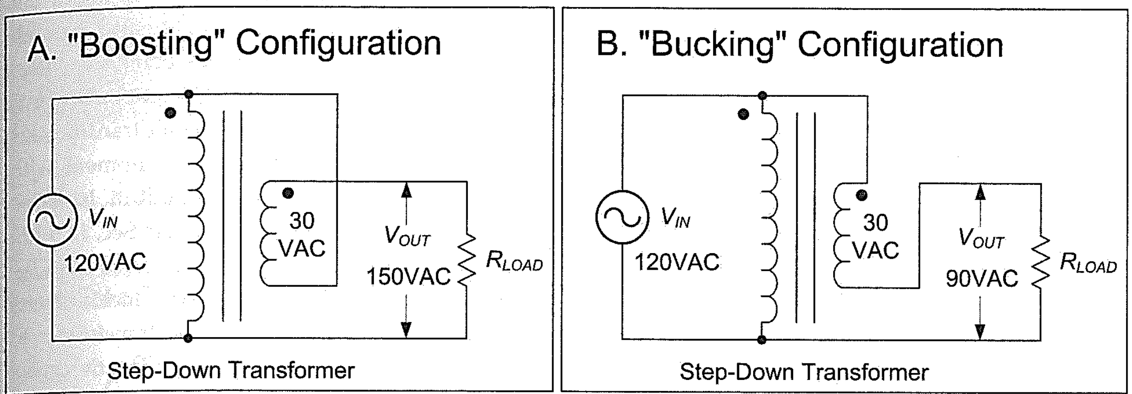


FIGURE 3.110

In the boosting configuration, the secondary coil's polarity is oriented so that its voltage directly adds to the primary voltage. In the bucking configuration, the secondary coil's polarity is oriented so that its voltage directly subtracts from the primary voltage. An autotransformer does the same job as the boosting and bucking functions displayed here, but using only a single winding, making it cheaper and lighter to manufacture.

3.8.4 Circuit Isolation and the Isolation Transformer

Transformers perform an important role in isolating one circuit from another. Figure 3.111 shows an example application that uses a transformer to isolate a load connected to an ac outlet. In this application, there is no need to step up or step down the voltage, so the transformer has a 1:1 winding ratio. Such a transformer is referred to as an *isolation transformer*. In Fig. 3.111, a mains isolation transformer is used to isolate a load from the source, as well as provide ground fault protection. An isolation transformer should be used whenever you work on nongrounded equipment, with no input isolation, such as switch-mode power supplies.

In your home wiring, the neutral (white) and the ground (green) connections are tied together at the main junction box, so they are basically at the same potential—

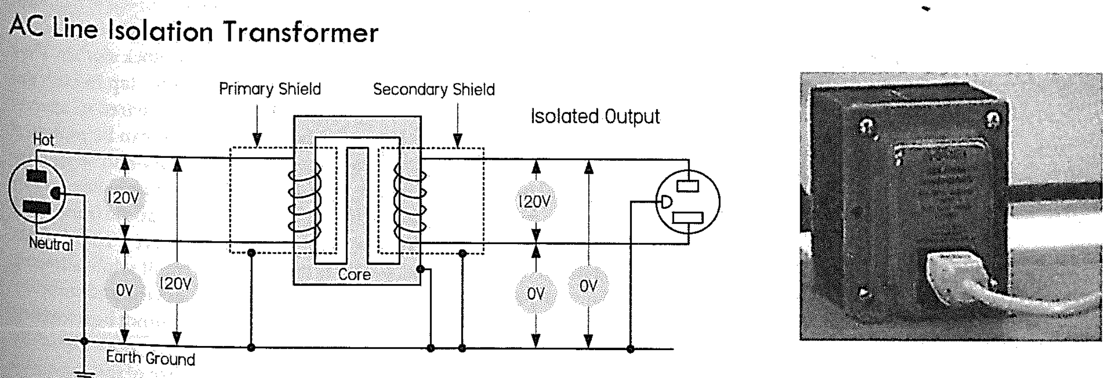


FIGURE 3.111

0 V, or earth ground. If you accidentally touch the hot wire while being in contact with a grounded object, current will pass through your body and give you a potentially fatal shock. With an isolation transformer, the secondary winding leads act as a 120-V source and return, similar to the mains' hot and neutral, but with an important difference. Neither the secondary source nor return runs are tied to earth ground! This means that if you touch the secondary source or return while being in contact with a grounded object, no current will flow through your body. Current only wants to pass between the secondary source and return runs. (Note that all transformers provide isolation, not just line isolation transformers. Therefore, equipment with input power transformers already have basic isolation protection built in. Isolation transformers used for laboratory work are explained in greater detail in Sec. 14.5.12.)

Isolation transformers are also typically constructed with two isolated Faraday shields between the primary and secondary windings. The use of the two shields diverts high-frequency noise, which would normally be coupled across the transformer to ground. Increasing the separation between the two Faraday shields minimizes the capacitance between the two and, hence, the coupling of noise between the two. Therefore, the isolation transformer acts to clean up line power noise before being delivered to a circuit.

3.8.5 *Various Standard and Specialized Transformers*

Power Transformers

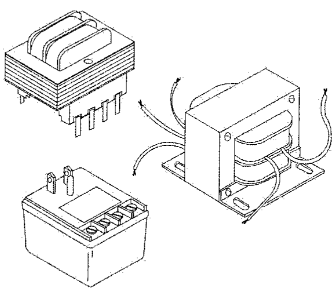


FIGURE 3.112

These transformers are used primarily to reduce line voltage. They come in a variety of different shapes, sizes, and primary and secondary winding ratios. They often come with taps and multiple secondary windings. Color-coded wires are frequently used to indicate primary and secondary leads (e.g., black wires for primary, green for secondary, and yellow for tap lead is one possibility). Other transformers use pins for primary, secondary, and tapped leads, allowing them to be mounted on a PC board. You can also find transformers in wall-mount packages that plug directly into an ac outlet, with screw-in terminals as secondary and tapped leads.

Audio Transformers

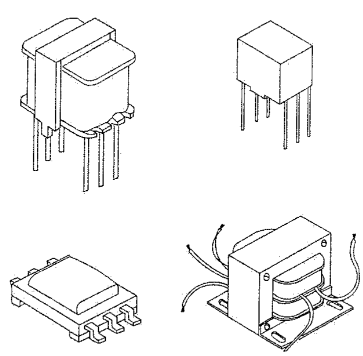


FIGURE 3.113

Audio transformers are used primarily to match impedances between audio devices (e.g., between microphone and amplifier or amplifier and speaker), though they can be implemented in other ways as well. They work best at audio frequencies from 20 Hz to 20 kHz. Outside this range they will reduce or block signals. They come in a variety of shapes and sizes and typically contain a center tap in both the primary and secondary windings. Some come with color-coded wires to specify leads, while other audio transformers have pinlike terminals that can be mounted on PC boards. Spec tables provide dc resistance values for primary and secondary windings to help you select the appropriate transformer for the particular matching application. Besides performing simple impedance matching, audio transformers can be used to step up or step down a signal voltage, convert a circuit from unbalanced to balanced and vice versa, block dc current in a circuit while allowing ac current to flow, and provide basic isolation between one device and another. Note that audio transformers have a maximum input level that cannot be exceeded without causing distortion. Also, audio transformers cannot step up a signal by more than about 25 dB when used in typical audio circuits. Because of this, an audio transformer cannot be substituted for a microphone preamp. If more than 25 dB of gain is required, an active preamp must be used instead of a transformer.

Air Core RF Transformers

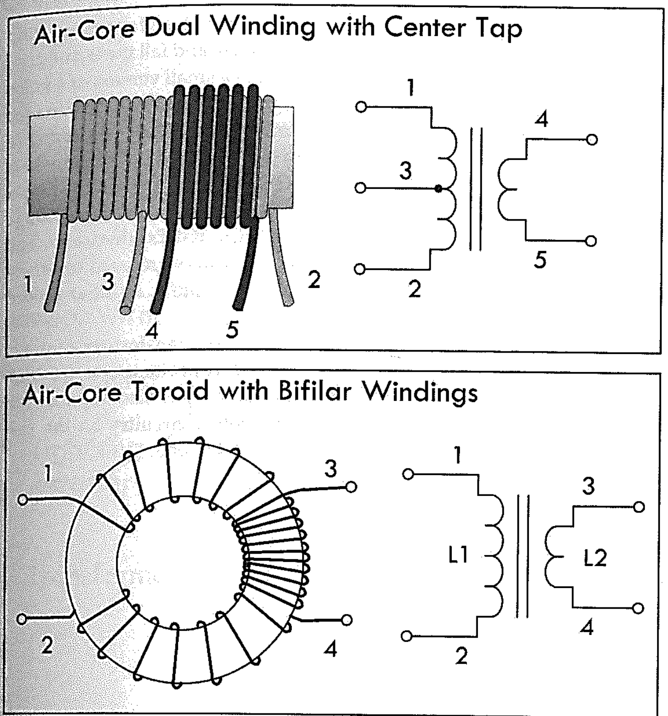


FIGURE 3.114

Air core transformers are special devices used in radio-frequency circuits. (They are used for RF coupling, such as antenna tuning and impedance matching.) Unlike steel or ferrite core transformers, the core is made from a nonmagnetic form, usually a hollow tube of plastic. The degree of coupling between windings in an air core transformer is much less than that of a steel core transformer; however, there are no losses associated with eddy currents, hysteresis, saturation, and so on, as is the case with magnetic cores. This becomes critically important in RF applications—at high frequencies, steel core transformers experience significant losses. Toroidal air core transformers aren't common nowadays, except in VHF (very high frequency) work. Today, special coupling networks and RF powdered-iron and ferrite toroids have generally replaced air cores, except in situations where the circuit handles very high power or the coils must be very temperature stable.

Ferrite and Powdered-Iron Toroidal Transformers

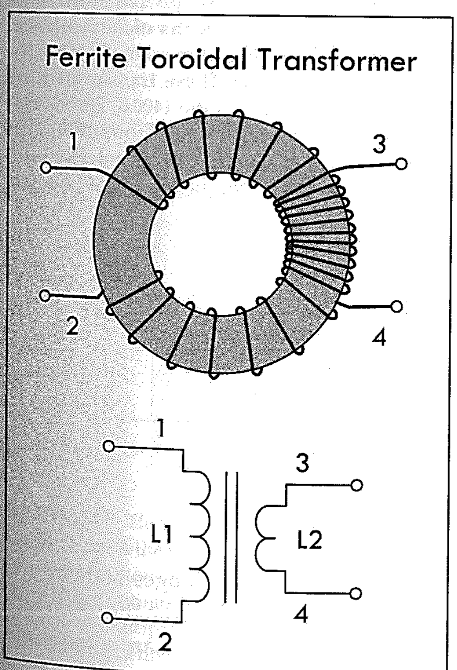


FIGURE 3.115

Toroidal ferrite and powdered-iron transformers are used from a few hundred hertz well into the UHF spectrum. The principal advantage of this type of core is self-shielding and low losses due to eddy currents. The permeability/size ratio is also very large, making them compact devices requiring fewer coil turns than traditional transformers. The most common ferrite toroid transformer is the conventional broadband transformer. Broadband transformers provide dc isolation between the primary and secondary circuits. The primary of a step-down impedance transformer is wound to occupy the entire core, with the secondary wound over the primary, as shown in Fig. 3.115. This style of transformer is frequently used in impedance matching. In standard broadcast radio receivers, these transformers operate in a frequency range from 530 to 1550 kHz. In shortwave receivers, RF transformers are subjected to frequencies up to about 20 MHz; in radar, it approaches upward of 200 MHz.

Pulse and Small Signal Transformers

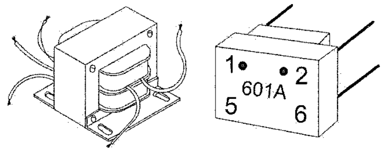


FIGURE 3.116

Pulse transformers are special transformers optimized for transmitting rectangular electrical pulses—ones with fast rise and fall times and constant amplitude. A small signal transformer is a small version of a pulse transformer. These devices are used in digital logic and telecom circuits, often for matching logic drivers to transmission lines. Medium-size power versions are used in power-control circuits such as camera flash controllers, while larger-power versions are used in electrical power distribution to interface low-voltage control circuitry with high-voltage power semiconductive gates, such as TRIACs, IGBTs, thyristors, and MOSFETs. Special high-voltage pulse transformers are used to generate high-power pulses for radar, particle accelerators, or other pulsed power applications.

To minimize pulse shape distortion, a pulse transformer requires very low leakage inductance and distributed capacitance, and a high open-circuit inductance. Low coupling capacitance is also important in power-pulse transformer applications to protect circuitry on the primary side from high-power transients created by load.

Current Transformers

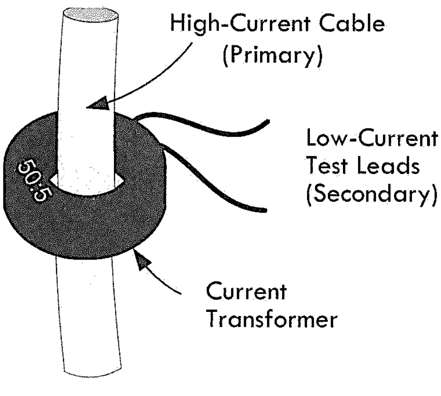


FIGURE 3.117

Current transformers are special devices used primarily to measure larger currents that would be too dangerous to measure with an ammeter. They are designed to provide a current in their secondary that is proportional to the current flowing in the primary. A typical current transformer resembles a toroidal core inductor with many secondary windings. The primary coil consists of simply passing a single cable-to-be-measured (insulated) through the center of the toroid. The output current through the secondary is many times smaller than the actual current through the cable (primary). These transformers are specified by their input and output current ratio (400:5, 2000:5, etc.) Current transformers designed for electrical supply applications are designed to drive 5-A (full-scale) meters. There are also wideband current transformers used to measure high-frequency waveforms and pulsed currents.

3.8.6 Transformer Applications

There are three principal uses for transformers: to transform voltages and currents from one level to another, to physically isolate the primary circuit from the secondary, and to transform circuit impedances from one level to another. Here are some examples in action.

Center-Tap Pole Transformer

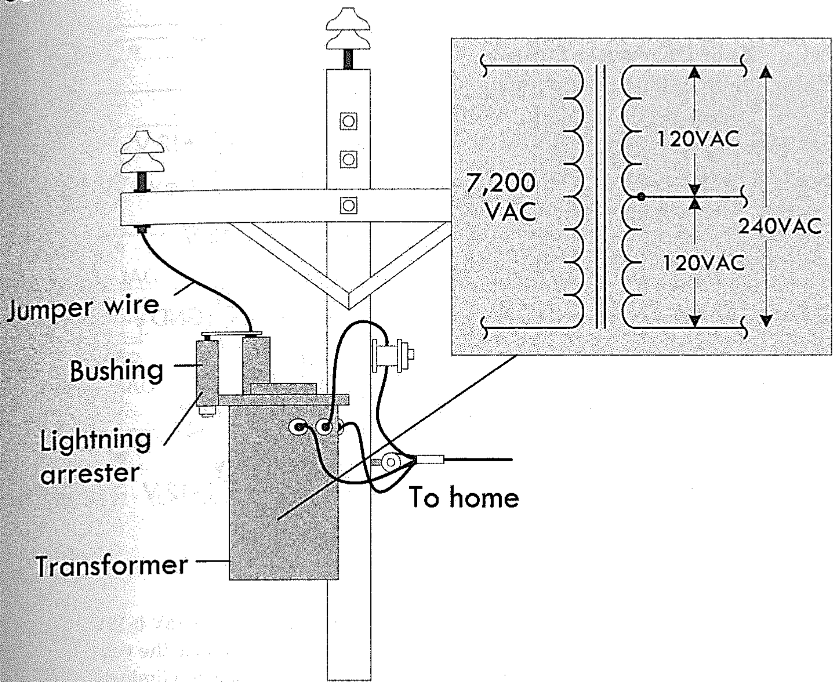


FIGURE 3.118 In the United States, main power lines carry ac voltages upward of several thousand volts. A center-tap pole transformer is used to step down the line voltage to 240 V. The tap then acts to break this voltage up into 120-V portions. Small appliances, such as TVs, lights, and hair dryers can use either the top line and the neutral line or the bottom line and the neutral line. (The neutral is grounded to a ground rod through a link between neutral and ground buses in the breaker box.) Larger appliances, such as stoves, refrigerators, and clothes dryers often make use of the 240-V terminals and often use the neutral terminal as well. See App. A for more on power distribution and home wiring.

Transformer Used for Landscape Lighting

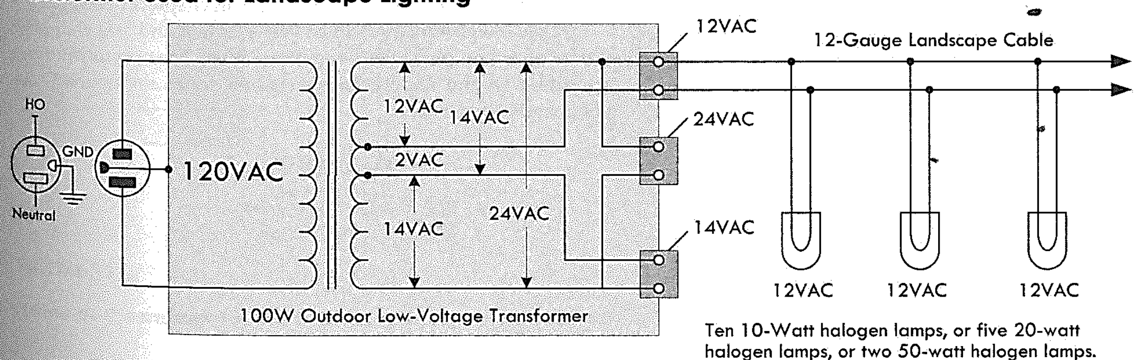


FIGURE 3.119 Here a step-down low-voltage transformer is used to drive quartz halogen landscape lamps. The lamps in this case don't care if the voltage is ac since the frequency (60 Hz) is too fast for there to be any noticeable variation in luminous output. Most commercial transformers used for landscape wiring, or for driving solenoid-powered sprinkler systems, will come with multiple outputs. This transformer provides 12-V, 24-V, and 14-V outputs. The 14-V output may be used to drive 12-V lamps if there is an anticipated voltage drop along long cable runs; the 24-V output may be used to drive 24-V devices. Note that the total load should not consume more power than the transformer's rated output capacity. For example, this 100-W transformer should not be used to drive more than, say, ten 10-watt lamps or five 20-watt lamps. Exceeding this will result in lamp dimming.

Step-Down Transformer for DC Power Supply

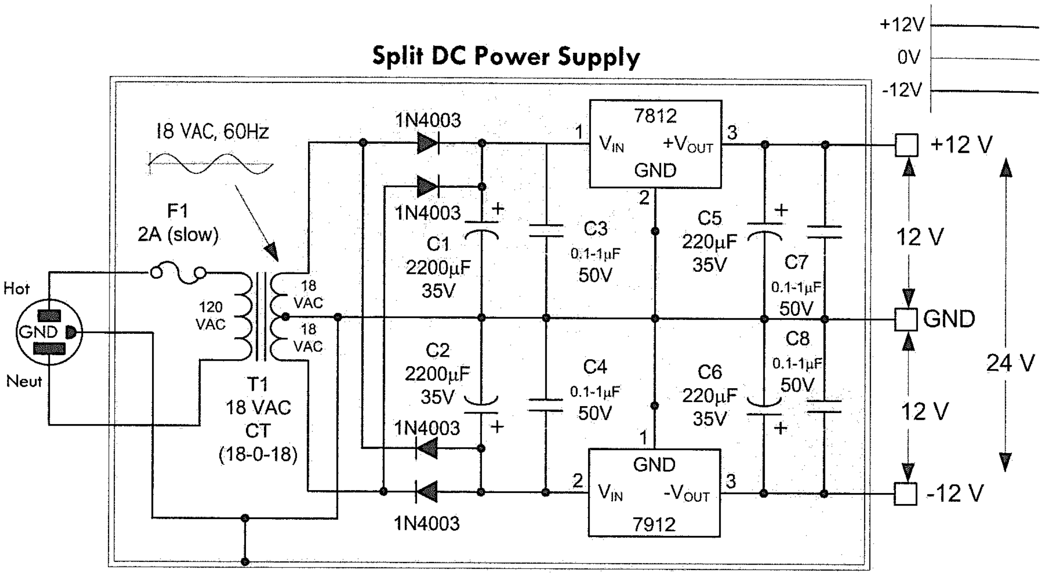
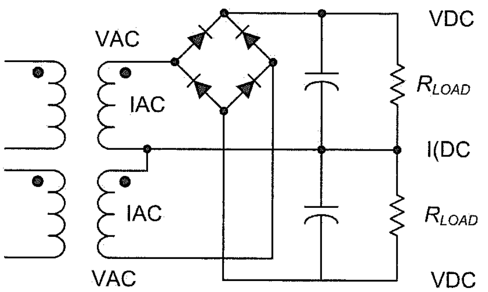


FIGURE 3.120 Transformers are essential ingredients in power supply design. Here a 120-V to 18V-0-18V center-tap transformer is used to create a split ±12-V dc power supply. The transformer acts to reduce the voltage to 18 VAC across each coil end and the center tap. The rectifier section built from diodes acts to eliminate negative swings in the upper positive section and eliminate positive swings in the lower section. Capacitors are thrown in to remove the pulsating dc and make the voltages appear dc. The regulators are used to set the dc voltages to exactly +12 V and −12 V. See Chap. 10 on power supplies for more details.

Various Transformer/Rectifier Arrangements

A. Dual Complementary Rectifier

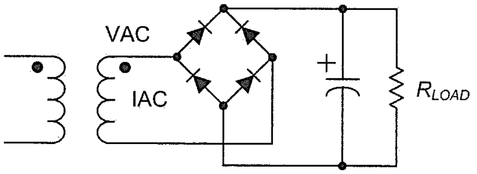


There are various ways in which to create dc power supplies. Figure 3.121 shows the four basic schemes used. Each scheme has its pros and cons, which are briefly described here and in greater detail in the sections on diodes and power supply in chapters to come.

(a) *Dual complementary rectifier:* Very efficient and best choice for two balanced outputs with a common return. The output windings are bifilar wound for precisely matched series resistances, coupling, and capacitance.

$$V_{AC} = 0.8 \times (V_{DC} + 2)$$
$$I_{AC} = 1.8 \times I_{DC}$$

B. Full-Wave Bridge

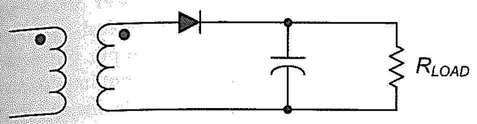


(b) *Full-wave bridge:* Most efficient use of transformer's secondary winding. Best for high-voltage outputs.

$$V_{AC} = 0.8 \times (V_{DC} + 2)$$
$$I_{AC} = 1.8 \times I_{DC}$$

FIGURE 3.121

C. Half-Wave Rectifier



(c) *Half-wave rectifier:* This design should be avoided for power supply design, as it is an inefficient use of the transformer. This arrangement causes the core to become polarized and to saturate in one direction.

D. Full-Wave Center Tap

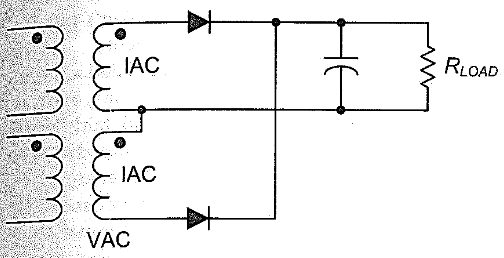


FIGURE 3.121 (*Continued*)

(d) *Full-wave center tap:* While more efficient than the half-wave rectifier circuit, the full wave does not make full use of secondaries, but is good for high-current, low-voltage applications, as there is only one diode drop per positive half cycle.

$$V_{AC} = 1.7 \times (V_{DC} + 1)$$
$$I_{AC} = 1.2 \times I_{DC}$$

Audio Impedance Matching

A. Need for Matching Impedances

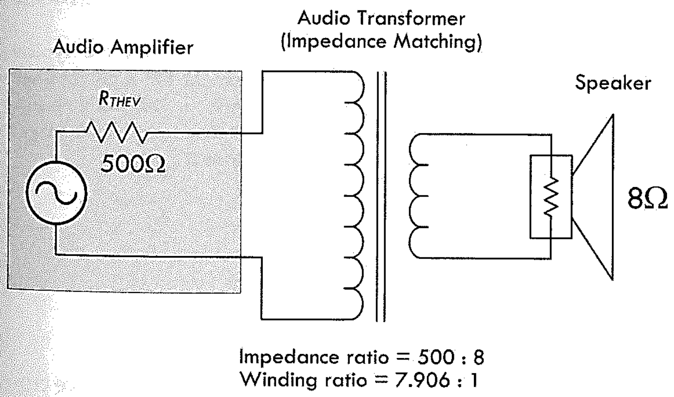


FIGURE 3.122

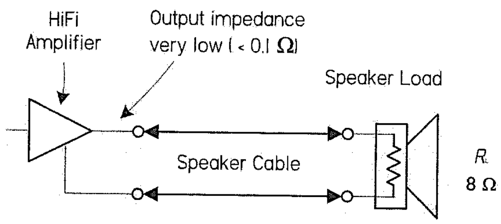
(a) Maximum power is transferred to a load if the load impedance is equal to the Thevenin impedance of the network supplying power. To supply maximum power transfer from the audio amplifier with an output impedance of 500 Ω to an 8-Ω speaker, we must properly match the load impedance with that of the output impedance (or Thevenin impedance) of the source. If we were not to match impedance and attempt to drive the 8-Ω speaker directly, the impedance mismatch would result in very poor (low peak power) performance. Also, the amplifier would dissipate considerable power in the form of heat as it tries to drive the low-impedance speaker.

When going from a high-impedance (high-voltage, low-current) source to a low-impedance (low-voltage, high-current) load, we need to use a step-down transformer. To determine the turns ratio required, we refer back to Eq. 5:

$$\frac{N_P}{N_S} = \sqrt{\frac{Z_P}{Z_S}} = \sqrt{\frac{500\ \Omega}{8\ \Omega}} = 7.906$$

In other words, the required winding ratio is 7.906:1. With such a transformer in place, the speaker will load the amplifier to just the right degree, drawing power at the correct voltage and current levels for the most efficient power transfer to load.

B. No Need for Matching



Virtually all audio power from amplifer is transferred into speaker.

C. Microphone Input Transformer

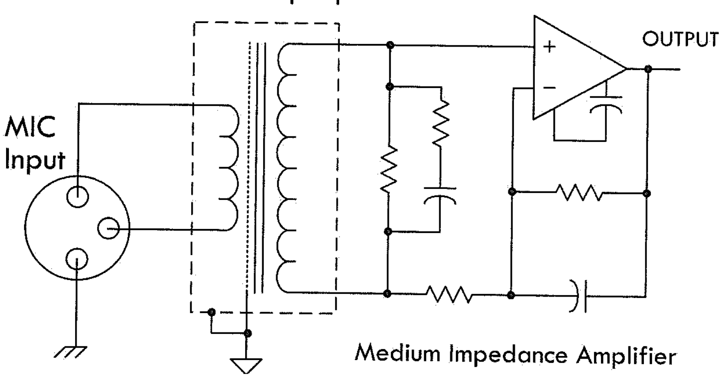


FIGURE 3.122 (*Continued*)

(b) Note that most hi-fi amplifier and speaker systems have amplifiers with output impedances much lower than the speaker impedance. A typical speaker impedance is 8 Ω, for example, but most hi-fi amplifiers have an output impedance of 0.1 Ω or less. This not only ensures that most of the audio energy is transferred to the speaker, but also that the amplifier's low output impedance provides good electrical damping for the speaker's moving voice coil—giving higher fidelity.

Older valve amplifiers needed a different form of impedance matching, because output valves generally had fairly fixed and relatively high output impedance so they couldn't deliver audio energy efficiently into the low load impedance of a typical speaker. So an output transformer had to be used to produce a closer impedance match. The transformer stepped up the impedance of the speaker, so that it gave the output valve an effective load of a few thousand ohms; this was at least comparable to the valve's own output impedance, so only a small amount of energy was wasted as heat in the valve.

(c) The only area in audio where impedance matching (of a different kind) tends to be important is with transducers such as microphones, gramophone pickups, and tape heads. Here, the transducer often needs to be provided with particular load impedance, but not in order to maximize power or signal transfer.

The diagram in (c) shows a typical matching arrangement for a microphone connected through a matching transformer to an input stage (unity gain stage) of an audio amplifier IC.

3.9 Fuses and Circuit Breakers

Fuses and circuit breakers are devices designed to protect circuits from excessive current flows, which are often a result of large currents that result from shorts or sudden power surges. A fuse contains a narrow strip of metal that is designed to melt when current flow exceeds its current rating, thereby interrupting power to the circuit. Once a fuse blows (wire melts), it must be replaced with a new one. A circuit breaker is a mechanical device that can be reset after it "blows." It contains a spring-loaded contact that is latched into position against another contact. When the current flow exceeds a breaker's current rating, a bimetallic strip heats up and bends. As the strip bends, it "trips" the latch, and the spring pulls the contacts apart. To reset the breaker, a button or rockerlike switch is pressed to compress the spring and reset the latch.

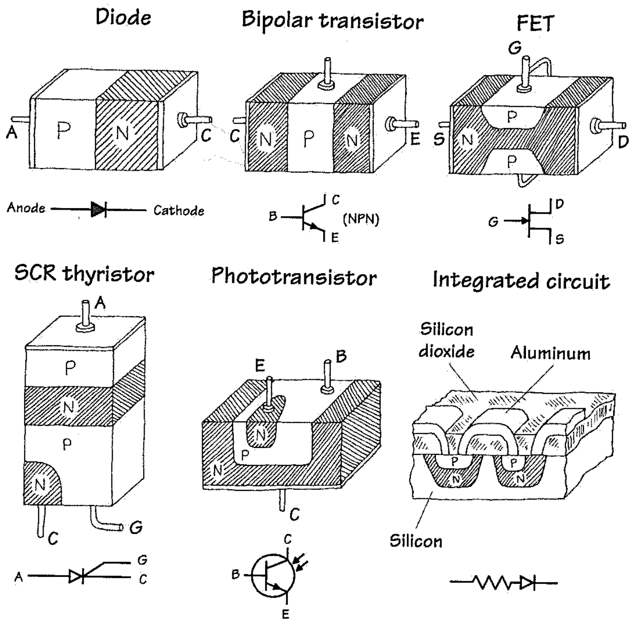


FIGURE 4.9

4.2 Diodes

A *diode* is a two-lead semiconductor device that acts as a one-way gate to electric current flow. When a diode's *anode* lead is made more positive in voltage than its *cathode* lead—a condition referred to as *forward biasing*—current is permitted to flow through the device. However, if the polarities are reversed (the anode is made more negative in voltage than the cathode)—a condition referred to as *reversed biasing*—the diode acts to block current flow.

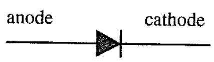


FIGURE 4.10

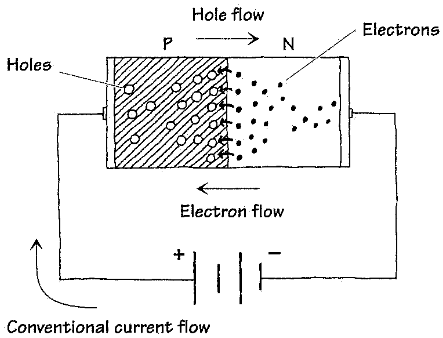
Diodes are used most commonly in circuits that convert ac voltages and current into dc voltages and currents (e.g., ac/dc power supply). Diodes are also used in voltage-multiplier circuits, voltage-shifting circuits, voltage-limiting circuits, and voltage-regulator circuits.

4.2.1 How p-n Junction Diodes Work

A *pn-junction diode* (*rectifier diode*) is formed by sandwiching together *n*-type and *p*-type silicon. In practice, manufacturers grow an *n*-type silicon crystal and then abruptly change it to a *p*-type crystal. Then either a glass or plastic coating is placed around the joined crystals. The *n* side is the cathode end, and the *p* side is the anode end.

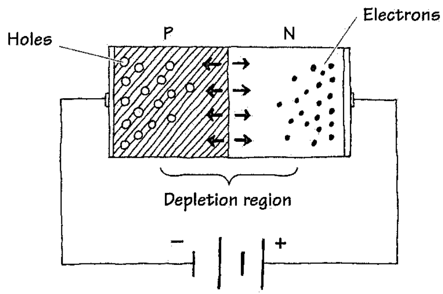
The trick to making a one-way gate from these combined pieces of silicon is getting the charge carriers in both the *n*-type and *p*-type silicon to interact in such a way that when a voltage is applied across the device, current will flow in only one direction. Both *n*-type and *p*-type silicon conducts electric current; one does it with electrons (*n*-type), and the other does it with holes (*p*-type). Now the important feature to note here, which makes a diode work (act as a one-way gate), is the manner in which the two types of charge carriers interact with each other and how they interact with an applied electrical field supplied by an external voltage across its leads. Below is an explanation describing how the charge carriers interact with each other and with the electrical field to create an electrically controlled one-way gate.

Forward-Biased ("Open Door")



When a diode is connected to a battery, as shown here, electrons from the n side and holes from the p side are forced toward the center (pn interface) by the electrical field supplied by the battery. The electrons and holes combine, and current passes through the diode. When a diode is arranged in this way, it is said to be *forward-biased.*

Reverse-Biased ("Closed Door")



When a diode is connected to a battery, as shown here, holes in the n side are forced to the left, while electrons in the p side are forced to the right. This results in an empty zone around the p-n junction that is free of charge carriers, better known as the *depletion region.* This depletion region has an insulative quality that prevents current from flowing through the diode. When a diode is arranged in this way, it is said to be *reverse-biased.*

FIGURE 4.11

A diode's one-way gate feature does not work all the time. That is, it takes a minimal voltage to turn it on when it is placed in forward-biased direction. Typically for silicon diodes, an applied voltage of 0.6 V or greater is needed; otherwise, the diode will not conduct. This feature of requiring a specific voltage to turn the diode on may seem like a drawback, but in fact, this feature becomes very useful in terms of acting as a voltage-sensitive switch. Germanium diodes, unlike silicon diodes, often require a forward-biasing voltage of only 0.2 V or greater for conduction to occur. Figure 4.12 shows how the current and voltage are related for silicon and germanium diodes.

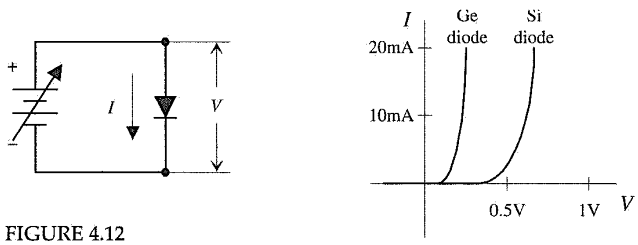


FIGURE 4.12

Another fundamental difference between silicon diodes and germanium diodes, besides the forward-biasing voltages, is their ability to dissipate heat. Silicon diodes do a better job of dissipating heat than germanium diodes. When germanium diodes get hot—temperatures exceeding 85°C—the thermal vibrations affect the physics inside the crystalline structure to a point where normal diode operation becomes unreliable. Above 85°C, germanium diodes become worthless.

4.2.2 Diode Water Analogy

A *diode* (or *rectifier*) acts as a one-way gate to current flow—see the water analogy in Fig. 4.13. Current flows in the direction of the arrow, from anode (+) to cathode (−), provided the *forward voltage* V_F across it exceeds what's called the *junction threshold voltage.* As a general rule of thumb, silicon p-n junction diodes have about a 0.6-V threshold, germanium diodes a 0.2-V threshold, and Schottky diodes a 0.4-V threshold. However, don't take this rule too seriously, because with real-life components, you'll find these thresholds may be a few tenths of a volt off. For example, it's entirely possible for a p-n junction diode's threshold to be anywhere between 0.6 and 1.7 V; for germanium, 0.2 to 0.4 V; and for Schottky diodes, 0.15 to 0.9 V.

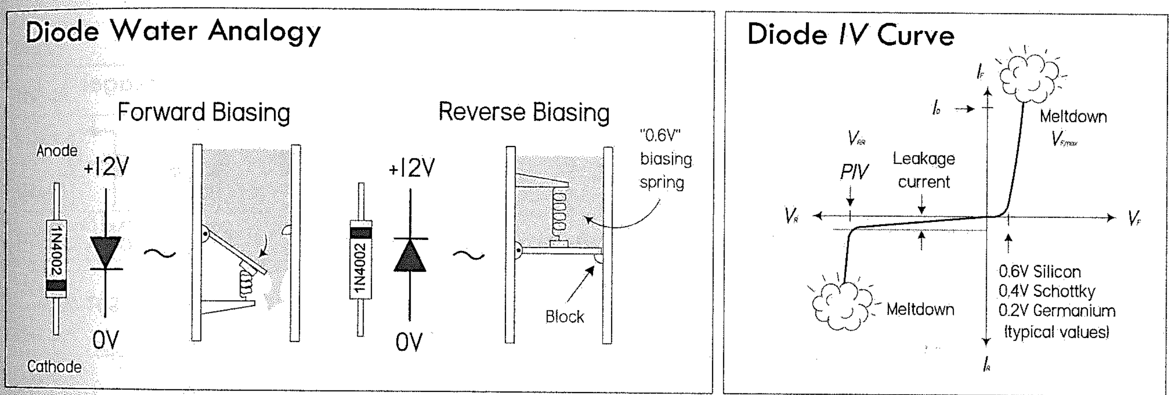


FIGURE 4.13

In terms of limits, avoid supplying a diode with a forward current I_F beyond its *peak current rating* (I_{Omax}). If you do, you'll get internal junction meltdown. Likewise avoid applying a reverse voltage V_R any bigger than the diode's *peak inverse voltage* (PIV) *rating*. This, too, can render a diode worthless. See the graph in Fig. 4.13.

4.2.3 Kinds of Rectifiers/Diodes

There are numerous types of diodes, each specifically designed to work better in one application or another. Diodes for high-power applications (switching, power supplies, etc.) which draw lots of current or rectify high voltages typically go by the name *rectifier diodes.* On the other hand, diodes that go by names such as *signal, switching, fast recovery,* or *high speed* are designed to provide a low internal capacitance (they store less charge but usually have weaker junctions for large currents). At high speeds, these diodes will reduce RC switching time constants, which means fewer time delays and lower signal losses.

Schottky diodes have a particularly low junction capacitance and faster switching (~10 ns) when compared to silicon p-n junction diodes due to their special metal-semiconductor-junction interface. They also have a lower junction threshold voltage—as low as 0.15 V, but usually a bit more (0.4 V average). Both these characteristics enable them to detect low-voltage, high-frequency signals that ordinary p-n junction diodes would not see. (A Schottky with a 0.3-V threshold can pass signals greater than 0.3 V, but a silicon p-n junction diode with a 0.7-V threshold can only pass signals greater than 0.7 V). For this reason, Schottky diodes are very popular in low-voltage signal rectifiers in RF circuits, signal switching in telecommunication, small dc/dc converters, small low-voltage power supplies, protection circuits, and voltage clamping arrangements. Their high-current density and low voltage drop also make them great in power supplies, since they generate less heat, requiring smaller heat sinks to be used in design. Therefore, you'll find both rectifier and fast-switching Schottky diodes listed in the catalogs.

In terms of *germanium diodes*, they are used mostly in RF signal detection and low-level logic design due to their small threshold voltage of about 0.2 V. You do not see them in high-current rectifying applications, since they are weaker and leak more than silicon diodes when temperatures rise. In many applications, a good Schottky signal diode can replace a germanium diode.

Common Diode/Rectifier Packages

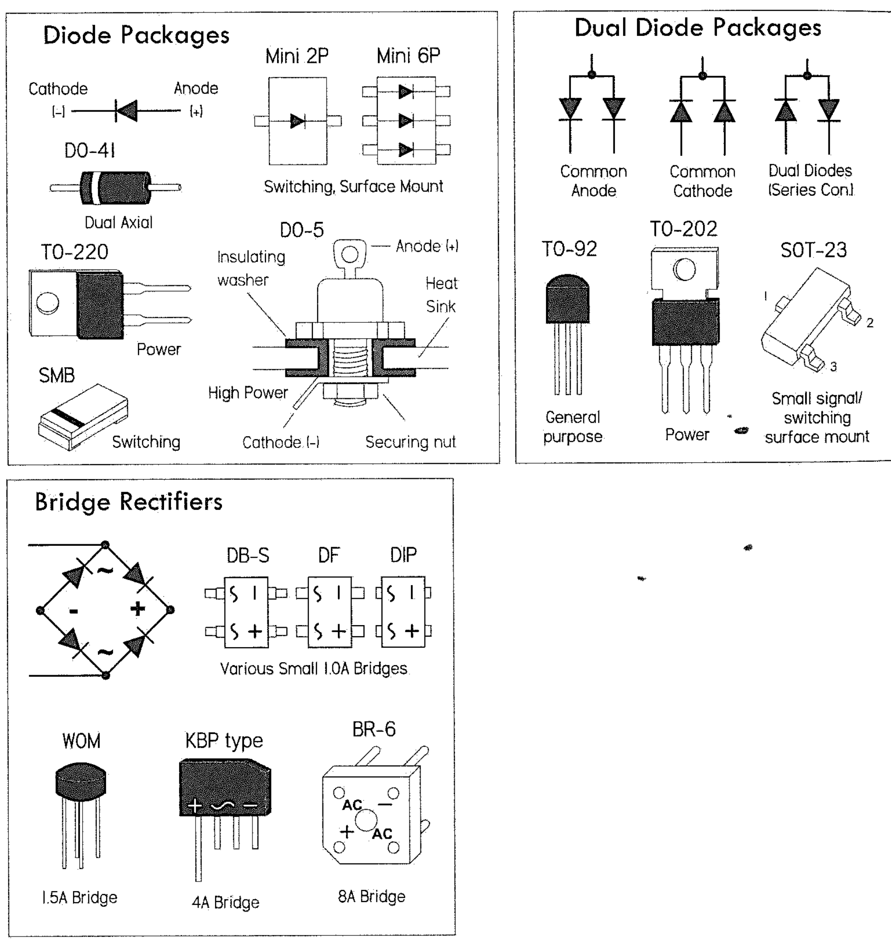


FIGURE 4.14

4.2.4 Practical Considerations

Five major specs to consider when choosing a diode are peak inverse voltage, PIV; forward current-handling capacity, $I_{O(\max)}$; response speed t_R (time for diode to switch on and off); reverse-leakage current, $I_{R(\max)}$; and maximum forward-voltage drop, $V_{F(\max)}$. Each of these characteristics can be manipulated during the manufacturing process to produce the various special-purpose diodes. In rectification applications (e.g., power supplies, transient protection), the most important specs are PIV and current rating. The peak negative voltages that are stopped by the diode must be smaller in magnitude than the PIV, and the peak current through the diode must be less than $I_{O(\max)}$. In fast and low-voltage applications, t_R and V_F become important characteristics to consider. In the applications section that follows, you'll get a better sense of what all these specs mean.

TABLE 4.1 Selection of Popular Diodes

DEVICE	TYPE	PEAK INVERSE VOLTAGE PIV (V)	MAX. FORWARD CURRENT $I_{O\,(MAX)}$	MAX. REVERSE CURRENT $I_{R\,(MAX)}$	PEAK SURGE CURRENT I_{FSM}	MAX. VOLTAGE DROP V_F (V)
1N34A	Signal (Ge)	60	8.5 mA	15 µA		1.0
1N67A	Signal (Ge)	100	4.0 mA	5 µA		1.0
1N191	Signal (Ge)	90	5.0 mA			1.0
1N914	Fast Switch	90	75 mA	25 nA		0.8
1N4148	Signal	75	10 mA	25 nA	450 mA	1.0
1N4445	Signal	100	100 mA	50 nA		1.0
1N4001	Rectifier	50	1 A	0.03 mA	30 A	1.1
1N4002	Rectifier	100	1 A	0.03 mA	30A	1.1
1N4003	Rectifier	200	1 A	0.03 mA	30 A	1.1
1N4004	Rectifier	400	1 A	0.03 mA	30 A	1.1
1N4007	Rectifier	1000	1 A	0.03 mA	30 A	1.1
1N5002	Rectifier	200	3 A	500 µA	200 A	
1N5006	Rectifier	600	3 A	500 µA	200 A	
1N5008	Rectifier	1000	3 A	500 µA	200 A	
1N5817	Schottky	20	1 A	1 mA	25 A	0.75
1N5818	Schottky	30	1 A		25 A	
1N5819	Schottky	40	1 A		25 A	0.90
1N5822	Schottky	40	3 A			
1N6263	Schottky	70	15 mA		50 mA	0.41
5052-2823	Schottky	8	1 mA	100 nA	10 mA	0.34

Diodes come in a variety of different packages. Some are standard two-lead deals; others are high-power packages with heat-sink attachments (e.g., TO-220, DO-5). Some come in surface-mount packages, and others contain diode arrays in IC form, used for switching applications. Dual-diode and diode-bridge rectifiers also come in a variety of package sizes and shapes for varying power levels.

4.2.5 Diode/Rectifier Applications

Voltage Dropper

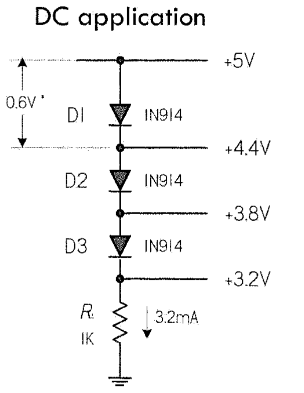


FIGURE 4.15

When current passes through a diode, there is a voltage drop across it of about 0.6 V, for a silicon p-n junction diode. (Germanium diodes have around a 0.2-V drop; Schottky, around 0.4V—all these values vary slightly, depending on the specific diode used.) By placing a number of diodes in series, the total voltage drop across the combination is the sum of the individual voltage drops across each diode. Voltage droppers are often used in circuits where a fixed small voltage difference between two sections of a circuit is needed. Unlike resistors that can be used to lower the voltage, the diode arrangement typically doesn't waste as much power to resistive heating and will supply a stiffer regulated voltage that is less dependent on current variations. Later in this chapter, you'll see that a single zener diode can often replace a multiple series diode arrangement like the one shown here.

Voltage Regulator

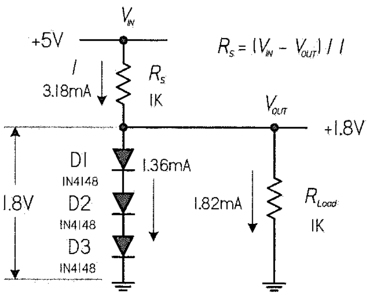


FIGURE 4.16

Here's a spin-off of the last circuit, making use of the three diodes to create a simple regulated (steady) low-voltage output equal to the sum of the threshold voltages of the diodes: 0.6V + 0.6V + 0.6V = 1.8V. The series resistor is used to set the desired output current (I) and should be equal to:

$$R_S = \frac{V_{in} - V_{out}}{I}$$

Diodes and the series resistor must have proper power ratings for the amount of current drawn. Use $P = IV$. Note that for higher-power critical voltage sources, you'll typically use a zener diode regulator or, more commonly, a special regulator IC instead.

Reverse-Polarity Protection

Battery reversal or power polarity reversal can be fatal to portable equipment. The best design is to use a mechanical block to safeguard against reverse installation. However, even momentarily fumbling around and making contacts can lead to problems. This is especially true for one or more single-cell battery applications that use AA-alkaline, NiCad, and NiMH batteries. For these systems you must ensure that any flow of reverse current is low enough to avoid damaging the circuit or the battery.

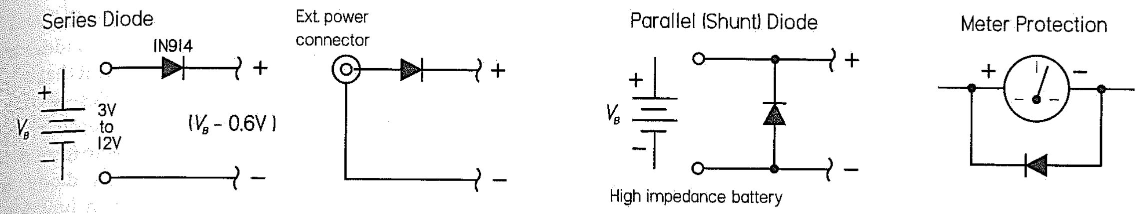


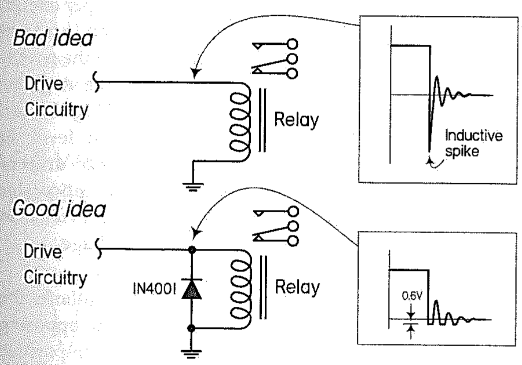
FIGURE 4.17 *Series diode:* This is the simplest battery-reversal protection. It can be used with external power connections, too—plug-and-jack. The diode allows current from a correctly installed battery to flow to load, but blocks current flow from a backward-installed battery. The drawback with a series diode is that the diode must handle the full load current. Also, the forward voltage drop of the diode shortens the equipment's operating time—cuts off about 0.6V right away. Schottky diodes with low thresholds can do better. See Problem 1 at the end of Section 4.2 for another reverse-polarity protection circuit.

Parallel diode: In applications that call for alkaline or other batteries that have high output impedances, you can guard against reverse installations by using a parallel (shunt) diode, while eliminating the diode's voltage drop. This approach protects the load but draws high current from the backward-installed battery. The diode must be properly rated for current and power. Another application of the parallel diode is in meter protection, where it acts to divert large currents entering the negative terminal of the meter.

Note: In more sophisticated battery-powered designs, special ICs or transistor arrangements are used to provide essentially zero voltage drop protection, while providing a number of other special features, such as reverse polarity protection, thermal shutdown, and voltage level monitor.

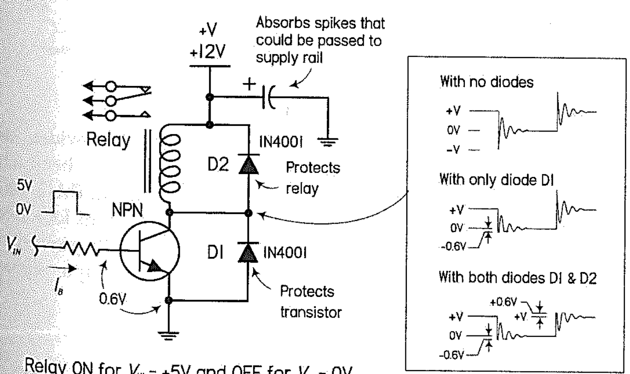
Transient Suppression with Fly-Back Diodes

Transient Protection



When current flowing through an inductor is suddenly switched off, the collapsing magnetic field will generate a high-voltage spike in the inductor's coils. This voltage spike or transient may have an amplitude of hundreds or even thousands of volts. This is particularly common within relay coils. A diode—referred to as a fly-back diode for this type of application—placed across the relay's coil can protect neighboring circuitry by providing a short circuit for the high-voltage spike. It also protects the relay's mechanical contacts, which often get viciously slapped shut during an inductive spike. Notice, however, that the diode is ineffective during turn-on time. Select a rectifier diode with sufficient power ratings (1N4001, 1N4002, etc.). Schottky rectifiers (e.g., 1N5818) work well, too.

Transistor Relay Driver with Protection Diodes



Relay ON for V_{IN} = +5V and OFF for V_{IN} = 0V

FIGURE 4.18

Here's a more practical example for driving a relay that contains an extra diode placed across a transistor driver in order to protect the transistor from damage due to inductive spikes generated from the relay's coil when the transistor is turned off. This arrangement also deadens spikes during turn-on time. This dual diode arrangement is sometimes used in voltage regulator circuits, where one diode is wired from the output to the input and another is wired from ground to the output. This prevents any attached loads from sending damaging spikes back into the IC's output.

Motor Inductive Kickback Protection

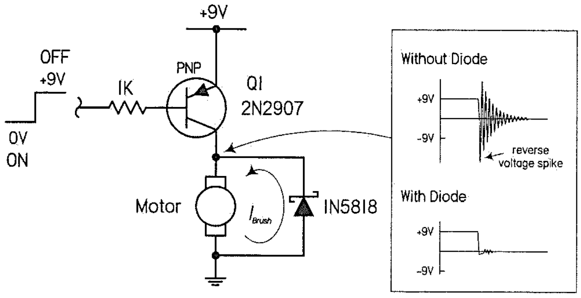


FIGURE 4.18 (*Continued*)

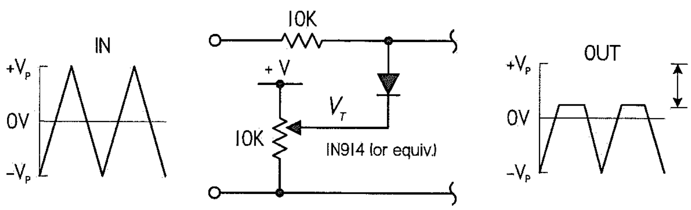
Here's another example of how inductive kickback from a motor that is running and then suddenly turned off can generate a voltage transient that can potentially damage connected electronics—in this case, a 2N2907 transistor. The diode reroutes or shorts the induced voltage to the opposite terminal of the motor. Here a 1N5818 Schottky diode is used—though you could use other p-n junction types, too. The Schottky diode happens to be a bit faster and will clip the transient voltage a bit lower down—at around 0.4 V.

Note: Devices such as TVs and varistors are specially designed for transient suppression. See the section on transient suppressors later in this chapter.

Diode Clamps

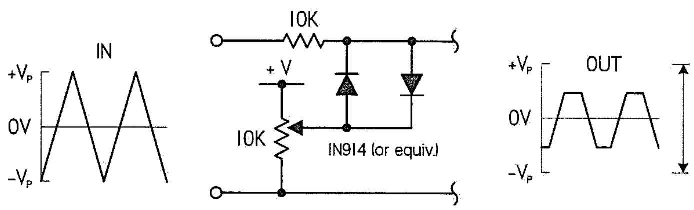
Diode clamps are used to clip signal levels, or they can shift an ac waveform up or down to create what's called a pulsing dc waveform—one that doesn't cross the 0-V reference.

Adjustable Waveform Clipper



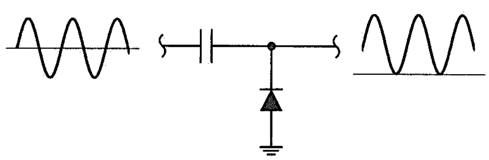
In the adjustable waveform clipper circuit, the maximum output is clipped to a level determined by the resistance of the potentiometer. The idea is to set the negative end of the diode to about 0.6V higher than the maximum desired output level, to account for the forward voltage drop of the diode. That's what the potentiometer is intended to do. +V should be a volt or so higher than the peak input voltage.

Adjustable Attenuator



The adjustable attenuator is similar to the last circuit, but the additional opposing diode allows for clipping on both positive and negative swings. You can use separate potentiometers if you want separate positive and negative clipping level control. +V should be a volt or so higher than the peak input voltage.

Diode Voltage Clamp (DC Restoration)



The diode voltage clamp provides dc restoration of a signal that has been ac-coupled (capacitively coupled). This is important for circuits whose inputs look like diodes (e.g., a transistor with grounded emitter); otherwise, an ac-couple signal would fade away.

FIGURE 4.19

Diode Switch

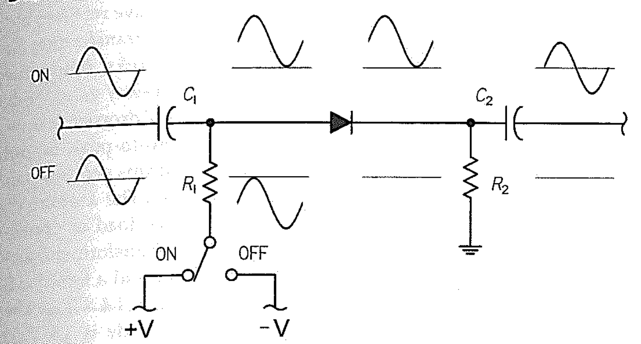
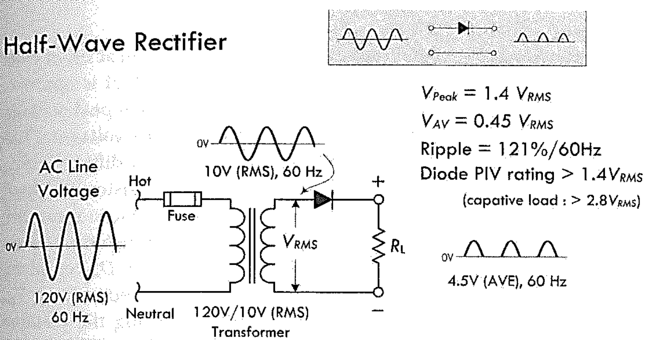


FIGURE 4.19 *(Continued)*

In the diode switch circuit, an input waveform is ac-coupled to the diode through C_1 at the input and C_2 at the output. R_2 provides a reference for the bias voltage. When the switch is thrown to the ON position, a positive dc voltage is added to the signal, forward-biasing the diode and allowing the signal to pass. When the switch is thrown to the OFF position, the negative dc voltage added to the signal reverse-biases the diode and the signal does not get through.

Rectifier Circuits

Half-Wave Rectifier



Half-wave rectifier: Used to transform an ac signal into pulsing dc by blocking the negative swings. A filter is usually added (especially in low-frequency applications) to the output to smooth out the pulses and provide a higher average dc voltage. The peak inverse voltage (PIV)—the voltage that the rectifier must withstand when it isn't conducting—varies with load, and must be greater than the peak ac voltage ($1.4 \times V_{rms}$). With a capacitor filter and a load drawing little or no current, it can rise to $2.8 \times V_{rms}$ (capacitor voltage minus the peak negative swing of voltage from transformer secondary).

Full-Wave Center-Tap Rectifier

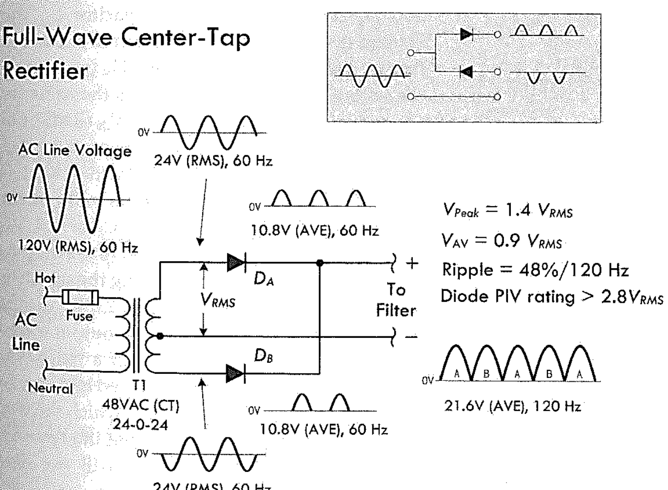


FIGURE 4.20

Full-wave center-tap rectifier: This commonly used circuit is basically two combined half-wave rectifiers that transform both halves of an ac wave into a pulsing dc signal. When designing power supplies, you need only two diodes, provided you use a center-tap transformer. The average output voltage is 0.9 V_{rms} of half the transformer secondary; this is the maximum that can be obtained with a suitable choke-input filter. The peak output voltage is $1.4 \times V_{rms}$ of half the transformer secondary; this is the maximum voltage that can be obtained from a capacitor-input filter. The PIV impressed on each diode is independent of the type of load at the output. This is because the peak inverse voltage condition occurs when diode A conducts and diode B does not conduct. As the cathodes of diodes A and B reach a positive peak (1.4 V_{rms}), the anode of diode B is at the negative peak, also 1.4 V_{rms}, but in the opposite direction. The total peak inverse voltage is therefore 2.8 V_{rms}. The frequency of the output pulses is twice that of the half-wave rectifier, and thus comparatively less filtering is required. Since the diodes work alternately, each handles half of the load current. The current rating of each rectifier need be only half the total current drawn from the supply.

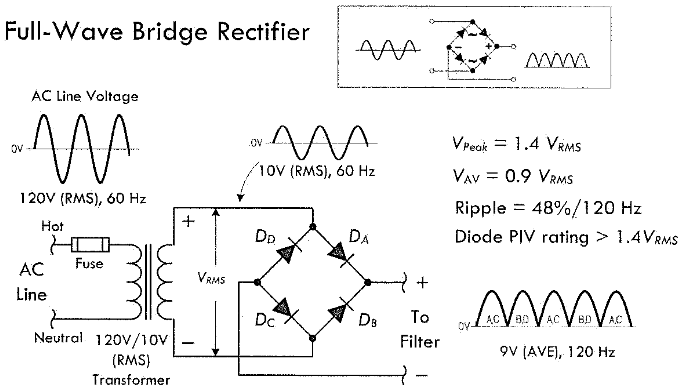


FIGURE 4.20 (*Continued*)

Full-wave bridge rectifier: This rectifier produces a similar output as the last full-wave rectifier, but doesn't require a center-tap transformer. To understand how the device works, follow the current through the diode one-way gates. Note that there will be at least a 1.2-V drop from zero-to-peak input voltage to zero-to-peak output voltage (there are two 0.6-V drops across a pair of diodes during a half cycle). The average dc output voltage into a resistive load or choke-input filter is $0.9 \times V_{rms}$ of the transformer's secondary; with a capacitor filter and a light load, the maximum output voltage is $1.4 \times V_{rms}$. The inverse voltage across each diode is 1.4 V_{rms}; there the PIV of each diode is more than 1.4 V_{rms}.

See the following text for the pros and cons of the various rectifier configurations.

Voltage Multiplier Circuits

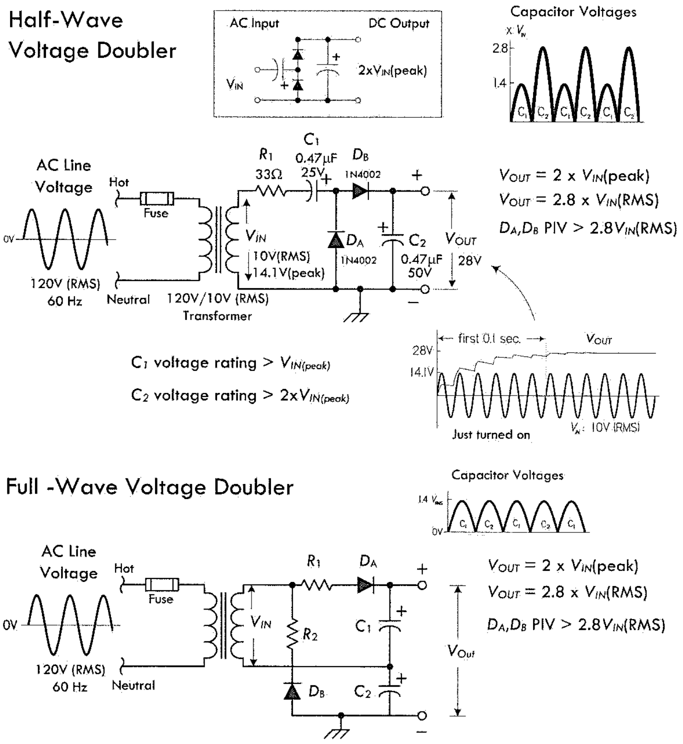


FIGURE 4.21

Half-wave voltage doubler: Takes an ac input voltage and outputs a dc voltage that is approximately equal to twice the input's peak voltage (or 2.8 times the input's RMS voltage). (The actual multiplication factor may differ slightly, depending on the capacitor, resistor, and load values.) In this circuit, we take V_{IN} to mean the secondary voltage from the transformer. During the first negative half cycle, D_A conducts, charging C_1 to the peak rectified voltage V_{IN} (peak), or 1.4 V_{IN} (RMS). During the positive half cycle of the secondary voltage, D_A is cut off and D_B conducts, charging capacitor C_2. The voltage delivered to C_2 is the sum of the transformer peak secondary voltage, V_{IN} (peak) plus the voltage stored in C_1, which is the same, so the sum gives 2 V_{IN} (peak), or 2.8 V_{IN} (RMS). On the next negative cycle, D_B is nonconducting and C_2 will discharge into an attached load. If no load is present, the capacitors will remain charged—C_1 to 1.4 V_{IN} (RMS), C_2 to 2.8 V_{IN} (RMS). When a load is connected to the output, the voltage across C_2 drops during the negative half cycle and is recharged up to 2.8 V_{IN} (RMS) during the positive half cycle. The output waveform across C_2 resembles that of a half-wave rectifier circuit because C_2 is pulsed once every cycle. Figure 4.21 shows levels to which the two capacitors are charged throughout the cycle. In actual operation, the capacitor will not discharge all the way to zero, as shown.

Full-wave doubler: During the positive half cycle of the transformer secondary voltage, D_A conducts discharging C_1 to V_{IN} (peak) or 1.4 V_{IN} (RMS). During the negative half cycle, D_B conducts, charging C_2 to the same value. The output voltage is the sum of the two capacitor voltages, which will be 2 V_{IN} (peak) or 2.8 V_{IN} (RMS) under no-load conditions. The graph shows each capacitor alternately receiving a charge once per cycle. The effective filter capacitance is that of C_1 and C_2 in series, which is less than the capacitance of either C_1 or C_2 alone. R_1 and R_2 are used to limit the surge current through the rectifiers. Their values are based on the transformer voltage and the rectifier surge current rating, since at the instant the power supply is turned on, the filter capacitors look like a short-circuited load. Provided the limiting resistors can withstand the surge current, their current-handling capacity is based on the maximum load current from the supply. The peak inverse voltage across each diode is 2.8 V_{IN} (RMS).

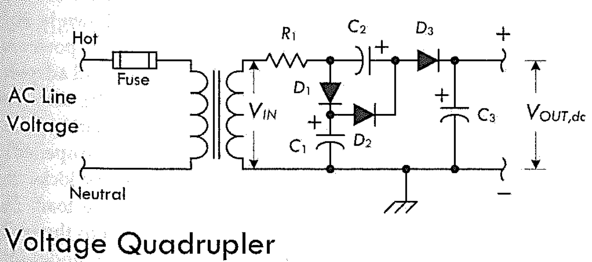
Pros and Cons of the Rectifier Circuits

Comparing the full-wave center-tap rectifier and the full-wave bridge rectifier, you'll notice both circuits have almost the same rectifier requirements. However, the center-tap version has half the number of diodes as the bridge. These diodes will require twice the maximum inverse voltage ratings of the bridge diodes (PIV > 2.8 V_{rms}, as opposed to >1.4 V_{rms}). The diode current ratings are identical for the two circuits. The bridge makes better use of the transformer's secondary than the center-tap rectifier, since the transformer's full winding supplies power during both half cycles, while each half of the center-tap circuit's secondary provides power only during its positive half-cycle. This is often referred to as the *transformer utilization factor,* which is unity for the bridge configuration and 0.5 for the full-wave center-tap configuration.

The bridge rectifier is often not as popular as the full-wave center-tap rectifier in high-current, low-voltage applications. This is because the two forward-conducting series-diode voltage drops in the bridge introduce a volt or more of additional loss, and thus consume more power (heat loss) than a single diode would within a full-wave rectifier.

In regard to the half-wave configuration, it's rarely used in 60-Hz rectification for other than bias supplies. It does see considerable use, however, in high-frequency switching power supplies in what are called forward converter and fly-back converter topologies.

Voltage Tripler



Voltage Quadrupler

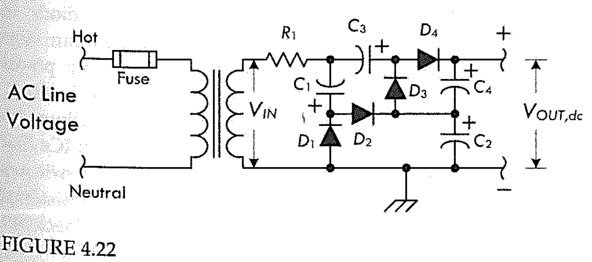


FIGURE 4.22

Voltage tripler: On one half of the ac cycle, C_1 and C_3 are charged to V_{IN} (peak) through D_1, D_2, and D_3. On the opposite half of the cycle, D_2 conducts and C_2 is charged to twice V_{IN} (peak), because it sees the transformer plus the charge in C_1 as its source. (D_1 is cut off during this half cycle.) At the same time, D_3 conducts, and with the transformer and the charge in C_2 as the source, C_3 is charged to three times the transformer voltage.

Voltage quadrupler: Works in a similar manner as the previous one. In both these circuits, the output voltage will approach an exact multiple of the peak ac voltage when the output current drain is low and the capacitance values high.

Capacitance values are usually 20 to 50 μF, depending on the output current drain. Capacitor dc ratings are related to V_{IN} (peak) by:

C_1—Greater than V_{IN} (peak) or 0.7 V_{IN} (RMS)
C_2—Greater than 2 V_{IN} (peak) or 1.4 V_{IN} (RMS)
C_3—Greater than 3 V_{IN} (peak) or 2.1 V_{IN} (RMS)
C_4—Greater than 4 V_{IN} (peak) or 2.8 V_{IN} (RMS)

Diode Logic Gates

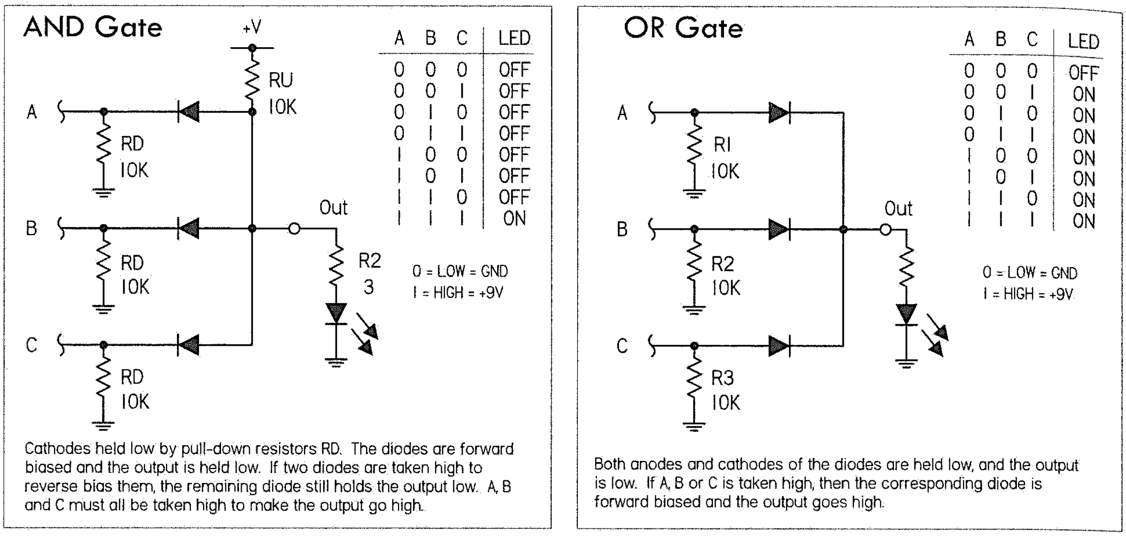


FIGURE 4.23 These simple diode logic gates are useful for learning the basics of digital logic, and can be also be adapted for non-logic-level electronics (e.g., higher-voltage and power analog-like circuits)—see the following battery-backup example (Fig. 4.24). When designing high-power circuits, make sure your diodes have the proper PIV and current ratings for the job. It's also important to note that the recovery time of power diodes won't be as fast as digital logic ICs or fast-switching diodes.

Battery Backup

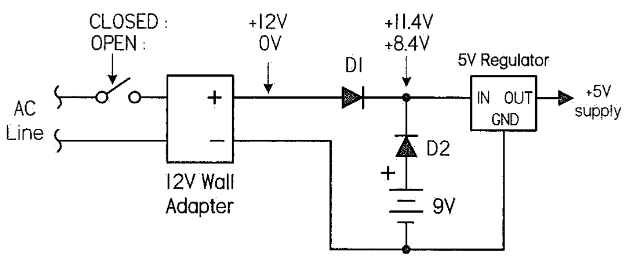


FIGURE 4.24

Devices are powered by a wall adapter with battery backup, typically diode-OR for the battery and wall-adapter connections, as shown in Fig. 4.24. Normally if the switch is closed, power is delivered to the load from the 12-V wall adapter through D_1; D_2 is reverse-biased (off), since its negative end is 2.4V more positive than its positive end. If power is interrupted (switch opened), D_1 stops conducting, and the battery kicks in, sending current through D_2 into the load; D_1 blocks current from flowing back into the wall adapter. There is a penalty for using diodes for battery backup, however, since the diode in series with the battery limits the minimum voltage at which the battery can supply power (around a 0.6-V drop for silicon p-n junction, 0.4 V for Schottky). Better battery-backup designs implement transistors or special ICs that contain an internal comparator which switches over battery power through a low-resistance transistor without the 0.6-V penalty. Check out MAXIM's website for some example ICs.

AM Detector

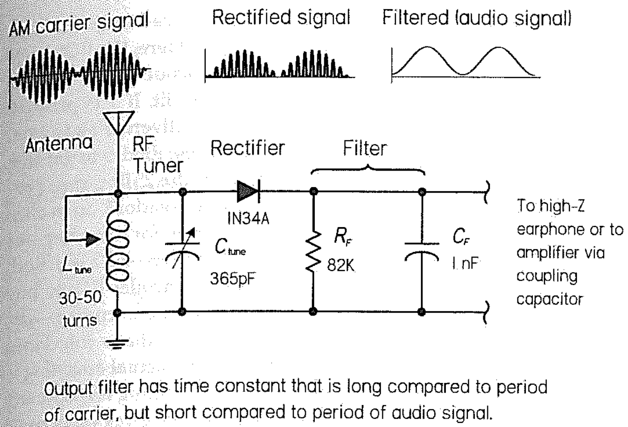


FIGURE 4.25

Diodes are often used in the detection of amplitude modulated (AM) signals, as demonstrated in the simple AM radio in Fig. 4.25. Within an AM radio signal, an RF carrier signal of constant high frequency (550 to 1700 kHz) has been amplitude modulated with an audio signal (10 to 20,000 Hz). The audio information is located in duplicate in both upper and lower sidebands, or the envelope of the AM signal. Here, an antenna and LC-tuning circuit act to "resonate" in on the specific carrier frequency of interest (transform radio signal into corresponding electrical signal). A signal diode (e.g., 1N34) is then used to rectify out the negative portion of the incoming signal so it can be manipulated by the next dc stages. The rectified signal is then stripped of its high-frequency carrier by passing through a low-pass filter. The output signal is the audio signal. This signal can be used to drive a simple crystal earpiece, a modern sensitive headphone, or a telephone receiver earpiece. (Low-impedance earphones or speakers will require additional amplification via a coupling capacitor of 1 μF or so.)

Schottky Diode Termination

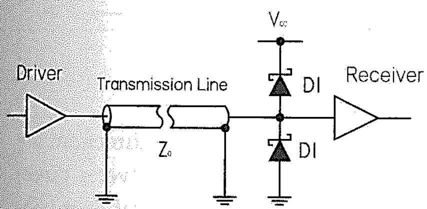


FIGURE 4.26

Schottky diode termination can be used to counteract the high-speed transmission line effects, which cause over/undershoots from signal reflections, reduce noise margins, and destroy timing. These types of distortions can cause false triggering in clock lines and erroneous data on address, data, and control lines, as well as contribute significantly to clock and signal jitter. For applications where transmission line impedance is variable or unknown, it's not possible to specify a termination resistance value—an alternative is needed. The Schottky diode termination has the ability to maintain signal integrity, save significant power, and permit flexible system design. A Schottky diode termination consists of a diode series combination, where one diode clamps to V_{CC}, or supply voltage, and the other to ground. The diodes at the end of the transmission line minimize the effect of reflection via a clamping operation. The top diode clamps voltages that exceed V_{CC} by the forward-bias threshold limit. This clamping will minimize overshoots caused by reflections. For falling edge signals, a clamp diode to ground affects a similar termination. This clamping function does not depend on matching the transmission line characteristic impedance, making it useful in situations where the line impedance is unknown or variable.

Read-Only Memory (ROM)

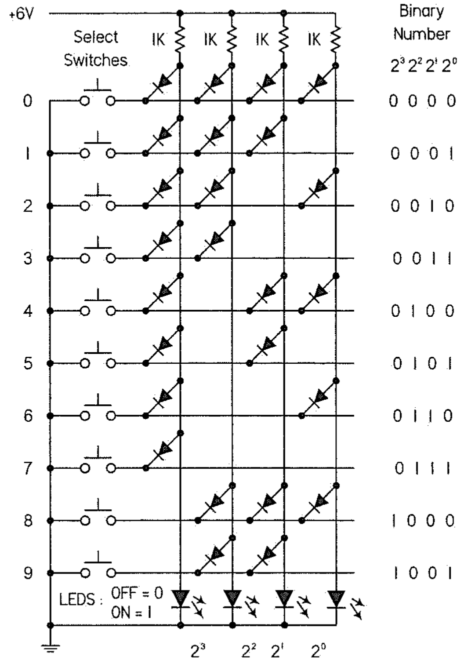


FIGURE 4.27

This circuit is a simple read-only memory (ROM) made with diodes. Here, the ROM acts as a decimal-to-binary encoder. With no buttons pressed, all LEDs are lit. If 1 is pressed, current from the supply is diverted away from the 2^3, 2^2, and 2^1 lines via the diodes to ground, but is allowed to pass on the 2^0 line, thus presenting 0001 on the LED readout. In reality, using a PROM such as this for encoding—or anything else, for that matter—isn't practical. Usually there is a special encoder IC you buy or you simply take care of the encoding—say, with a multiplexed keypad that's interfaced with a microcontroller—the actual encoding is taken care of at the programming level. At any rate, it's a fun circuit, and this gives you a basic idea of how read-only memory works.

4.2.6 Zener Diodes

A zener diode acts like a two-way gate to current flow. In the forward direction, it's easy to push open; only about 0.6 V—just like a standard diode. In the reverse direction, it's harder to push open; it requires a voltage equal to the *zener's breakdown voltage* V_Z. This breakdown voltage can be anywhere between 1.8 and 200 V, depending on the model (1N5225B = 3.0 V, 1N4733A = 5.1 V, 1N4739A = 9.1 V, etc.). Power ratings vary from around 0.25 to 50 W.

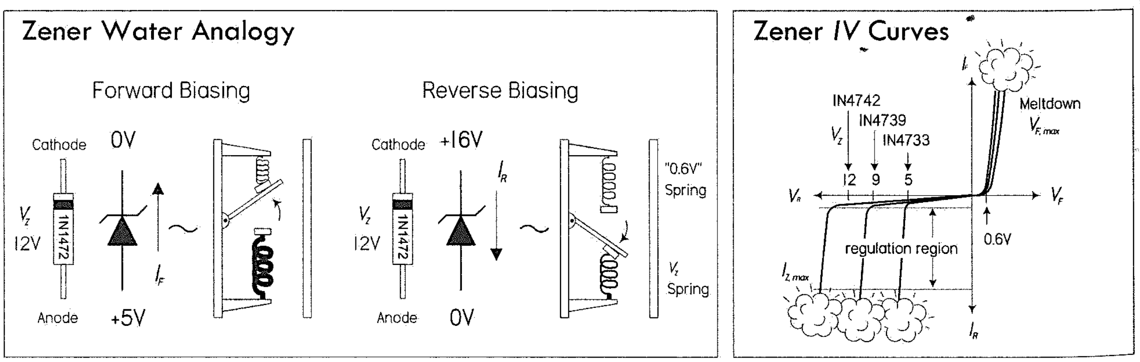


FIGURE 4.28 The reverse-bias direction is the standard configuration used in most applications, along with a series resistor. In this configuration, the zener diode acts like a pressure release value, passing as much current as necessary to keep the voltage across it constant, equal to V_Z. In other words, it can act as a voltage regulator. See application in Fig. 4.29.

Zener Voltage Regulator

These circuits act as voltage regulators, preventing any supply voltage or load current variations from pulling down the voltage supplied to the load. The following explains how the zener diode compensates for both line and load variations.

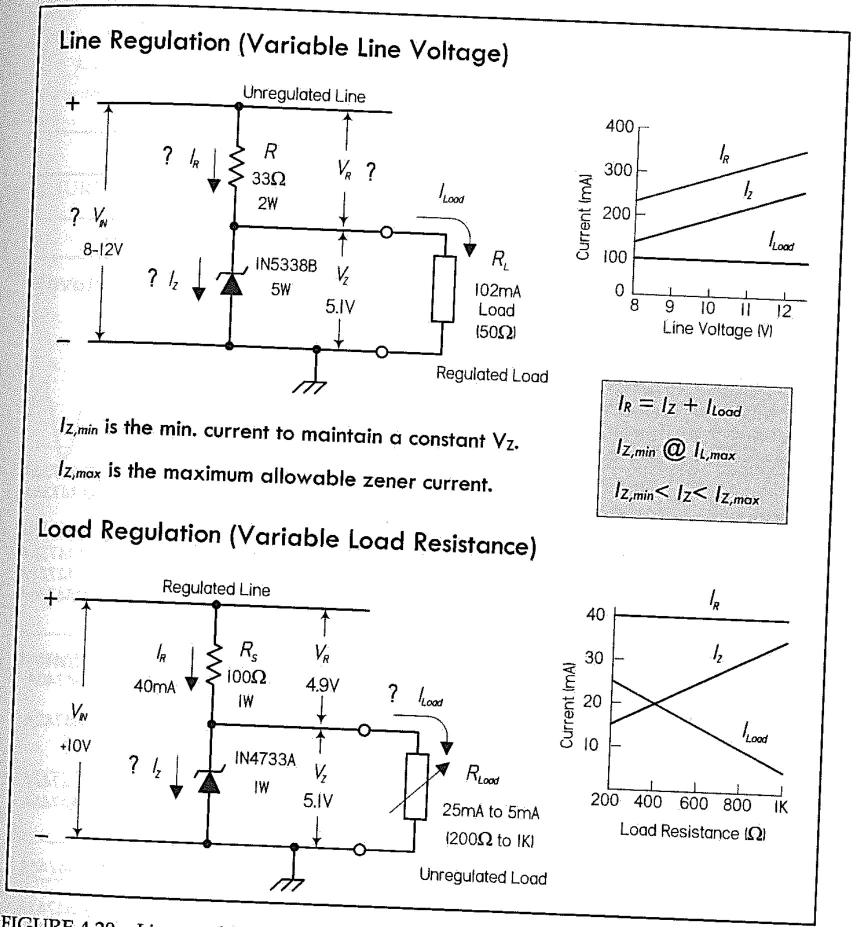


FIGURE 4.29 *Line regulation example:* If the line voltage increases, it will cause an increase in line current. Since the load voltage is constant (maintained by the zener), the increase in line current will result in an increase in zener current, thus maintaining a constant load current. If the line voltage decreases, less line current results, and less current is passed by the zener. See graph in Fig. 4.29, top right.

Load regulation example: If the load voltage attempts to decrease as a result of decreased load resistance (increased load current), the increase in load current is offset by the decrease in zener current. The voltage across the load will remain fairly constant. If the load voltage attempts to increase due to an increase in load resistance (decrease in load current), the decrease in load current is offset by an increase in zener current. See graph in Fig. 4.29, bottom right.

The following formulas can be used when selecting the component values:

$$R_S = \frac{V_{\text{in,min}} - V_Z}{I_{Z,\text{min}} + I_{L,\text{max}}}; \quad P_R = \frac{(V_{\text{in,max}} - V_Z)^2}{R_S}$$

$$P_{Z,\text{max}} = V_Z \frac{(V_{\text{in,max}} - V_Z)}{R_S}$$

See Problem 3 at end of this section for a design example.

Note that zener regulators are somewhat temperature dependent and aren't the best choice for critical applications. A linear regulator IC, though more expensive, is less dependent on temperature variations due to an internal error amplifier. They do typically use an internal zener to supply the reference, nonetheless.

Selection of Popular Zener Diodes

Zener Diode Packages

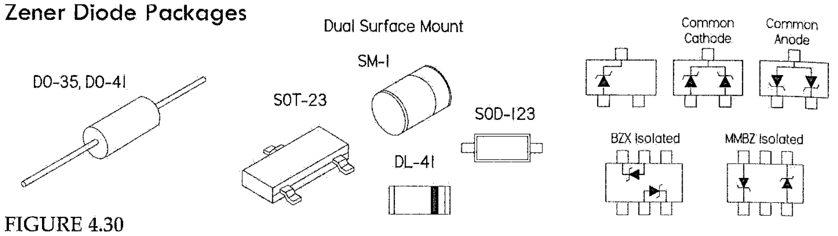


FIGURE 4.30

TABLE 4.2

ZENER VOLTS VZ VOLTS	CASE AND POWER RATING					
	AXIAL LEAD			SURFACE MOUNT		
	500 MW	1 W	5 W	200 MW	500 MW	1 W
2.4	1N5221B			BZX84C2V4, MMBZ5221B	BZT52C2V4	
2.7	1N5222B			BZX84C2V7	BZT52C2V7	
3.0	1N5225B			BZX84C3V0, MMBZ52251B	BZT52C3V0, ZMM5225B	
3.3	1N5226B	1N4728A	1N5333B	BZX84C3V3, MMBZ5226B	BZT52C3V3, ZMM5226B	ZM4728A
3.6	1N5227B	1N4729A	1N5334B	BZX84C3V6, MMBZ5227B	BZT52C3V6, ZMM5227B	
3.9	1N5228B	1N4730A	1N5335B	BZX84C3V9, MMBZ5228B	BZT52C3V9, ZMM5228B	ZM4730A
4.3	1N5229B	1N4731A	1N5336B		BZT52C4V3, ZMM5229B	ZM4731A
4.7	1N5230B	1N4732A	1N5337B	BZX84C4V7, MMBZ5230B	BZT52C4V7, ZMM5230B	ZM4732A
5.1	1N5231B	1N4733A	1N5338B	BZX84C5V1, MMBZ5231B	BZT52C5V1, ZMM5231B	SMAZ5V1, ZM4733A
5.6	1N5232B	1N4734A	1N5339B	BZX84C5V6, MMBZ5232B	BZT52C5V6, ZMM5232B	SMAZ5V6, ZM4734A
6.0	1N5233B		1N5340B		BZT52C6V0, ZMM52330B	
6.2	1N5234B	1N4735A	1N5341B	BZX84C6V2, MMBZ5234B	BZT52C6V2, ZMM5234B	SMAZ6V2, ZM4735A
6.8	1N5235B	1N4736A	1N5342B	BZX84C6V8, MMBZ5235B	BZT52C6V8, ZMM5235B	SMAZ6V8, ZM4736A
7.5	1N5236B	1N4737A	1N5343B	BZX84C7V5, MMBZ5236B	BZT52C7V5, ZMM5236B	SMAZ7V5, ZM4737A
8.2	1N5237B	1N4738A	1N5344B	BZX84C8V2, MMBZ5237B	BZT52C8V2, ZMM5237B	SMAZ8V2, ZM4738A
8.7	1N5238B		1N5345B		BZT52C8V7, ZMM5238B	
9.1	1N5239B	1N4739A	1N5346B	BZX84C9V1, MMBZ5239B	BZT52C9V1, ZMM5239B	SMAZ9V1, ZM4739A
10.0	1N5240B	1N4740A	1N5347B	BZX84C10	BZT52C10, ZMM5240B	SMAZ10, ZM4740A
11	1N5241B	1N4741A	1N5348B	BZX84C11, MMBZ5241B	BZT52C11, ZMM5241B	ZM4741A
12	1N5242B	1N4742A	1N5349B	BZX84C12, MMBZ5242B	BZT52C12, ZMM5242B	SMAZ12, ZM4742A
13	1N5243B	1N4743A	1N5350B	MMBZ5243B	BZT52C13, ZMM5243B	ZM4743A
14	1N5244B		1N5351B		BZT52C14, ZMM5244B	
15	1N5245B	1N4744A	1N5352B	BZX84C15, MMBZ5245B	BZT52C15, ZMM5245B	SMAZ15, ZM4744A
16	1N5246B	1N4745A	1N5353B	BZX84C16, MMBZ5246B	BZT52C16, ZMM5246B	SMAZ16, ZM4745A
17	1N5247B		1N5354B		ZMM5247B	
18	1N5248B	1N4746A	1N5355B	BZX84C18, MMBZ5248B	BZT52C18, ZMM5248B	SMAZ18, ZM4746A
19	1N5249B		1N5356B		ZMM5249B	
20	1N5250B	1N4747A	1N5357B	BZX84C20, MMBZ5250B	BZT52C20, ZMM5250B	SMAZ20, ZM4747A
22	1N5251B	1N4748A	1N5358B	BZX84C22, MMBZ5251B	BZT52C22, ZMM5251B	SMAZ22, ZM4748A
24	1N5252B	1N4749A	1N5359B	BZX84C24, MMBZ5252B	BZT52C24, ZMM5252B	SMAZ24, ZM4749A
25	1N5253B		1N5360B		ZMM5253B	
27	1N5254B	1N4750A	1N5361B	BZX84C27, MMBZ5254B	BZT52C27, ZMM5254B	SMAZ27, ZM4750A
28	1N5255B		1N5362B	MMBZ5255B	ZMM5255B	
30	1N5256B	1N4751A	1N5363B	BZX84C30	BZT52C30, ZMM5256B	SMAZ30, ZM4751A
33	1N5257B	1N4752A	1N5364B	BZX84C33	BZT52C33, ZMM5257B	SMAZ33, ZM4752A
36	1N5258B	1N4753A	1N5365B	BZX84C36, MMBZ5258B	BZT52C36, ZMM5258B	SMAZ36, ZM4753A
39	1N5259B	1N4754A	1N5366B	BZX84C39, MMBZ5259B	BZT52C39, ZMM5259B	SMAZ39, ZM4754A
43	1N5260B	1N4755A	1N5367B		BZT52C43, ZMM5260B	ZM4755A
47	1N5261B	1N4756A	1N5368B		BZT52C47, ZMM5261B	ZM4756A
51	1N5262B	1N4757A	1N5369B		BZT52C51, ZMM5262B	ZM4757A
56	1N5263B	1N4758A	1N5370B			ZM4758A
60	1N5264B		1N5371B			
62	1N5265B	1N4759A	1N5372B		ZMM5265B	ZM4759A
68	1N5266B	1N4760A	1N5373B		ZMM5266B	ZM4760A
75	1N5267B	1N4761A	1N5374B			ZM4761A
82	1N5268B	1N4762A	1N5375B			ZM4762A
87	1N5269B					
91	1N5270B	1N4763A	1N5377B			ZM4763A
100	1N5271B	1N4764A	1N5378B			ZM4764A

4.2.7 Zener Diode Applications

Split Supply from Single Transformer Winding

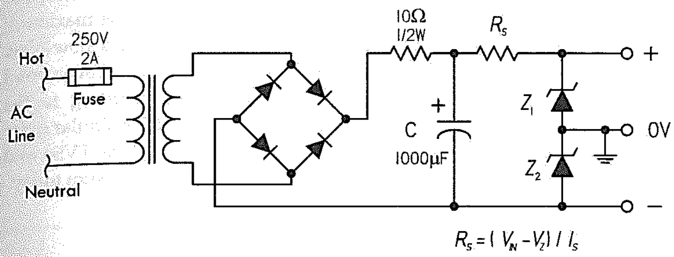


FIGURE 4.31

Here's a method for obtaining a split supply from a non-center-tapped transformer using two zener diodes. Z_1 and Z_2 are selected of equal voltage and power rating for desired split voltage and load. As with the previous example, the temperature dependency of the zener diodes makes this arrangement less accurate than a supply that uses two separate regulator ICs. However, it's a simple alternative for noncritical applications. See Chap. 10 on power supplies.

Waveform Modifier and Limiter

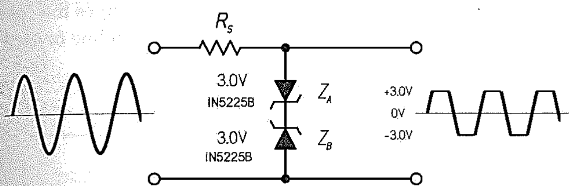


FIGURE 4.32

Two opposing zener diodes act to clip both halves of an input signal. Here a sine wave is converted to a near squarewave. Besides acting to reshape a waveform, this arrangement can also be placed across the output terminal of a dc power supply to prevent unwanted voltage transients from reaching an attached load. The breakdown voltages in that case must be greater than the supply voltage, but smaller than the maximum allowable transient voltage. A single bidirectional TVS does the same thing—see the section on transient suppressors.

Voltage Shifter

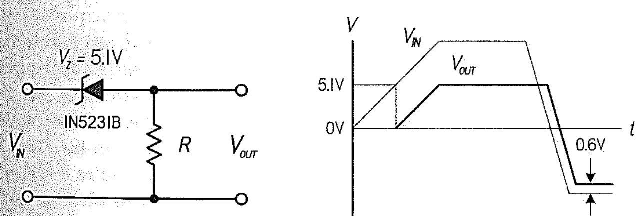


FIGURE 4.33

This circuit shifts the input voltage down by an amount equal to the breakdown voltage of the zener diode. As the input goes positive, the zener doesn't go into breakdown until it reaches 5.1 V (for the 1N5281B). After that, the output follows the input, but shifted 5.1 V below it. When the input goes negative, the output will follow the input, but shifted by 0.6 V—the forward threshold voltage drop of the zener.

Voltage Regulator Booster

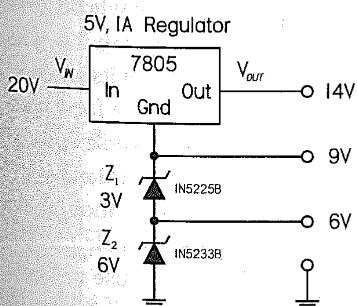


FIGURE 4.34

Zener diodes can be used to raise the level of a voltage regulator and obtain different regulated voltage outputs. Here 3-V and 6-V zener diodes are placed in series to push the reference ground of a 5-V regulator IC up 9 V to a total of 14 V. Note that in real designs, capacitors may be required at the input and output. See the section on voltage regulator ICs.

Overvoltage Protection

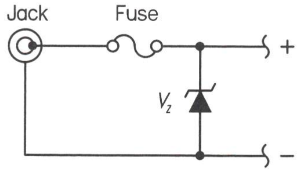


FIGURE 4.35

If excessive voltage is applied to the jack (say, via an incorrectly rated wall plug-in supply), the zener diode will conduct until the fuse is blown. The breakdown voltage of the zener should be slightly above the maximum tolerable voltage that the load can handle. Either a fast- or a slow-blow fuse can be used, depending on the sensitivity of the load. The current and voltage ratings of the fuse must be selected according to the expected limits of the application. Note that there are other, similar over-voltage protection designs that use special devices, such as TVSs and Varistors. These devices are cheap and are very popular in design today.

Increasing Wattage Rating of Zener

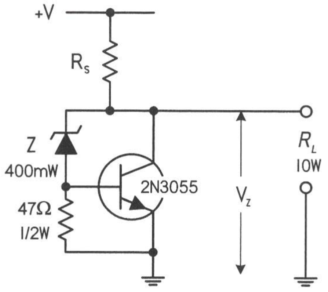


FIGURE 4.36

Here's a simple circuit that effectively increases the wattage ratting (current-handling capacity) of a zener diode by letting a power transistor take care of the majority of the regulating current. The zener itself takes a small portion of the total current and creates a base voltage/current (with the help of the base-to-ground resistor) that changes the collector-to-emitter current flow according to any variations in line or load current.

Simple LED Voltmeter

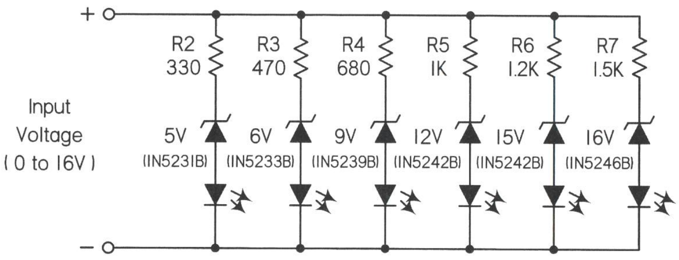


FIGURE 4.37

Here's a simple circuit voltmeter that uses the sequence of zener diodes with increasing breakdown voltages. LEDs glow in sequence as the input voltage rises. It's okay to use different zener diodes so long as the series resistors limit current through LED to a safe level. Most LEDs are happiest around 20 mA or so. You can calculate the worst-case scenario to be at the 5-V LED leg when V_{in} = 16 V. If you're looking for more sophistication, you can always use an analog-to-digital converter, along with a microcontroller and LCD or LED display.

4.2.8 Varactor Diodes (Variable Capacitance Diodes)

A *varactor* or variable capacitance diode (also called a *varicap*) is a diode whose junction capacitance can be altered with an applied reverse voltage. In this way, it acts as a variable capacitor. As the applied reverse voltage increases, the width of its junction increases, which decreases its capacitance. The typical capacitance range for varactors ranges from a few picofarads to over 100 pF, with a maximum reverse voltage range from a few volts to close to a hundred volts, depending on device. (Many standard diodes and zener diodes can be used as inexpensive varactor diodes, though the relationship between reverse voltage and capacitance isn't always as reliable.)

The low capacitance levels provided by a varactor usually limit its use to high-frequency RF circuits, where the applied voltage is used to change the capacitance of an oscillator circuit. The reverse voltage may be applied via a tuning potentiometer, which acts to change the overall frequency of an oscillator, or it may be applied by a modulating signal (e.g., audio signal), which acts to FM-modulate the oscillator's high-frequency carrier. See the examples that follow.

When designing with varactor diodes, the reverse-bias voltage must be absolutely free of noise, since any variation in the bias voltage will cause changes in capacitance. Unwanted frequency shifts or instability will result if the reverse-bias voltage is noisy. Filter capacitors are used to limit such noise.

Varactors come in both single and dual forms. The dual varactor configuration contains two varactors in series-opposing, with common anodes and separate cathodes. In this configuration, the varactors acts as series capacitors that change capacitance levels together when a voltage is applied to the common anode lead. See "Oscillator with Pot-Controlled Varactor Tuning."

FM Modulator

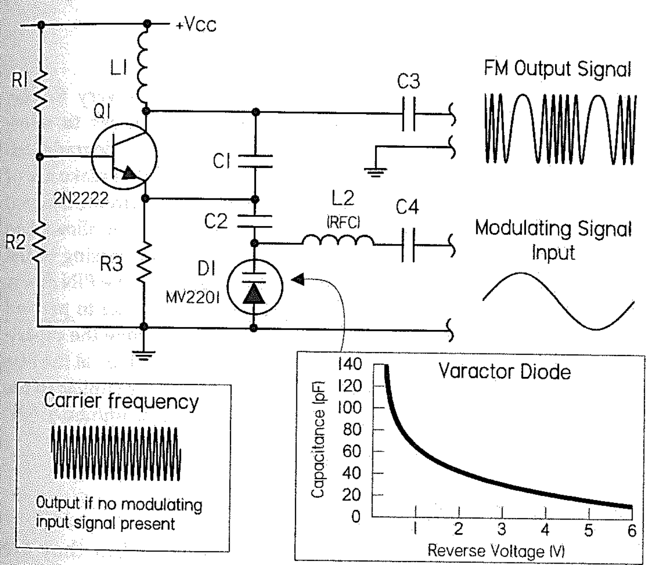


FIGURE 4.38

FM modulation: FM (frequency modulation) is produced when the frequency of a carrier is changed instantaneously according to the magnitude of an applied modulating signal. (The frequency of the carrier is usually in the megahertz, while the modulating signal is typically in the hertz to kilohertz range, e.g., audio modulating radio signal.) One way to produce FM is to use a voltage-controlled oscillator. The oscillator will have an output frequency proportional to the modulating signal's amplitude. As the amplitude of the modulating signal increases, the frequency of the carrier increases. Here a Colpitts LC oscillator uses a varactor diode in place of one of its regulator capacitors that form the tuned circuit. The modulating voltage is applied across the diode and changes the diode's capacitance in proportion. This causes the oscillator frequency to change, thus generating FM in the process. L_2 (RFC) is a radiofrequency choke that prevents high-frequency signals from feeding backing into the modulating source. C_3 and C_4 are ac-coupling capacitors. The rest of the components go into making the Colpitts oscillator.

Oscillator with Pot-Controlled Varactor Tuning

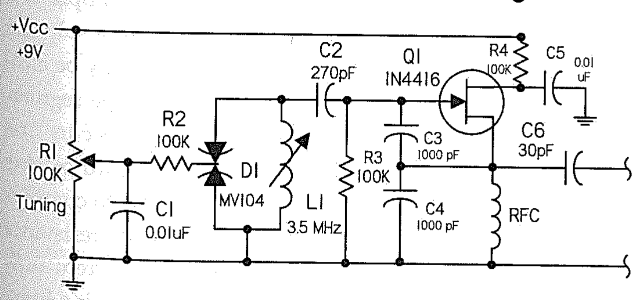


FIGURE 4.39

Unlike the preceding circuit, this circuit acts simply as a variable high-frequency oscillator, whose frequency is varied via a potentiometer (R_1). The voltage from the pot is applied to a dual varactor diode D_1 through a low-frequency filter (C_1, R_2) to ensure that the varactor bias is clean dc. This alters the effective capacitance of the D_1-L_1 tuned circuit, which changes the frequency of the entire oscillator. C_2 and C_6 are dc-blocking (ac-coupling) capacitors. Q_1 is an N-channel JFET in common drain configuration with feedback to the gate through C_3. R_3 is the gate bias resistor. R_4 is the drain voltage resistor with filter capacitor CF.

4.2.9 PIN Diodes

PIN diodes are used as RF and microwave switches. To high-frequency signals, the PIN diode acts like a variable resistor whose value is controlled by an applied dc forward-bias current. With a high dc forward bias, the resistance is often less than an ohm. But with a small forward bias, the resistance appears very large (kiloohms) to high-frequency signals. PIN diodes are constructed with a layer of intrinsic (undoped) semiconductor placed between very highly doped P-type and N-type material, creating a PIN junction.

In terms of application, PIN diodes are used primarily as RF and microwave switches—even at high power levels. A common application is their use as transmit/receive switches in transceivers operating from 100 MHz and up. They are also used as photodetectors in fiber-optic systems. For the most part, you'll never need to use them, unless you are a graduate student in electrical engineering or physics, or are working for a high-tech firm.

RF Switching with PIN Diodes

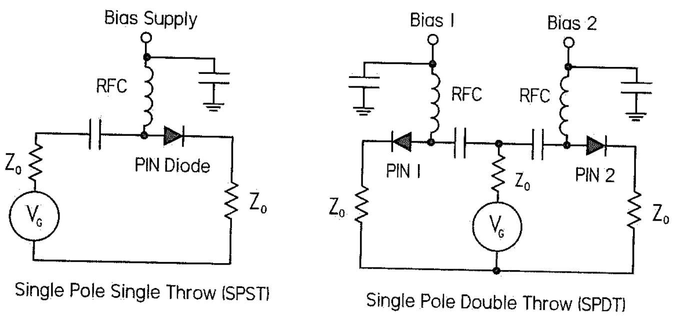


FIGURE 4.40

At RF frequencies, switching is very finicky, requiring special design techniques to minimize signal contamination and degradation. Here are two switching circuits that make use of PIN diodes. In the SPST switch circuit, a signal from a RF generator (VG), can be allowed to pass, or can be prevented from passing to the load by applying a bias voltage to the PIN diode. The RFC is a high-frequency choke to prevent RF from entering bias supply, while the capacitor to ground is used supply clean dc at the bias input. The SPDT switch circuit is similar to the first, but with, of course, two bias inputs.

4.2.10 Microwave Diodes (IMPATT, Gunn, Tunnel, etc.)

There are a number of diodes that you'll probably never have to use, but they are around nevertheless. These diodes are used for very special purposes at the high-frequency end—microwave and millimeter wave (>20 GHz) range, often in microwave amplifiers and oscillators. Most standard diodes and bipolar transistors usually won't cut it at such high speeds, due to the relatively slow diffusion or migration of charge carriers across semiconductor junctions. With the tunnel, Gunn, IMPATT, and other diodes, the variable effects that lead to useful alterations in, say, an amplifier's gain or an oscillators resonant frequency, involve entirely different physics—physics that allows for alterations at essentially the speed of light. The physics may be electron tunneling (through electrostatic barrier separating P-type and N-type regions, rather than being thermionically emitted over the barrier, as generally occurs in a diode)—tunnel diode. Or it may be due to a negative resistance at forward biasing because of an increase in effective mass (slowing down) of electrons due to complex conduction band symmetry—Gunn diodes. It may also be a negative resistance resulting in electrons moving to higher, less mobile bands, reducing current flow with applied forward bias—IMPATT diodes. Anyway, you get the idea—it's hairy high-frequency stuff that should probably be left to the experts. (Note: TRAPATT and Baritt diodes are also used in microwave applications.)

4.2.11 Problems

Problem 1: What does this circuit do? What's the final output voltage? What are the individual voltage drops across each diode with plug tip-positive and plug tip-negative? (Assume each diode has a 0.6-V forward voltage drop.) To prevent diode meltdown, what would be the minimum load resistance, assuming 1N4002 diodes?

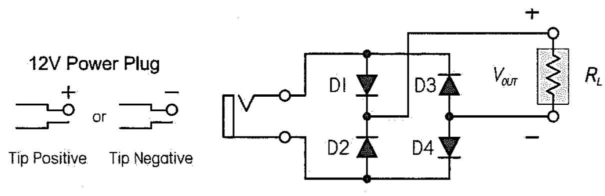


FIGURE 4.41

Answer: Polarity protection circuit that will output the same polarity regardless of the polarity applied to input. The final output voltage is 11.4 V. Tip-positive: $VD_1 = 0.6$ V, $VD_2 = 11.4$ V, $VD_3 = 11.4$ V, $VD_4 = 0.6$ V; Tip-negative: $VD_1 = 11.4$ V, $VD_2 = 0.6$ V, $VD_3 = 0.6$ V, $VD_4 = 11.4$ V. Load resistance should not drop below 11.4 Ω, assuming 1N4002 diodes, since they have a maximum current rating of 1 A. It's a good idea to keep the current to around 75 percent of the maximum value for safety, so 15 Ω would be a better limit.

Problem 2: What does the output look like for the circuit to the left in Fig. 4.42? What happens if a load of 2.2K is attached to the output?

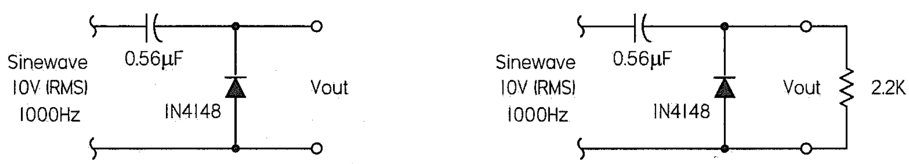


FIGURE 4.42

Answer: Clamp circuit, where the output is shifted so that it's practically pure alternating dc, for the exception of a 0.6-V negative dip due to the diode drop. This gives a maximum peak of 27.6 V and a minimum of −0.6 V. (Recall $V_{peak} = 1.41 \times V_{rms}$.) With the load attached, the output level decreases slightly—the capacitor/load resistor acts like a high-pass filter, with a cutoff frequency of $1/(2\pi RC)$. In simulation, the output goes to 8.90 V(RMS) or 24.5 peak, −0.6 V minimum.

Problem 3: A 10- to 50-mA load requires a regulated 8.2 V. With a 12-V ± 10 percent power supply and 8.2-V zener diode, what series resistance is required? Assume from the data sheets (or experimentation) that the zener diode's minimum regulation current is 10 mA. Determine the power ratings for the resistor and zener diode.

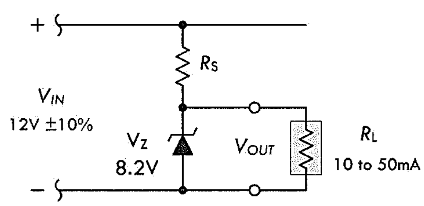
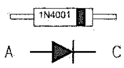
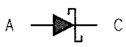
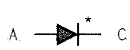


FIGURE 4.43

Answer: $V_{in,max} = 13.2$ V, $V_{in,min} = 10.8$ V: $R_S = (10.8\text{ V} - 8.2\text{ V})/(10\text{ mA} + 50\text{ mA}) = 43\ \Omega$; $P_R = (13.2\text{ V} - 8.2\text{ V})^2/(43\ \Omega) = 0.58$ W; $P_Z = 8.2\text{ V}(13.2\text{ V} - 8.2\text{ V})/(43\ \Omega) = 0.95$ W. See Fig. 4.29 for details.

TABLE 4.3

DIODE TYPE	SYMBOL	MODE OF OPERATION
p-n Junction		Acts as one-way gate to current-flow, from anode (A) to cathode (C). Comes in silicon and germanium types. Both require a forward-bias voltage to conduct; typically 0.6 to 1.7 V for silicon, and 0.2 to 0.4 V for germanium. Used in rectification, transient suppression, voltage multiplication, RF demodulation, analog logic, clamps, fast switches, and voltage regulation.
Schottky		Similar in operation to p-n junction diode, but designed with special metal semiconductor junction instead of a p-n junction. This provides for extremely low junction capacitance that stores less charge. Results of this junction yield quicker switching times, useful in fast clamping and high-frequency applications approaching the gigahertz range. Also, generally has a lower forward-bias voltage of around 0.4 V (average)—but can be from 0.15 to 0.9 V or more.Used in similar applications as p-n junction diode, but offers better low-signal level detection, speed, and low-power loss in rectification due to low forward threshold.
Zener		Conducts from A to C like p-n junction diode, but will also conduct from C to A if the applied reverse voltage is greater than the zener's breakdown voltage rating V_Z. Acts like a voltage-sensitive control valve. Comes with various breakdown voltages—1.2 V, 3.0 V, 5.1 V, 6.3 V, 9 V, 12 V, etc., and power ratings. Applications include voltage regulation, waveform clipping, voltage shifting, and transient suppression.
LED & Laser		Light-emitting diode (LED) emits a near constant wavelength of light when forward-biased (A > C) by a voltage of about 1.7 V. Comes in various wavelengths (IR through visible), sizes, power ratings, etc. Used as indicator and emitting source in IR and light-wave communications.Laser diode is similar to LED, but provides a much narrower wavelength spectrum (about 1 nm compared to around 40 nm for LED), usually in the IR region. They have very fast response times (lns). These features provide clean signal characteristics useful in fiber-optic systems, where minimized dispersion effects, efficient coupling, and limited degradation over long distances is important. They are also used in laser pointers, CD/DVD players, bar-code readers, and in various surgical applications.
Photo		Generates a current when exposed to light, or can be used to alter current flow passing through it when the light intensity changes. Operates in reverse-bias direction (current flows from C to A) when exposed to light. Current increases with light intensity. Very fast response times (ns). Not as sensitive as phototransistors, but their linearity can make them useful in simple light meters.
Varactor (Varicap)		Acts like a voltage-sensitive variable capacitor, whose capacitance decreases as the reverse-bias voltage on the diode increases. Designed with a junction specifically formulated to have a relatively large range of capacitance values for a modest range of reverse-bias voltages. Capacitance range in the picofarad range, so they are usually limited to RF applications, such as tuning receivers and generating FM.
PIN, IMPATT Gunn, Tunnel, etc.		Most of these are resistance devices used in RF, microwave, and millimeter wave applications (e.g., amplifiers and oscillators). Unique conduction physics yields much faster response times when compared to standard diodes that use charge carrier dispersion across a p-n junction.

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