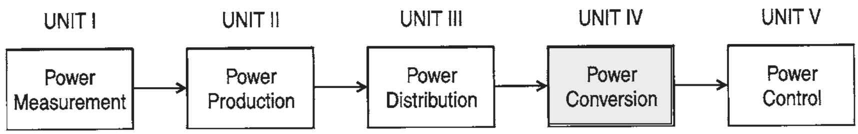
UNIT IV

Electrical Power Conversion Systems

One of the most important aspects of electrical power systems is the conversion of electrical power into some other form of energy. Electrical power is ordinarily converted into light, heat, or mechanical power. The power is converted using either resistive, inductive, or capacitive circuits. The fundamental characteristics of electrical power conversion systems are discussed in Chapter 11.

The basic types of electrical power conversion systems are studied further in the remaining chapters. Heating systems are discussed in Chapter 12. Those systems that convert electrical energy into heat energy use three methods, incorporating resistive, inductive, and capacitive circuits. Basic welding method systems are also included in this chapter, since they are a unique type of electrical load. Chapter 13 deals with the conversion of electrical energy into light energy. Lighting systems include incandescent, fluorescent, and vapor lighting systems. The systems that convert electrical energy into mechanical energy are discussed in Chapter 15. The major mechanical energy conversion takes place in electric motors. Both direct current (DC) and alternating current (AC) motors are studied in that chapter.

Figure IV shows the *electrical power systems model* used in this book, and the major topics of Unit IV—Electrical Power Conversion Systems.



Fundamentals of Electrical Loads (Chapter 11)
Heating Systems (Chapter 12)
Lighting Systems (Chapter 13)
Mechanical Systems (Chapter 14)

Figure IV. Electrical power systems model

UNIT OBJECTIVES

Upon completion of this unit, you should be able to:

1. Define the term "electrical load."
2. List the types and classifications of electrical loads.
3. Explain the differences between resistive, inductive, and capacitive circuits.
4. Calculate load (demand) factor and power factor.
5. Describe power factor correction, using static capacitors or synchronous capacitors.
6. Define true power, apparent power, and reactive power in AC circuits.
7. Calculate power per phase and total power for balanced or unbalanced three-phase loads.
8. Explain the differences between resistive, inductive, and capacitive electric loads.
9. Describe electric resistive and arc-welding systems as electrical loads.
10. Describe electric heating systems and these associated terms:
    BTU
    Design Temperature Difference
    Degree Days
    Thermal Resistance (R)
    Coefficient of Heat Transfer (U)
    Watts of Heat (W)
11. Describe heat pumps and air conditioning systems.
12. Describe the characteristics of light.
13. Define the terms candlepower, lumen, and footcandle as they relate to light.
14. Describe types of street lighting systems.
15. Explain the characteristics of incandescent, fluorescent, and vapor lighting.
16. Describe branch circuits used for controlling electrical lights from one, two, or three locations.
17. Calculate the minimum number of branch circuits and total power requirements for lighting circuits in buildings.
18. Describe the following factors that affect lighting fixture design:
    Luminaire

Coefficient of Utilization (CU)
Room Ratio
Depreciation Factor (DF)

19. Calculate light output of a lighting system.
20. Describe the basic principles of electric motor operation.
21. Identify and describe the following types of electric motors:
    DC Motors
    Single-Phase AC Motors
    Three-Phase AC Motors
22. Explain the operation of synchro/servo systems and DC stepping motors.
23. Calculate the following, as each relates to electric motor operation:
    Horsepower
    Speed Regulation
    Starting Current
    Synchronous Speed
    Slip
    Rotor Frequency
    Efficiency

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Chapter 11

Fundamentals of Electrical Loads

The electrical load devices that are used in industry, in our homes, and in commercial buildings are very important parts of electrical power systems. The load of any system performs a function that involves power conversion. A load converts one form of energy to another form. An electrical load converts electrical energy to some other form of energy, such as heat, light, or mechanical energy. Electrical loads may be classified according to the function that they perform (lighting, heating, mechanical), or by the electrical characteristics that they exhibit (resistive, inductive, capacitive).

IMPORTANT TERMS

Chapter 11 deals with fundamentals of electrical loads. After studying this chapter, you should have an understanding of the following terms:

Load
Resistive Load
Capacitive Load
Inductive Load
Load (Demand) Factor
Power Factor
Power Factor Correction
True Power
Apparent Power
Reactive Power
Static Capacitor

Synchronous Capacitor
Balanced Three-phase Load
Unbalanced Three-phase Load
Line Voltage (V_L)
Phase Voltage (V_P)
Line Current (I_L)
Phase Current (I_P)
Power per Phase (P_P)
Total Three-phase Power (P_T)

LOAD CHARACTERISTICS

In order to plan for power system load requirements, we must understand the electrical characteristics of all the loads connected to the power system. The types of power supplies and distribution systems that a building uses are determined by the load characteristics. All loads may be considered as either resistive, inductive, capacitive, or a combination of these. We should be aware of the effects that various types of loads will have on the power system. The nature of AC results in certain specific electrical circuit properties.

You should review that portion of Chapter 2 that deals with resistive, inductive, and capacitive effects in an electrical circuit. One primary factor that affects the electrical power system is the presence of inductive loads. These are mainly electric motors. To counteract the inductive effects, utility companies use power factor corrective capacitors as part of the power system design. Capacitor units are located at substations to improve the power factor of the system. The inductive effect, therefore, increases the cost of a power system and reduces the actual amount of power that is converted to another form of energy.

Load (Demand) Factor

One electrical load relationship that is important to understand is the *load* (or *demand)* factor. Load factor expresses the ratio between the average power requirement and the peak power requirement, or:

$$\text{load demand factor} = \frac{\text{average demand (kW)}}{\text{peak demand (kW)}}$$

<u>Sample Problem</u>:

Given: a factory has a peak demand of 12 MW and an average power demand of 9.86 MX.

Find: the load (demand) factor for the factory.

Solution:

$$DF = \frac{\text{Avg. Demand}}{\text{Peak Demand}}$$

$$= \frac{9.86\text{ MW}}{12\text{MW}}$$

$$DF = \quad 0.82$$

The average demand of an industry or commercial building is the average electrical power used over a specific time period. The peak demand is the maximum amount of power (kW) used during that time period. The load profile shown in Figure 11-1 shows a typical industrial demand-versus-time curve for a working day. Demand peaks that far exceed the average demand cause a decrease in the load factor ratio. Low load factors result in an additional billing charge by the utility company.

Utility companies must design power distribution systems that take peak demand time into account, and ensure that their generating capacity will be able to meet this peak power demand. Therefore, it is inefficient electrical design for an industry to operate at a low-load factor, since this represents a significant difference between peak-power demand and average-power demand. Every industry should attempt to raise its load factor to the maximum level it can. By minimizing the peak demands of indus-

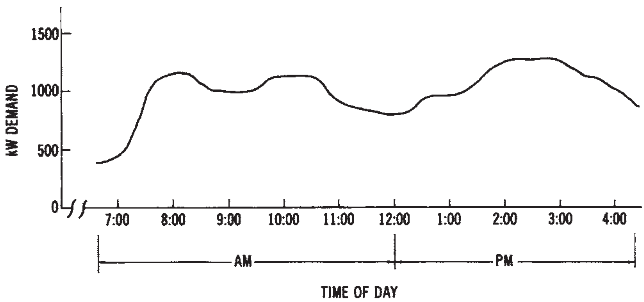

Figure 11-1. Load profile for an industrial plant

trial plants, power demand control systems and procedures can help increase the efficiency of our nation's electrical power systems.

Be careful not to confuse the load factor of a power system with the power factor. The power factor is the ratio of power converted (true power), to the power delivered to a system (apparent power). If necessary, you should review power factor (see Chapter 2).

Most industries use a large number of electric motors; therefore, industrial plants represent highly inductive loads. This means that industrial power systems operate at a power factor of less than unity (1.0). However, it is undesirable for an industry to operate at a low-power factor, since the electrical power system will have to supply more power to the industry than is actually used.

A given value of volt-amperes (voltage × current) is supplied to an industry by the electrical power system. If the power factor (pf) of the industry is low, the current must be higher, since the power converted by the total industrial load equals VA × pf. The value of the power factor decreases as the reactive power (unused power) drawn by the industry increases. This is shown in Figure 11-2. We will assume a constant value of true power, in order to see the effect of increases in reactive power drawn

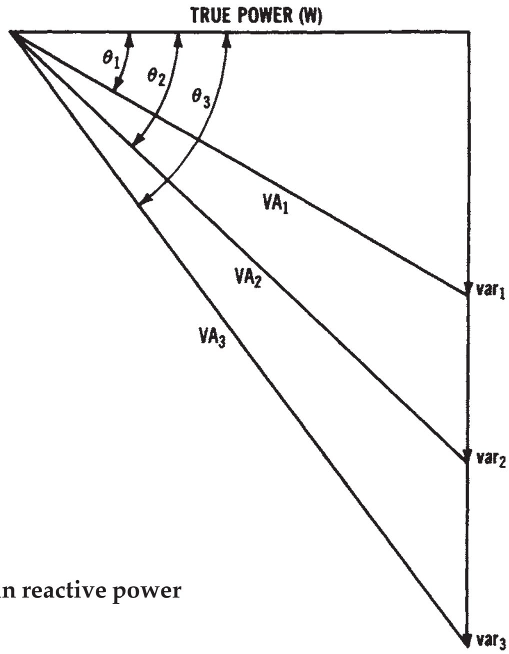

Figure 11-2. Effect of increases in reactive power (VAR) on apparent power (VA)

by a load. The smallest reactive power shown (VAR_1) results in the volt-ampere value of VA_1. As reactive power is increased, as shown by the VAR_2 and VAR_3 values, more volt-amperes (VA_2 and VA_3) must be drawn from the source. This is true since the voltage component of the supplied volt-amperes remains constant. This example represents the same effect as a decrease in the power factor, since pf = W / VA, and, as VA increases, the pf will decrease if W remains constant.

Utility companies usually charge industries for operating at power factors below a specified level. It is desirable for industries to "correct" their power factor to avoid such charges and to make more economical use of electrical energy. Two methods may be used to cause the power factor to increase: (1) power-factor-corrective capacitors, and (2) three-phase synchronous motors. Since the effect of capacitive reactance is opposite to that of inductive reactance, their reactive effects will counteract one another. Either power-factor-corrective capacitors, or three-phase synchronous motors, may be used to add the effect of capacitance to an AC power line.

An example of power factor correction is shown in Figure 11-3. We will assume from the example that both true power and inductive reactive power remain constant at values of 10 kW and 10 kVAR. In Figure 11-3A, the formulas show that the power factor equals 70 percent. However, if 5-kVAR capacitive reactive power is introduced into the electrical power system, the net reactive power becomes 5 kVAR (10-kVAR inductive minus 5-kVAR capacitive), as shown in Figure 11-3B. With the addition of 5-kVAR capacitive to the system, the power factor is increased to 89 percent. Now, in Figure 11-3C, if 10-kVAR capacitive is added to the power system, the total reactive power (kVAR) becomes zero. The true power is now equal to the apparent power; therefore, the power factor is 1.0, or 100 percent, which is characteristic of a purely resistive circuit. The effect of the increased capacitive reactive power in the system is to increase or "correct" the power factor and, thus, to reduce the current drawn from the power distribution lines that supply the loads. In many cases, it is beneficial for industries to invest in either power-factor-corrective capacitors, or three-phase synchronous motors, to correct their power factor. Calculations may be simplified by using the chart of Table 11-1.

Utility companies also attempt to correct the power factor of the power distribution system. A certain quantity of inductance is present in most of the power distribution system, including the generator windings,

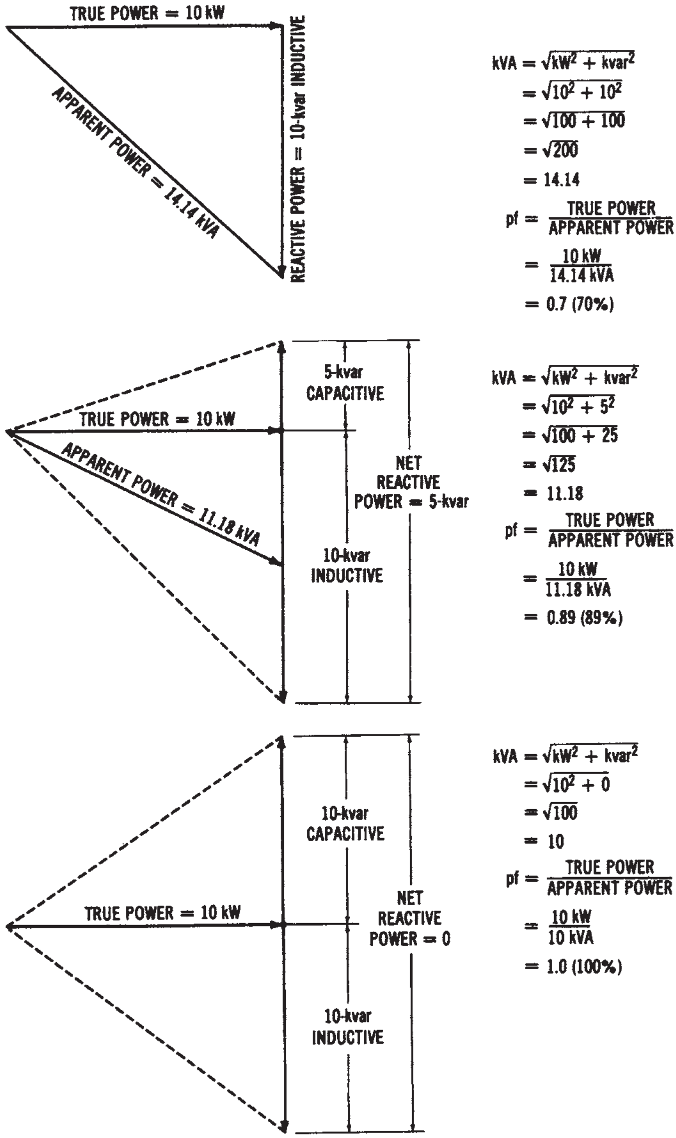

Figure 11-3. Illustration of the effect of capacitive reactance on an inductive circuit: (A) Reactive power = 10 kVAR inductive, (B) Reactive power = 10 kVAR inductive, and 5 kVAR capacitive, (C) Reactive power = 10 kVAR inductive, and 10 kVAR capacitive

the transformer windings, and the power lines. To counteract the inductive effects, utilities use power-factor-corrective capacitors.

Capacitors for Power Factor Correction

Static capacitors are used for power factor correction in the system. They are constructed similarly to the smaller capacitors used in electrical equipment, which have metal-foil plates separated by paper insulation. Ordinarily, static capacitors are housed in metal tanks, so that the plates can be immersed in an insulating oil to improve high-voltage operation. The usual operating voltages of static capacitors are from 230 volts to 13.8 kilovolts. These units are connected in parallel with power lines, usually at the industrial plants, to increase the system power factor. Their primary disadvantage is that their capacitance cannot be adjusted to compensate for changing power factors.

Power factor correction can also be accomplished by using *synchronous capacitors* connected across the power lines. (Three-phase synchronous motors are also called synchronous capacitors; see Chapter 14 for a discussion of three-phase synchronous motors.) The advantage of synchronous capacitors over static capacitors is that their capacitive effect can be adjusted as the system power factor increases or decreases. The capacitive effect of a synchronous capacitor is easily changed by varying the DC excitation voltage applied to the rotor of the machine. Industries considering the installation of either static or synchronous capacitors should first compare the initial equipment cost and the operating cost against the savings brought about by an increased system power factor.

THREE-PHASE LOAD CHARACTERISTICS

In Chapter 2 single-phase circuit fundamentals were discussed. However, the major type of load in electrical power systems is the three-phase load. Therefore, you should become familiar with the characteristics of three-phase loads.

Balanced Three-phase Loads

A balanced three-phase load means that the resistance or impedances connected across each phase of the system are equal. Three-phase motors are one type of balanced load. The following relationships exist in a balanced, three-phase delta system. The line voltages (V_L) are equal to the

Table 11-1. Kilowatt (kW) Multipliers for Determining Capacitor Kilovars (kVAR)

Original Power Factor in Percentage	Desired Power Factor in Percentage																				
	80	*81*	*82*	*83*	*84*	*85*	*86*	*87*	*88*	*89*	*90*	*91*	*92*	*93*	*94*	*95*	*96*	*97*	*98*	*99*	*1.0*
50	0.982	1.008	1.034	1.060	1.086	1.112	1.139	1.165	1.192	1.220	1.248	1.276	1.306	1.337	1.369	1.403	1.440	1.481	1.529	1.589	1.732
51	0.937	0.962	0.989	1.015	1.041	1.067	1.094	1.120	1.147	1.175	1.203	1.231	1.261	1.292	1.324	1.358	1.395	1.436	1.484	1.544	1.686
52	0.893	0.919	0.945	0.971	0.997	1.023	1.050	1.076	1.103	1.131	1.159	1.187	1.217	1.248	1.280	1.314	1.351	1.392	1.440	1.500	1.643
53	0.850	0.876	0.902	0.928	0.954	0.980	1.007	1.033	1.060	1.088	1.116	1.144	1.174	1.205	1.237	1.271	1.308	1.349	1.397	1.457	1.600
54	0.809	0.835	0.861	0.887	0.913	0.939	0.966	0.992	1.019	1.047	1.075	1.103	1.133	1.164	1.196	1.230	1.267	1.308	1.356	1.416	1.559
55	0.769	0.795	0.821	0.847	0.873	0.899	0.926	0.952	0.979	1.007	1.035	1.063	1.093	1.124	1.156	1.190	1.227	1.268	1.316	1.376	1.519
56	0.730	0.756	0.782	0.808	0.834	0.860	0.887	0.913	0.940	0.968	0.996	1.024	1.054	1.085	1.117	1.151	1.188	1.229	1.277	1.337	1.480
57	0.692	0.718	0.744	0.770	0.796	0.822	0.849	0.875	0.902	0.930	0.958	0.986	1.016	1.047	1.079	1.113	1.150	1.191	1.239	1.299	1.442
58	0.655	0.681	0.707	0.733	0.759	0.785	0.812	0.838	0.865	0.893	0.921	0.949	0.979	1.010	1.042	1.076	1.113	1.154	1.202	1.262	1.405
59	0.619	0.645	0.671	0.697	0.723	0.749	0.776	0.802	0.829	0.857	0.885	0.913	0.943	0.974	1.006	1.040	1.077	1.118	1.166	1.226	1.369
60	0.583	0.609	0.635	0.661	0.687	0.713	0.740	0.766	0.793	0.821	0.849	0.877	0.907	0.938	0.970	1.004	1.041	1.082	1.130	1.190	1.333
61	0.549	0.575	0.601	0.627	0.653	0.679	0.706	0.732	0.759	0.787	0.815	0.843	0.873	0.904	0.936	0.970	1.007	1.048	1.096	1.156	1.299
62	0.516	0.542	0.568	0.594	0.620	0.646	0.673	0.699	0.725	0.754	0.782	0.810	0.840	0.871	0.903	0.937	0.974	1.015	1.063	1.123	1.266
63	0.483	0.509	0.535	0.561	0.587	0.613	0.640	0.666	0.693	0.721	0.749	0.777	0.807	0.838	0.870	0.904	0.941	0.982	1.030	1.090	1.233
64	0.451	0.474	0.503	0.529	0.555	0.581	0.608	0.634	0.661	0.689	0.717	0.745	0.775	0.806	0.838	0.872	0.909	0.950	0.998	1.068	1.201
65	0.419	0.445	0.471	0.497	0.523	0.549	0.576	0.602	0.629	0.657	0.685	0.713	0.743	0.774	0.805	0.840	0.877	0.918	0.966	1.026	1.169
66	0.388	0.414	0.440	0.466	0.492	0.518	0.545	0.571	0.598	0.626	0.654	0.682	0.712	0.743	0.775	0.809	0.846	0.887	0.935	0.995	1.138
67	0.358	0.384	0.410	0.436	0.462	0.488	0.515	0.541	0.568	0.596	0.624	0.652	0.682	0.713	0.745	0.779	0.816	0.857	0.905	0.965	1.108
68	0.328	0.354	0.380	0.406	0.432	0.458	0.485	0.511	0.538	0.566	0.594	0.622	0.652	0.683	0.715	0.749	0.786	0.827	0.875	0.935	1.078
69	0.299	0.325	0.351	0.377	0.403	0.429	0.456	0.482	0.509	0.537	0.565	0.593	0.623	0.654	0.686	0.720	0.757	0.798	0.846	0.906	1.049
70	0.270	0.296	0.322	0.348	0.374	0.400	0.427	0.453	0.480	0.508	0.536	0.564	0.594	0.625	0.657	0.691	0.728	0.769	0.817	0.877	1.020
71	0.242	0.268	0.294	0.320	0.346	0.372	0.399	0.425	0.452	0.480	0.508	0.536	0.566	0.597	0.629	0.663	0.700	0.741	0.789	0.849	0.992
72	0.214	0.240	0.266	0.292	0.318	0.344	0.371	0.397	0.424	0.452	0.480	0.508	0.538	0.569	0.601	0.635	0.672	0.713	0.761	0.821	0.964
73	0.186	0.212	0.238	0.264	0.290	0.316	0.343	0.369	0.396	0.424	0.452	0.480	0.510	0.541	0.573	0.607	0.644	0.685	0.733	0.793	0.936

74	0.159	0.185	0.211	0.237	0.263	0.289	0.316	0.342	0.369	0.397	0.425	0.453	0.483	0.514	0.546	0.580	0.617	0.658	0.706	0.766	0.909
75	0.132	0.158	0.184	0.210	0.236	0.262	0.289	0.315	0.342	0.370	0.398	0.426	0.456	0.487	0.519	0.553	0.590	0.631	0.679	0.739	0.882
76	0.105	0.131	0.157	0.183	0.209	0.235	0.262	0.288	0.315	0.343	0.371	0.399	0.429	0.460	0.492	0.526	0.563	0.604	0.652	0.712	0.855
77	0.079	0.105	0.131	0.157	0.183	0.209	0.236	0.262	0.289	0.317	0.345	0.373	0.403	0.434	0.466	0.500	0.537	0.578	0.626	0.686	0.829
78	0.052	0.078	0.104	0.130	0.156	0.182	0.209	0.235	0.262	0.290	0.318	0.346	0.376	0.407	0.439	0.473	0.510	0.554	0.599	0.569	0.802
79	0.026	0.052	0.078	0.104	0.130	0.156	0.183	0.209	0.236	0.264	0.292	0.320	0.350	0.381	0.413	0.447	0.484	0.525	0.573	0.633	0.776
80	0.000	0.026	0.052	0.078	0.104	0.130	0.157	0.183	0.210	0.238	0.266	0.294	0.324	0.355	0.387	0.421	0.458	0.499	0.547	0.609	0.750
81		0.000	0.026	0.052	0.078	0.104	0.131	0.157	0.184	0.212	0.240	0.268	0.298	0.329	0.361	0.395	0.432	0.473	0.521	0.581	0.724
82			0.000	0.026	0.052	0.078	0.105	0.131	0.158	0.186	0.214	0.242	0.272	0.303	0.335	0.369	0.406	0.447	0.495	0.555	0.698
83				0.000	0.026	0.052	0.079	0.105	0.132	0.160	0.188	0.216	0.246	0.277	0.309	0.343	0.380	0.421	0.469	0.529	0.672
84					0.000	0.026	0.053	0.079	0.106	0.134	0.162	0.190	0.220	0.251	0.283	0.317	0.354	0.395	0.443	0.503	0.646
85						0.000	0.027	0.053	0.080	0.108	0.136	0.164	0.194	0.225	0.257	0.291	0.328	0.369	0.417	0.477	0.620
86							0.000	0.026	0.053	0.081	0.109	0.137	0.167	0.198	0.230	0.264	0.301	0.342	0.390	0.450	0.593
87								0.000	0.027	0.055	0.083	0.111	0.141	0.172	0.204	0.238	0.275	0.316	0.364	0.424	0.567
88									0.000	0.028	0.056	0.084	0.114	0.145	0.177	0.211	0.248	0.289	0.337	0.397	0.540
89										0.000	0.028	0.056	0.086	0.117	0.149	0.183	0.220	0.261	0.309	0.369	0.512
90											0.000	0.028	0.058	0.089	0.121	0.155	0.192	0.233	0.281	0.341	0.484
91												0.000	0.030	0.061	0.093	0.127	0.164	0.205	0.253	0.313	0.456
92													0.000	0.031	0.063	0.097	0.134	0.175	0.223	0.283	0.426
93														0.000	0.032	0.066	0.103	0.144	0.192	0.252	0.395
94															0.000	0.034	0.071	0.112	0.160	0.220	0.363
95																0.000	0.037	0.079	0.126	0.186	0.329
96																	0.000	0.041	0.089	0.149	0.292
97																		0.000	0.048	0.108	0.254
98																			0.000	0.060	0.203
99																				0.000	0.143
																					0.000

phase voltages (V_P). The line currents (I_L) are equal to the phase currents (I_P) multiplied by 1.73. Thus:

$$V_L = V_P$$
$$I_L = I_P \times 1.73$$

For a balanced three-phase wye system, the method used to find the voltages and currents is similar. The voltage across the AC lines (V_L) is equal to the square root of 3 (1.73) multiplied by the voltage across the phase windings (V_P), or

$$V_L = V_P \times 1.73.$$

The line currents (I_L) are equal to the phase currents (I_P), or

$$I_L = I_P$$

The power developed in each phase (P_P), for either a wye or a delta circuit, is expressed as:

$$P_P = V_P \text{ x } I_P \times pf$$

where:

pf is the power factor (phase angle between voltage and current) of the load.

The total power developed by all three phases of a three-phase generator (P_T) is expressed as:

$$\begin{aligned} P_T &= 3 \times P_P \\ &= 3 \times V_P \times I_P \times pf \\ &= 1.73 \times V_L \times I_L \times pf \end{aligned}$$

As an example, we can calculate the phase current (I_P), line current (I_L), and total power (P_T) for a 240-volt, three-phase, delta-connected system with 1000-watt load resistances connected across each power line. The phase current is:

$$I_P = \frac{P_P}{V_P}$$

$$= \frac{1000 \text{ watts}}{240 \text{ volts}}$$

$$= 4.167 \text{ amperes}$$

The line current is calculated as:

$$\begin{aligned} I_L &= I_P \times 1.73 \\ &= 4.167 \times 1.73 \\ &= 7.21 \text{ amperes} \end{aligned}$$

Thus, the total power is determined as:

$$\begin{aligned} P_T &= 3 \times P_P \\ &= 3 \times 1000 \text{ watts} \\ &= 3000 \text{ watts} \end{aligned}$$

Another way to calculate the total power is:

$$\begin{aligned} P_T &= 1.73 \times V_L \times I_L \times \text{pf} \\ &= 1.73 \times 240 \text{ volts} \times 7.21 \text{ amperes} \times 1 \\ &= 2993.59 \text{ watts} \end{aligned}$$

(Note that your answer depends upon the number of decimal places to which you carry your calculations. Round off I_L at 7.2 amperes, and your answer for the last calculation is 2989.44 watts, instead of 2993.59 watts.)

The following is an example of the power calculation for a three-phase wye system. For the problem, "find the line current (I_L) and power per phase (P_P) of a balanced, 20,000-watt, 277/480-volt, three-phase wye system operating at a 0.75 power factor," we use the formula:

$$P_T = V_L \times I_L \times 1.73 \times \text{pf}$$

Transposing and substituting, we have:

$$I_L = \frac{P_T}{V_L \times P_T \times \text{pf}}$$

$$= \frac{20{,}000 \text{ watts}}{480 \text{ volts} \times 1.73 \times 0.75}$$

$$= 32.11 \text{ amperes}$$

Then, for the power per phase (P_P), divide the 20,000 watts of the system by 3 (the number of phases), for a value of 6,666.7 watts (6.66 kW).

Unbalanced Three-phase Loads

Often, three-phase systems are used to supply power to both three-phase and single-phase loads. If three, identical, single-phase loads were connected across each set of power lines, the three-phase system would still be balanced. However, this situation is usually difficult to accomplish, particularly when the loads are lights. Unbalanced loads exist when the individual power lines supply loads that are not of equal resistances or impedances.

The total power converted by the loads of an unbalanced system must be calculated by looking at each phase individually. Total power of a three-phase unbalanced system is:

$$P_T = P_{P-A} + P_{P-B} + P_{P-C}$$

where the power-per-phase (P_P) values are added. Power per phase is found in the same way as when dealing with balanced loads:

$$P_P = V_P \times I_P \times \text{power factor}$$

The current flow in each phase may be found if we know the power per phase and the phase voltage of the system. The phase currents are found in the following manner:

Sample Problem:

Given: the following 120-volt single-phase loads are connected to a 120/208-volt wye system. Phase A has 2000 watts at a 0.75 power factor, Phase B has 1000 watts at a 0.85 power factor, and Phase C has 3000 watts at a 1.0 power factor.

Find: the total power of the three-phase system, and the current flow through each line.

Solution: To find the phase currents, use the formula $P_P = V_P \times I_P \times$

power factor, and transpose. Thus, we have $I_P = P_P/V_P \times pf$. Substitution of the values for each leg of the system gives us:

1.
$$*I_{P-A} = \frac{P_{P-A}}{V_P \times pf}$$
$$= \frac{2000 \text{ watts}}{120 \text{ volts} \times 0.75}$$
$$= 22.22 \text{ amperes}$$

*This notation means phase current (I_P) of "A" power line.

2.
$$*I_{P-B} = \frac{P_{P-B}}{V_P \times pf}$$
$$= \frac{1000 \text{ watts}}{120 \text{ volts} \times 0.85}$$
$$= 9.8 \text{ amperes}$$

3.
$$*I_{P-C} = \frac{P_{P-C}}{V_P \times pf}$$
$$= \frac{3000 \text{ watts}}{120 \text{ volts} \times 1.0}$$
$$= 25.0 \text{ amperes}$$

To determine the total power, use the total power formula for a three-phase unbalanced system, which was just given:

$$\begin{aligned} P_T &= P_{P-A} + P_{P-B} + P_{P-C} \\ &= 2000 + 1000 + 3000 \\ &= 6000 \text{ watts (6 kW)} \end{aligned}$$

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Chapter 12

Heating Systems

Power conversion systems are commonly referred to by the function they perform. Power conversion takes place in the *load* of an electrical power system. Common types of power system loads are those that convert electrical energy into heat, light, or mechanical energy. There are various types of lighting, heating, and mechanical loads used in industry, commercial buildings, and homes. Several of these power conversion systems will be discussed in Chapters 12, 13, and 14.

IMPORTANT TERMS

Chapter 12 deals with heating systems. After studying this chapter, you should have an understanding of the following terms:

Resistive Heating
Induction Heating
Dielectric Heating
Electric Welding
Resistance Welding
Arc Welding
Induction Welding
SCR Contactors
Electric Heating Systems
British Thermal Units (Btus)
Design Temperature Difference
Degree Days
Thermal Resistance (R)
Coefficient of Heat Transfer (U)
Heat Pump
Air Conditioning System

BASIC HEATING LOADS

Most loads that are connected to electrical power systems produce a certain amount of heat, mainly as the result of current flow through resistive devices. In many instances, heat represents a power loss in the circuit, since heat energy is not the type of energy that the system was intended to produce. Lights, for instance, produce heat energy as well as light energy. The conversion of electrical energy to heat energy in a light-producing load reduces the efficiency of that load device, since not all of the available source energy is converted to light energy. There are, however, several types of power conversion systems that are mainly heating loads. Their primary function is to convert electrical energy into heat energy. Some basic systems include resistance heating, inductive heating, and dielectric (capacitive) heating.

Resistance Heating

Heat energy is produced when an electrical current flows through a resistive material. In many instances, the heat energy produced by an electrical current is undesirable; however, certain applications require controlled resistance heating. Useful heat may be transferred from a resistive element to a point of utilization by the common methods of heat transfer—convection, radiation, or conduction. A heating-element enclosure is needed to control the transfer of heat by convection and radiation. For heat transfer by conduction, the heating element is in direct contact with the material to be heated. Actual heat transfer usually involves a combination of these methods.

Figure 12-1 illustrates the principle of resistance heating. The self-contained heating element uses a coiled resistance wire, which is placed inside a heat-conducting material and enclosed in a metal sheath. This principle may be used to heat water, oil, the surrounding atmosphere, or various other media. This type of heater may be employed in the open air or immersed in the media to be heated. The useful life of the resistance elements depends mainly upon the operating temperature. As the temperature increases, the heat output also increases. Basically, the heat energy produced is dependent upon the current flow and the resistance of the element; it can be calculated as current squared times resistance (I^2R).

Induction Heating

The principle of induction heating is illustrated in Figure 12-2. Heat is produced in magnetic materials when they are exposed to an alternating current (AC) field. In the example shown, current is induced in the material heated by electromagnetic induction. This is brought about by the application of an AC to the heating coil. The material to be heated must be a *conductor* in order for current to be induced. Ordinarily, a high-frequency AC source in the range of 100-500 kHz is used to produce a high heat output. This high heat output is due to greater amounts of induced voltage.

As the magnetic field created by the high-frequency AC source moves across the material to be heated, the induced voltage causes *eddy currents* (circulating currents) to flow in the material. Heat results because of the resistance of the material to the flow of the eddy currents. The heat is produced rapidly by this method, which is an advantage.

The major application of the induction-heating process is in metal-working industries, for such processes as hardening, soldering, melting, and annealing of metals. Compared to that of other methods of heating

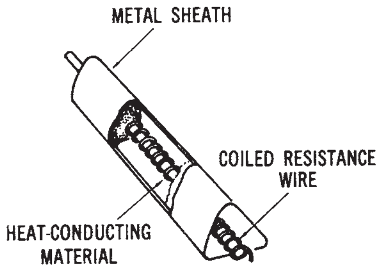

Figure 12-1. Resistance heating principle

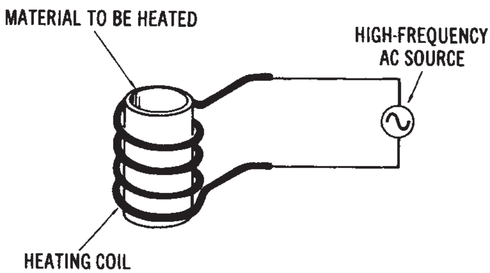

Figure 12-2. Induction heating principle

the heat production of this process is extremely rapid. The area of the metal that is actually heated can be controlled by the size and position of the heating coils of the induction heater. This type of control is difficult to accomplish by other methods. Induction furnaces use the induction-heating principle.

By varying the frequency of the voltage applied to the induction heater windings, it is possible to vary the depth of heat penetration into the heated metal. At higher frequencies the heat produced by the induced current from the heating coils will not penetrate as deeply, because of the so-called "skin effect." Thus, heat will penetrate more deeply at lower frequencies. When heat must be localized onto the surface of a material only-for example, for surface hardening of a metal—higher frequencies are used. The cost of higher-frequency induction heaters is greater, because more complex oscillator circuits are required to produce these frequencies.

Dielectric (Capacitive) Heating

Induction heating can only be used with conductive materials. Therefore, some other method must be used to heat nonconductive materials. Such a method is illustrated in Figure 12-3 and is referred to as *dielectric* or *capacitive* heating. Nonconductors may be heated by placing them in an electrostatic field, created between two metal electrodes that are supplied by a high-frequency AC source. The material to be heated becomes the dielectric or insulation of a capacitive device. The metal electrodes constitute the two plates.

When high-frequency AC is applied to a dielectric heating assembly, the changing nature of the applied AC causes the internal atomic structure of the dielectric material to become distorted. As the frequency of the AC increases, the amount of internal atomic distortion also increases.

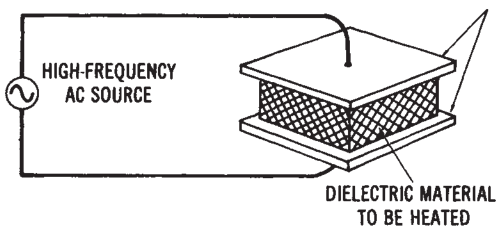

Figure 12-3. Capacitive heating principle

This internal friction produces a large amount of heat in the nonconductive material. Frequencies in the 50-Mhz range may be used for dielectric heating. Dielectric heating produces rapid heating, which is spread evenly throughout the heated material. Common applications of this heating method are the gluing of plywood and the bonding together of plastic sheets.

ELECTRICAL WELDING LOADS

Electrical welding is another common type of a heat-producing power conversion system. The types of electrical welding systems include resistance welding, electric arc welding, and induction welding.

Resistance Welding

Several familiar welding methods, such as spot welding, seam welding, and butt welding, are resistance welding processes. All of these processes rely upon the resistance heating principle. Spot welding, illustrated in Figure 12-4A, is performed on overlapping sheets of metal, which are usually less than 1/4-inch thick. The metal sheets are clamped between two electrodes, and an electrical current is passed through the electrodes and metal sheets. The current causes the metals to fuse together. The instantaneous current through the electrodes is usually in excess of 5000 amperes, while the voltage between the electrodes is less than 2 volts.

Seam welding, shown in Figure 12-4B, is accomplished by passing sheets of metal between two pressure rollers, while a continuously interrupted current is passed through the electrodes. The operational principle of seam welding is the same as that of spot welding. Several other similar methods, which are referred to as butt welding, edge welding, and projection welding, are also commonly used.

Electric Arc Welding

While resistance welding utilizes pressure on the materials to be welded, electric arc welding produces welded metals by localized heating without pressure, as shown in Figure 12-5. An electric arc is created when the electrode of the welder is brought in contact with the metal to be welded. Carbon electrodes are used for DC or AC arc welding of nonferrous metals and alloys. Not all metals can be welded by the arc welding process. When metals are welded together, part of the metals to be welded

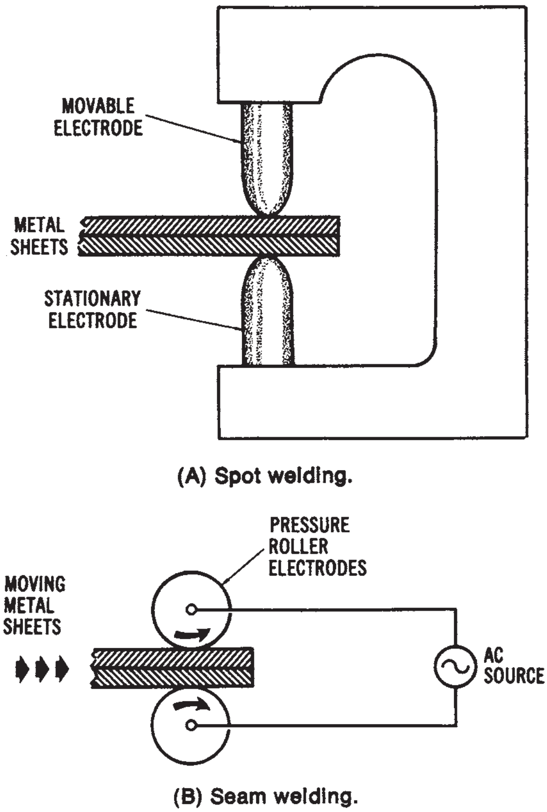

Figure 12-4. Resistance welding methods: (A) Spot welding, (B) Seam welding

are melted, creating a metal pool that is added to, when necessary, by the use of a filler rod. The puddle (molten metal pool) then fills in the gap (arc crater) that was created by the arc of the electrode. Various types and various current-voltage ratings of electric arc welders are available.

A smaller amount of current is required for arc welding than for resistance welding. The currents may range from 50 to 200 amperes, or higher for some applications. Voltages typically range from 10 to 50 volts. An electric arc welder may be powered by a portable generator, a storage-battery unit, a step-down transformer, or a rectification unit.

Induction Welding

The induction welding process uses the principle of induction heating to fuse metals together. High-frequency AC is applied to a heating coil,

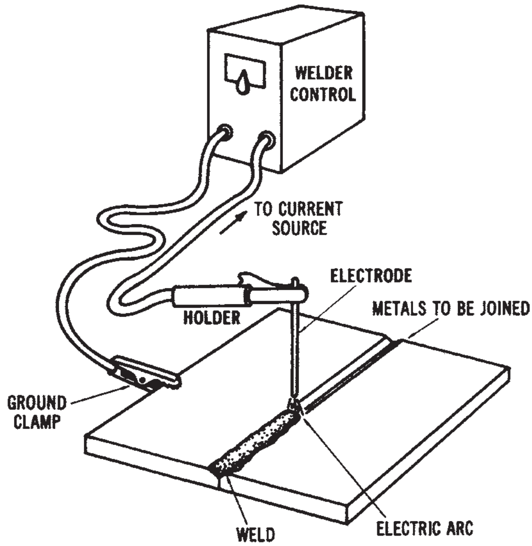

Figure 12-5. Electric arc welding

into which the materials to be welded are placed. Tubular metal is often welded in this way.

POWER CONSIDERATIONS FOR ELECTRIC WELDERS

Electric welders are rather specialized types of equipment, since they use very high amounts of current at low voltage levels. They have a peculiar effect on the power system operation. They draw large amounts of current for short periods of time. Silicon-controlled rectifiers (SCRs) are commonly used to control the starting and stopping of the large currents associated with electric welders. The current rating of these devices must be very high, sometimes in the range of 1000 to 100,000 amperes, and the power distribution equipment must be able to handle these high currents. SCRs are discussed in Chapter 17.

Figure 12-6 illustrates a typical electric welding system. The AC power supplied from the branch circuit of the power system is either stepped down by a transformer to deliver AC voltage to the welder, or rectified to produce DC voltage for DC welders. In either type of machine, an SCR contactor may be used to control the on and off time of the welder.

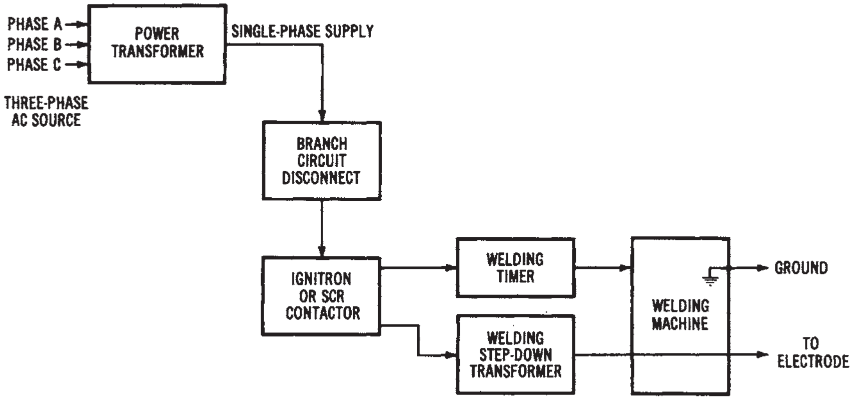

Figure 12-6. Block diagram of a typical electric welding system

SCR Contactors

SCR contactors are electronic control devices designed to handle large amounts of current. SCRs are triggered or turned on by pulses supplied by the timing or sequencing circuits of the welder. The SCRs are usually cooled by circulating water. The operating principles of SCRs are discussed in Chapter 17.

ELECTRIC HEATING AND AIR CONDITIONING SYSTEMS

A very important type of electrical power conversion is that which takes place in the heating and air conditioning systems of homes, industries, and commercial buildings. These loads convert a high percentage of the total amount of electrical power that is furnished. Although natural gas and fuel oil heating systems are still used, electrical heating is becoming more prevalent each year. Air conditioning systems are also becoming more commonly used to cool buildings. The use of electric heating and air conditioning systems has made us even more dependent upon electrical power. We now use electrical power to maintain a comfortable environment inside buildings.

Basics of Electric Heating

There are several important factors that you must understand in order to have a knowledge of electric heating. Heat is measured in British thermal units (Btus). One Btu is the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit. Heat energy in the amount of 3.4 Btus per hour is equivalent to one watt of electrical energy.

Another basic factor to be considered in the study of electric heating is *design temperature difference.* This is the difference between inside and outside temperatures in degrees Fahrenheit. The outside temperature is considered to be the lowest temperature that is expected to occur several times a year. The inside temperature is the desired temperature (thermostat setting).

A factor used in conjunction with design temperature difference is called *degree days.* The degree-day factor is used to determine the average number of degrees that the mean temperature is below 65°F. These data are averaged over seasonal periods for consideration in insulating buildings.

Importance of Insulation

The insulation of a building is a very important consideration in electric heating systems. Insulation is used to oppose the escape of heat. The quality of insulation is expressed by a thermal resistance factor (R). The total thermal resistance of a building is found by considering the thermal resistance of the entire structure (wood, concrete, insulation, et cetera). The inverse of thermal resistance is called the coefficient of heat transfer (U), which is an expression of the amount of heat flow through an area, expressed in Btus per square foot per hour per degree Fahrenheit. The following formulas are used in the conversion of either U or R to electrical units (watts):

$$\text{thermal resistance} = \frac{1}{\text{coefficient of heat transfer}}$$

$$\text{watts} = \frac{\text{coefficient of heat transfer}}{3.4}$$

or:

$$\text{watts} = 0.29 \times U$$

The manufacturers of insulation can supply various tables that can be used to estimate the heat loss that can occur in buildings of various types of construction. Heat loss occurs particularly through the windows and doors of buildings. The periodic opening of doors also has a considerable effect on heat loss. A building must have sufficient insulation to reduce heat loss; otherwise, electrical heating and air conditioning systems will be very inefficient. The heat loss of a building depends primarily upon the building construction, and upon the design temperature difference factor in the area where the building is located. Buildings made of concrete have a different amount of heat loss than those of a wood-frame construction. Heat loss will occur through the walls, floors, windows, and ceilings. Each of these must be considered when estimating the heat loss of a building.

The following sample problem will help you to understand the importance of adding insulation to a building.

Sample Problem:

Given: a building constructed to provide the following thermal resistance (R) factors:

(a) Exterior shingles are R = 0.80
(b) Plywood sheathing is R = 0.75
(c) Building paper used is R = 0.04
(d) Wall structure is R = 0.85
(e) Wall plaster is R = 0.35
(f) Insulation is R = 11.0

Find: the total thermal resistance (R), the coefficient of heat transfer (U), and the watts (W) of heat loss both with and without the insulation.

Solution (without insulation):

$$R = a + b + c + d + e$$

$$= 0.80 + 0.75 + 0.04 + 0.85 + 0.35 = 2.79$$

$$U = \frac{1}{R}$$

$$= \frac{1}{2.79}$$

$$= 0.3584 \text{ Btu per ft}^2 \text{ per hour per °F}$$

$$W = \frac{U}{3.4}$$

$$= \frac{0.3584}{3.4}$$

$$= 0.1054 \text{ watts heat loss}$$

Solution (with insulation):

$$R = a + b + c + d + e + f$$

$$= 0.80 + 0.75 + 0.04 + 0.85 + 0.35 + 11.0$$
$$= 13.79$$

$$U = \frac{1}{R}$$

$$U = \frac{1}{13.79}$$

$$= 0.0725 \text{ Btu per ft}^2 \text{ per hour per °F}$$

$$W = \frac{U}{3.4}$$

$$= \frac{0.0725}{3.4}$$

$$= 0.0213 \text{ watts heat loss}$$

You can see from the results of this problem that the adding of insulation into the walls of a building has a great effect upon heat loss. The insulation has a much greater effect in controlling heat loss than do the construction materials used for the building.

Electric Heating and Cooling Systems

Several types of electric heating systems are used today. Some common types are baseboard heaters, wall- or ceiling-mounted heaters, and heat pumps. Most of these systems use forced air to circulate the heat. Some electric heaters have individual thermostats, while others are connected to one central thermostat that controls the temperature in an entire building. The possibility of having temperature control in each room is an advantage of electric heating systems.

Heat Pumps

In recent years, the heat pump has become very popular as a combination heating and cooling unit for buildings. The heat pump is a heat-transfer unit. When the outside temperature is warm, the heat pump acts as an air conditioning unit and transfers the indoor heat to the outside of the building. This operational cycle is reversed during cool outside temperatures. In the winter, the outdoor heat is transferred to the inside of the building. This process can take place during cold temperatures, since there is always a certain amount of heat in the outside air, even at subzero temperatures. However, at the colder temperatures, there is less heat in the outside air.

Thus, heat pumps transfer heat rather than produce it. Since heat pumps do not produce heat, as resistive-heating units do, they are more economical in terms of energy conservation. Heating and cooling are reversible processes in the heat-pump unit; thus, the unit is self-contained. The reversible feature of heat pumps reduces the space requirement for separate heating and cooling units. Another advantage is that the changeover from heating to cooling can be made automatically. This feature might be desirable during the spring and autumn seasons, in the many areas where temperatures are very variable. In extremely cold areas, the heat pump can be supplemented by an auxiliary resistance-heating unit. This auxiliary unit will operate when the outside temperatures are very cold, and will be useful in maintaining the inside temperatures at a comfortable level. Air is circulated past these heating elements into the heat vents of the building.

Heat pumps are used for residential as well as commercial and industrial applications, and they are being used more extensively each year. Figure 12-7 shows a simplified circuit arrangement of a heat pump, in which a compressor takes a refrigerant from a low-temperature, low-pressure evaporator and converts it to a high temperature and a high pressure. The refrigerant is then delivered to a condenser, in much the same way as in a refrigerator.

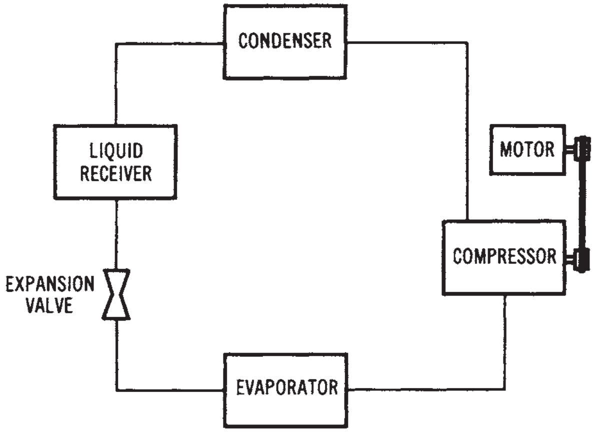

Figure 12-7. A simplified heat-pump circuit diagram

Air Conditioning Systems

The increased use of air conditioning systems provides greater comfort in homes, industrial plants, and commercial facilities. Most air conditioning units are used for the purpose of controlling the inside temperature of buildings, so as to make working and living conditions more comfortable. However, many units are used to cool the insides of various types of equipment. Both air temperature and relative humidity are changed by air conditioning units. In the design of air conditioning systems, all heat-producing items in the immediate environment must be considered. Body heat, electrical appliances, and lights represent some common sources of heat. The diffusion of heat takes place through floors, walls, ceilings, and the windows of buildings. A simplified diagram of a room air conditioning unit is shown in Figure 12-8.

Considerations for Heating Loads

Heating systems used for residential, commercial, and industrial applications are usually referred to as HVAC systems. This means heating ventilation and air conditioning system. The electrical power requirement for HVAC systems is a major concern for electrical system design for a building. Electrical HVAC systems provide individual thermostatic temperature control, have long equipment life, and are safe to use. A well-insulated building is necessary to reduce heat loss for economical use of HVAC systems.

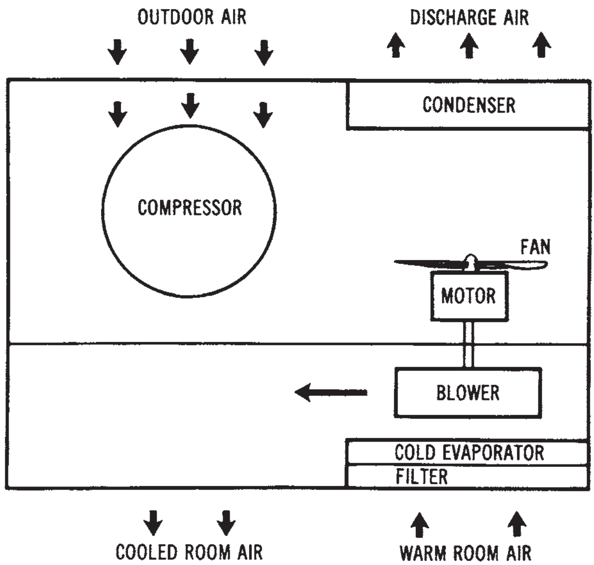

Figure 12-8. A simplified diagram of a room air conditioning unit

Electrically energized comfort heating systems are widely used today to produce heat for commercial, industrial, and residential buildings. Electrical energy is readily available at nearly any building site, and it has a number of advantages over fuel-burning methods of producing heat. Ecologically, any fuel needed to produce electricity is burned or consumed at a power plant, which is usually located some distance from the building where it is being used. With this method of heating, there is less pollution than there would be if fuel were burned at each building. Electric heat is also clean to use, easy to control, and highly efficient.

Electric heating is important today because of its high level of efficiency. Theoretically, when electrical energy is applied to a system, virtually all of it is transformed into heat energy. Essentially, this means that, when a specified amount of electricity is applied, it produces an equivalent Btu output. One thousand watts or 1 kW of electricity, when converted to heat, produces 3412 Btus of heat energy.

Heating can be achieved in a variety of ways through the use of electricity. Comfort heating systems contain an energy source, transmission path, control load device, and the possibility of one or more optional indicators. The primary difference between heat-pump and resistance electrical systems is in the production of heat energy. Resistance heating is accomplished by passing an electrical current through wires or conductors to the load device. By comparison, the heat pump operates by circulating a gas or liquid through pipes that connect an inside coil to an outside coil. Electricity is needed in both cases as an energy source to make the systems operational.

Resistance Heating in Buildings

When an electric current flows through a conductive material, it encounters a type of opposition called resistance. In most circuits this opposition is unavoidable, to some extent, because of the material of the conductor, its length, its cross-sectional area, and its temperature. The conductor wires of a heating system are purposely kept low in resistance to minimize heat production between the source and the load device. Heavy-gauge insulated copper wire is used for this part of the system.

The load device of a resistance heating system is primarily responsible for the generation of heat energy. The amount of heat developed by the load depends upon the value of current that passes through the resistive element. Element resistance is purposely designed to be quite high compared to that of the connecting wires of the system. An alloy of nickel and chromium called Nichrome is commonly used for the heating elements.

Resistive elements may be placed under windows, or at strategic locations throughout the building. In this type of installation, the elements are enclosed in a housing that provides electrical safety and efficient use of the available heat. Air entering at the bottom of the unit circulates around the fins to gain heat, than exits at the top. Different configurations may be selected according to the method of circulation desired, unit length, and heat-density production.

Resistive elements are also used as a heat source in forced-air central heating systems. In this application, the element is mounted directly in the main airstream of the system. The number of elements selected for a particular installation is based upon the desired heat output production. Individual elements are generally positioned in a staggered configuration to provide uniform heat transfer and to eliminate hot spots. The element has spring-coil construction supported by ceramic insulators. Units of this type provide an auxiliary source of heat when the outside temperature becomes quite cold. Air circulating around the element is warmed and forced into the duct network for distribution throughout the building.

Heat Pump Systems in Buildings

A heat pump is defined as a reversible air conditioning system that transfers heat either into or away from an area that is being conditioned. When the outside temperature is warm, the heat pump takes indoor heat and moves it outside, thus acting as an air conditioning unit. Operation during cold weather causes it to take outdoor heat and move it indoors, functioning as a heating unit. Heating can be performed even during cold temperatures, because there is always a certain amount of heat in the outside air. At 0°F (–22°C), for example, the air will have approximately 89 percent of the heat that it has at 100°F (38°C). Even at subzero temperatures, it is possible to develop some heat from the outside air. However, it is more difficult to develop heat when the temperature drops below 20°F (–6°C). For installations that encounter temperatures colder than this, heat pumps are equipped with resistance heating coils to supplement the system.

A heat pump, like an air conditioner, consists of a compressor, an outdoor coil, an expansion device, and an indoor coil. The compressor is responsible for pumping a refrigerant between the indoor and outdoor coils. The refrigerant is alternately changed between liquid and gaseous states, depending upon its location in the system. Electric fans or blowers are used to force air across the respective coils, and to circulate cool or warm air throughout the building.

A majority of the heat pumps in operation today consist of indoor and outdoor units that are connected together by insulated pipes or tubes. The indoor unit houses the supplemental electric heat elements, the blower and motor assembly, the electronic air cleaner, the humidifier, the control panel, and the indoor coil. The outdoor unit is covered with a heavy-gauge steel cabinet that encloses the outdoor coil, the blower fan assembly, the compressor, the expansion device, and the cycle-reversing valve. Both units are designed for maximum performance, high operational efficiency, and low electrical power consumption.

The Heating Cycle of a Heat Pump

If a unit air conditioner were turned around in a window during its operational cycle, it would be extracting heat from the outside air and pumping it into the building. This condition, which is the operational basis of the heat pump, is often called the reverse-flow air conditioner principle. The heat pump is essentially "turned around" from its cooling cycle by a special valve that reverses the flow of refrigerant through the system.

When the heating cycle occurs, the indoor coil, outdoor coil, and fans are reversed. The outdoor coil is now responsible for extracting heat from the outside air and passing it along the indoor coil, where it is released into the duct network for distribution.

During the heating cycle, any refrigerant that is circulating in the outside coil is changed into a low-temperature gas. It is purposely made to be substantially colder than the outside air. Since heat energy always moves from hot to cold, there is a transfer of heat from the outside air to the cold refrigerant. In a sense, we can say that the heat of the cold outside air is absorbed by the much colder refrigerant gas.

The compressor of the system is responsible for squeezing together the heat-laden gas that has passed through the outside coil. This action is designed to cause an increase in the pressure of the gas that is pumped to the indoor coil. As air is blown over the indoor coil, the high-pressure gas gives up its heat to the air. Warm air is then circulated through the duct network to the respective rooms of the system.

When the refrigerant gas of the indoor coil gives up its heat, it cools and condenses into a liquid. It is then pumped back to the outside coil by compressor action. Once again it is changed into a cool gaseous state and is applied to the outside coil to repeat the cycle. If the outside temperature drops too low, the refrigerant may not be able to collect enough heat to satisfy the system. When this occurs, electric-resistance heaters are energized to supplement the heating process. The place where electric heat is supplied to the system is called the *balance point.*

Figure 12-9 shows an illustration of heat-pump operation during its heating cycle. At (1), the heat is absorbed from the cold outside air by the pressurized, low-temperature refrigerant circulating through the outside coil. As (2), the refrigerant is applied to the compressor and compressed into a high-temperature, high-pressure gas. At (3), the heated gas is transferred to the indoor coil and released as heat. At (4), warm air is circulated through the duct network. Note that the supplemental resistance heat element is placed in this part of the system. At (5), the refrigerant is returned to the compressor and then to an expansion device, where the liquid refrigerant is condensed and then returned to the outdoor coil. The cycle repeats itself from this point.

The Cooling Cycle of a Heat Pump

A heat pump is designed to respond as an air conditioning unit during the summer months. For this to occur, the reversing valve must be

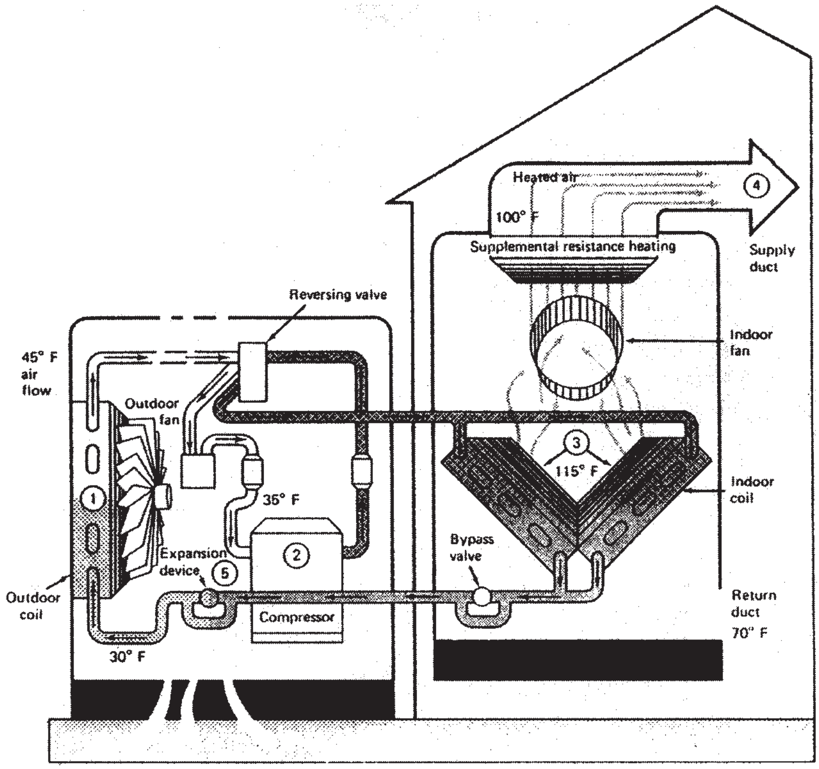

Figure 12-9. Heating cycle operation

placed in the cooling-cycle position. In some systems this is accomplished by a manual changeover switch, whereas in others it is achieved automatically, according to the thermostat setting. The operating position of the valve simply directs the flow path of the refrigerant.

When the cooling cycle is placed in operation, it first causes the refrigerant to flow from the compressor into the indoor coil. During this part of the cycle the refrigerant Is in a low-pressure gaseous state and is quite cool. As the circulation process continues, the indoor coil begins to absorb heat from the inside air of the building. Air passing over the indoor coil is cooled and circulated into the duct network for distribution throughout the building.

After leaving the indoor coil, the refrigerant must pass through the reversing valve and into the compressor. The compressor is responsible for increasing the pressure of the refrigerant and circulating it into the outdoor coil. At this point of the cycle, the refrigerant gives up its heat to the outside air, is cooled, and is changed into a liquid state. It then returns to the compressor, where it is pumped through an expansion device and returned to the indoor coil. The process then repeats itself

Figure 12-10 shows an illustration of the heat pump during its air conditioning cycle. At (1), heat is absorbed from the inside air and cool air is transferred into the building. At (2), the pressure of the heat-laden refrigerant is increased by the compressor and cycled into the outside coil for transfer to the air. At (3), cool, dehumidified air is circulated through the duct network as a result of passing through the cooled indoor coil. At (4), the refrigerant condenses back into a liquid as it circulates through the outdoor coil. At (5), the liquid refrigerant flows through the compressor and expansion device, where it is vaporized and returned to the indoor coil to complete the cycle.

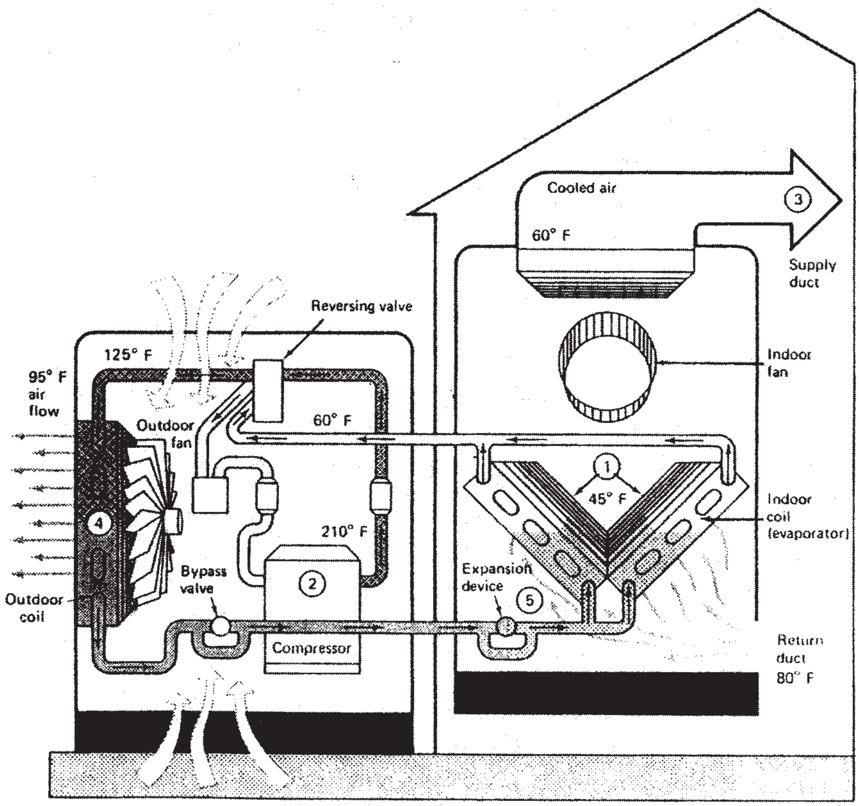

Figure 12-10. Cooling cycle operation

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Chapter 13

Lighting Systems

Electrical lighting systems are designed to create a comfortable and safe home or working environment. There are several types of lighting systems in use today. Among the most popular are incandescent, fluorescent, and vapor lights, as well as several special-purpose types of lighting. Lighting systems are one type of electrical *load.*

The three types of lighting systems discussed in this chapter constitute most of the lighting loads placed on electrical power systems. Incandescent, fluorescent, and vapor lights are used for many lighting applications. However, there are a few other specialized types of lighting that are also used. These include zirconium and xenon arc lights, glow lights, black lights, and infrared lights. The planning involved in obtaining proper lighting is quite complex and may involve several types of lights.

IMPORTANT TERMS

Chapter 13 deals with lighting systems. After studying this chapter, you should have an understanding of the following terms:

Visible Light
Electromagnetic Spectrum
Candlepower
Lumen
Footcandle
Reflection Factor Footlambert
Street Lighting
Incandescent Lighting
Fluorescent Lighting
Vapor Lighting
Lighting Circuits
Three-Way Switch

Four-Way Switch
Lighting Branch Circuits
Lighting Fixture
Luminaire
Coefficient of Utilization (CU)
Room Ratio
Depreciation Factor (DF)
Light Output

CHARACTERISTICS OF LIGHT

In order to better understand lighting systems, you should know something about the basic characteristics of light. Light is a visible form of radiation that is actually a narrow band of frequencies along the vast electromagnetic spectrum. The electromagnetic spectrum, shown in Figure 13-1, includes bands of frequencies for radio, television, radar, infrared radiation, visible light, ultraviolet light, x-rays, gamma rays, and various other frequencies. The different types of radiation, such as light, heat, radio waves, and x-rays, differ only with respect to their frequencies, or wavelengths.

The human eye responds to electromagnetic waves in the *visible light* band of frequencies. Each color of light has a different frequency, or wavelength. In order of increasing frequency (or decreasing wavelengths), the colors are red, orange, yellow, green, blue, indigo, and violet. The wavelengths of visible light are in the 400-millimicrometer (violet) to 700-millimicrometer (red) range. A micrometer (mm), which is also called a micron (μm), is one millionth of a meter, and a nanometer (nm) is 1×10^{-3} micrometer. Angstrom units (Å) are also used for light measurement. An angstrom unit is one-tenth of a nanometer. In order to avoid confusion, use the conversion chart given in Table 13-1.

Visible light ranges from 4000 Å to 7000 Å. The response of the human eye to visible light exhibits a frequency selective characteristic, as shown in Figure 13-2. The greatest sensitivity is near 5500 Å. The poorest sensitivity is around 4000 Å on the lower wavelengths, and 7000 Å on the higher wavelengths. Our eyes perceive various degrees of brightness, depending on their response to the wavelengths of light. The normal human eye cannot see a wavelength of less than 4000 Å (<400 nm), or more than 7000 Å (>700 nm).

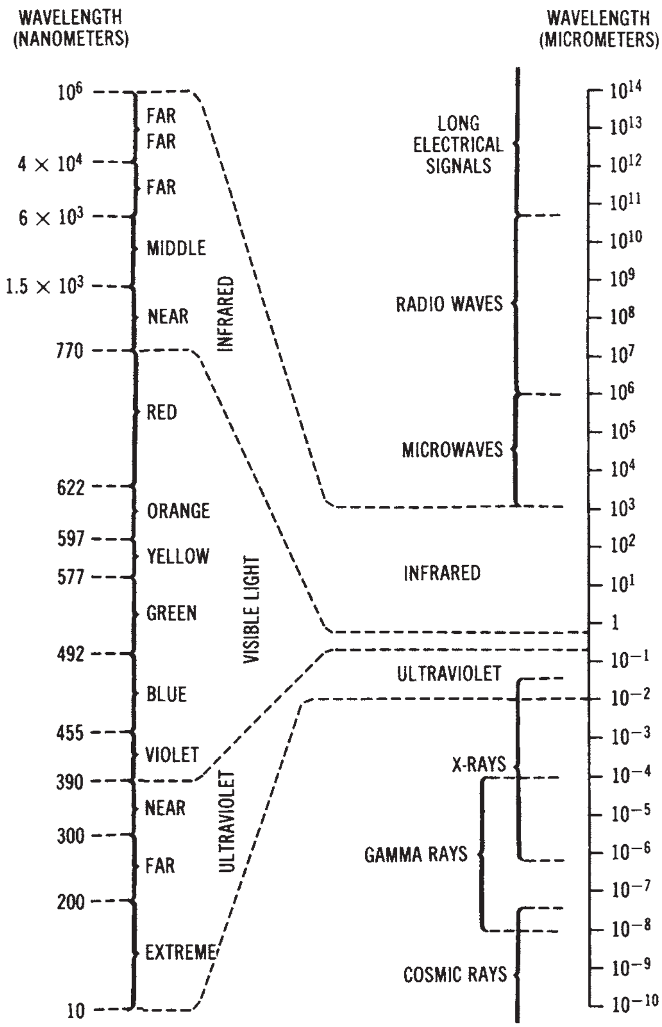

Figure 13-1. The electromagnetic spectrum

When dealing with light, there are several characteristic terms that you should understand. The unit of luminous intensity is a standard light source called a *candela* or *candlepower.* The intensity of light is expressed in one of these units. The amount of light falling on a unit surface, all points of which are a unit distance from a uniform light source of one candela, is one *lumen.* The illumination of a surface is the number of lumens falling

Table 13-1. Conversion Chart for Electromagnetic Wavelengths

Known Quantity	*Multiply by*	*Quantity To Find*
Angstrom (Å)	10	Nanometer (nm)
	10^4	Micron (μm)
	10^7	Millimeter (mm)
	10^8	Centimeter (cm)
	10^{10}	Meter (m)
	10^{13}	Kilometer (km)
Micron	10^{-4}	Angstrom (Å)
	10^{-3}	Nanometer (nm)
	10^3	Millimeter (mm)
	10^4	Centimeter (cm)
	10^6	Meter (m)
Nanometer	10^{-1}	Angstrom (Å)
	10^3	Micron (μm)
	10^6	Millimeter (mm)
	10^7	Centimeter (cm)
	10^9	Meter (m)

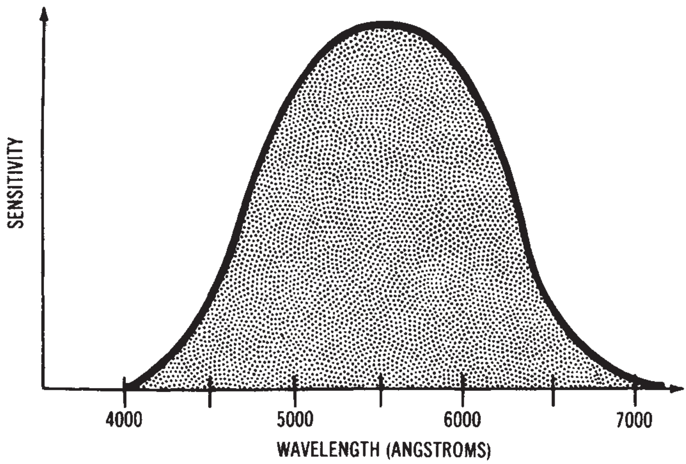

Figure 13-2. Response of the human eye to visible light

on it per unit area. The unit of illumination is the *lux* (lumens per square meter) or *footcandle* (lumens per square foot).

We see only light that is reflected. Reflected light is measured in candelas per square meter of surface (or footlamberts). The *reflection factor* is the percent of light reflected from a surface expressed as a decimal. Therefore, the light reflected from a surface is equal to the illumination of the surface times the reflection factor. The brightness of a surface that reflects one lumen per square foot is one *footlambert.*

Units of light measurement are given in both English and International Systems of Units (metric) units. This can become somewhat confusing. Table 13-2 summarizes the most common terms used for light measurement.

Table 13-2. Lighting Terms

Lighting			*Unit*		
Quantity	*Definition*	*Symbol*	*SI*	*English*	*Definition of Unit*
Luminous intensity (candlepower)	Ability of source to produce light in a given direction	I		Candela (cd)	Approximately equal to the luminous intensity produced by a standard candle
Luminous flux	Total amount of light	φ		Lumen (lm)	Luminous flux emitted by a 1 candela uniform point source
Illumination	Amount of light received on a unit area of surface (density)	*E*	Lux (lx)	Footcandle (fc)	One lumen equally distributed over one unit area of surface
Luminance (brightness)	Intensity of light per unit of area reflected or transmitted from	*L*	ed/m^2 (foot-lambert)	ed/ in.^{2}	A surface reflecting or emitting light at the rate of 1 candela per unit of projected area.

Incandescent Lighting

Incandescent lighting is a widely used method of lighting, used for many different applications. The construction of an incandescent lamp is shown in Figure 13-3. This lamp is simple to install and maintain. The initial cost is low; however, incandescent lamps have a relatively low efficiency and a short life span.

Incandescent lamps usually have a thin tungsten filament, which is in the shape of a coiled wire. This filament is connected through the lamp base to a voltage source (usually 120 volts AC). When an electric current is passed through the filament, the temperature of the filament rises to between 3000° to 5000° Fahrenheit. At this temperature range, the tungsten produces a high-intensity white light. When the incandescent lamp is manufactured, the air is removed from the glass envelope to prevent the filament from burning; also, an inert gas is added.

Incandescent lamps are purely resistive devices, and thus have a power factor of 1.0. As they deteriorate, their light output is reduced. Typically, at the time that an incandescent lamp bums out, its light output is less than 85 percent of its original output. A decrease in the voltage of the power system also reduces the light output. A 1 percent decrease in voltage will cause a 3 percent decrease in light output.

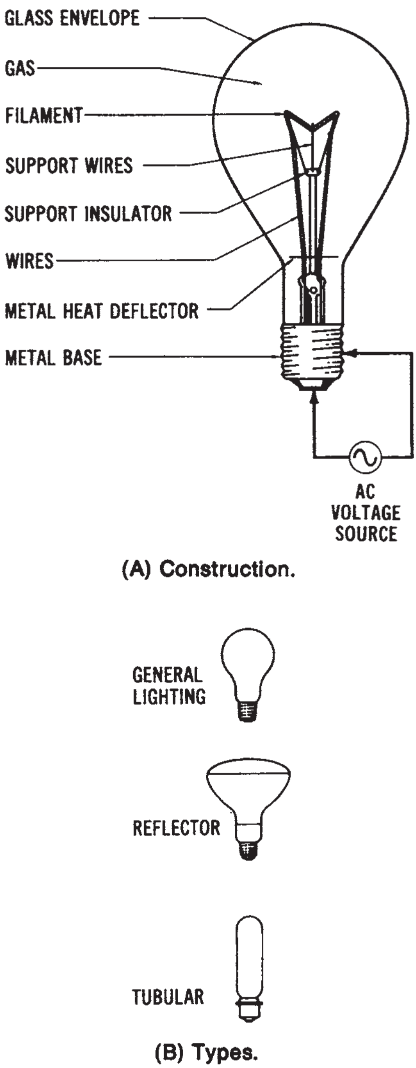

Figure 13-3. The incandescent lamp: (A) Construction, (B) Types

Fluorescent Lighting

Fluorescent lighting is used extensively today, particularly in industrial and commercial buildings. Fluorescent lamps are tubular bulbs with a filament at each end. There is no electrical connection between the two filaments. The operating principle of the fluorescent lamp is shown in Figure 13-4. The tube is filled with mercury vapor; thus, when an electrical current flows through the two filaments, a continuous arc is formed between them by the mercury vapor. High-velocity electrons passing between the filaments collide with the mercury atoms, producing an ultraviolet radiation. The inside of the tube has a phosphor coating that reacts with the ultraviolet radiation to produce visible light.

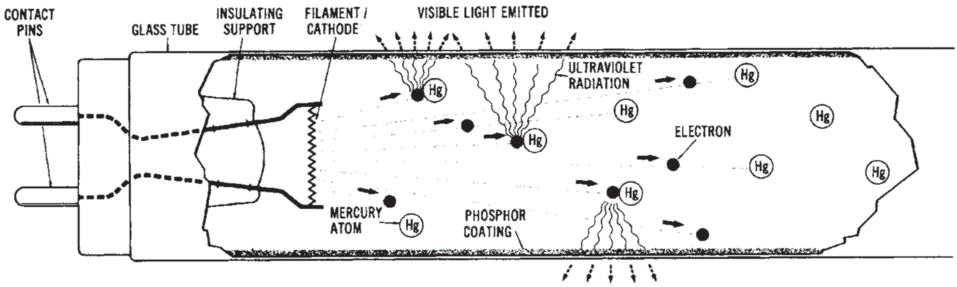

Figure 13-4. Operating principle of a fluorescent lamp

One circuit for a fluorescent light is shown in Figure 13-5. Note that a thermal starter, which is basically a bimetallic strip and a heater, is connected in series with the filaments. The bimetallic strip remains closed long enough for the filaments to heat and vaporize the mercury in the tube. The bimetallic switch will then bend and open as the result of the

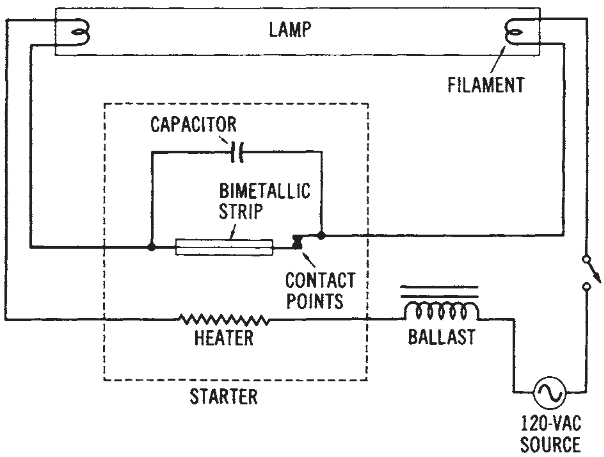

Figure 13-5. Circuit diagram of a fluorescent lamp

heat produced by current flow through the heater. The filament circuit is now opened. A capacitor is connected across the bimetallic switch to reduce contact sparking. Once the contacts of the starter open, a high voltage momentarily occurs between the filaments of the lamp, because of the action of the inductive ballast coil. The ballast coil has many turns of small-diameter wire, and, thus, it produces a high, counter-electromotive force when the contacts of the starter separate. This effect is sometimes called "inductive kickback." The high voltage across the filaments causes the mercury to ionize and initiates a flow of current through the tube. There are several other methods used to start fluorescent lights; however, this method illustrates the basic operating principle.

Fluorescent lights produce more light per watt than incandescent lights; therefore, they are cheaper to operate. Since the illumination is produced by a long tube, there is also less glare. The light produced by fluorescent bulbs is very similar to natural daylight. The light is whiter, and the operating temperature is much lower with fluorescent than with incandescent lights. Various sizes and shapes of fluorescent lights are available. The bulb sizes are expressed in eighths of an inch, with the common sizes being T-12 and T-8. (A T-12 bulb is 1-1/2 inches.) Common lengths are 24, 48, 72, and 96 inches.

Vapor Lighting

Another popular form of lighting is the vapor type. The mercury-vapor light is one of the most common types of vapor light. Another common type is the sodium-vapor light. These lights are filled with a gas that produces a characteristic color. For instance, mercury vapor produces a greenish-blue light, and argon a bluish white light. Gases may be mixed to produce various color combinations for vapor lighting. This is often done with signs used for advertising.

A mercury-vapor lamp is shown in Figure 13-6. It consists of two tubes with an arc tube placed inside an outer bulb. The inner tube contains mercury. When a voltage is applied between the starting probe and an electrode, an arc is started between them. The arc current is limited by a series resistor; however, the current is sufficient to cause the mercury in the inner tube to ionize. Once the mercury has ionized, an intense greenish-blue light is produced. Mercury-vapor lights are compact, long-lasting, and easy to maintain. They are used to provide a high-intensity light output. At low voltages, mercury is slow to vaporize, so these lamps require a long starting time (sometimes 4 to 8 minutes). Mercury-vapor lights can also be used for outdoor lighting.

The sodium-vapor light, shown in Figure 13-7, is popular for outdoor lighting and for highway lighting. This lamp contains some low-pressure neon gas and some sodium. When an electric current is passed through the heater, electrons are given off. The ionizing circuit causes a positive charge to be placed on the electrodes. As electrons pass from the heater to the positive electrodes, the neon gas is ionized. The ionization of the neon gas produces enough heat to cause the sodium to ionize. A yellowish light is produced by the sodium vapor. The sodium-vapor light can produce about three times the candlepower per watt as an incandescent light.

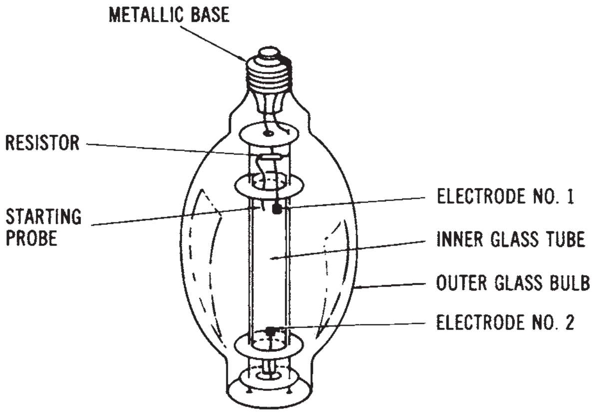

Figure 13-6. A mercury-vapor lamp

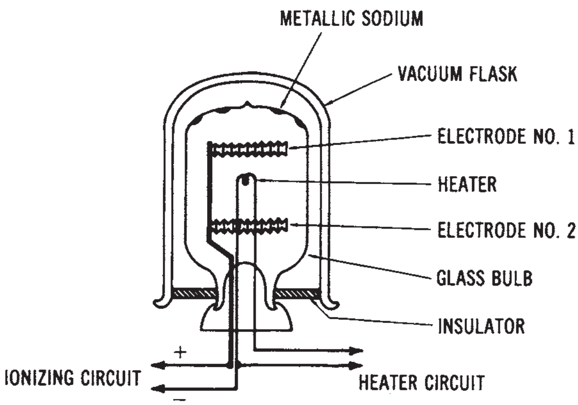

Figure 13-7. A sodium-vapor lamp.

Another type of vapor lamp is called a *metal halide* type. This light source is a high intensity mercury-vapor lamp in which metallic substances, called metal halides, are added to the bulb. The addition of these substances improves the efficacy of the lamps. The efficacy of a metal halide lamp is typically 75 lumens/watt, compared to approximately 50 lumens/watt for mercury-vapor lamps.

Another type of vapor lamp is the high-pressure sodium (HPS) lamp. Sodium is the primary element used to fill the lamp's tube when it is manufactured. These lamps have very high efficacies-approximately 110 lumens/watt.

Street Lighting

The lighting systems of today are highly reliable, compared to the systems that were installed many years ago. Earlier systems were turned on and off either manually, or by timing devices that were regulated by the time of day, rather than by the natural light intensity. Some were controlled by electrical impulses that were transmitted on the power lines. Now, most systems are controlled by automatic photoelectric circuits. The lights that are now used to illuminate streets and highways have photoelectric controls. They operate during periods of darkness and are automatically turned off when natural light is present. These street lights are usually connected to existing 120/240-volt power distribution systems.

There are many types of street lights in use. The earliest types of electric street lights used were 200- to 1000-watt incandescent lamps. Now, mercury-vapor and sodium-vapor lamps are the primary types used. (Mercury lamps produce a white light, and sodium lamps have a yellowish color.) Several different lamp designs and mounting fixture designs are used.

Several years ago, street lights were converted from incandescent lamps to mercury-vapor lamps. Now the trend in street lighting seems to be toward the use of sodium-vapor lights, and several areas of the country have converted to the use of sodium-vapor lamps. Sodium-vapor lights produce more illumination than a similar mercury-vapor light. They also require less electrical power to produce a specific amount of illumination. Thus, the ability of sodium-vapor lights to deliver more light with less power consumption makes them more economically attractive than mercury-vapor lights.

Comparison of Light Sources

The purpose of a light source is to convert electrical energy into light energy. A measure of how well this is done is called efficacy. Efficacy is the lumens of light produced per watt of electrical power converted. A comparison of some different types of light sources is shown below:

Lamp Type	*Efficacy (Lumens/watt)*
200 Watt incandescent lamp	20
400 Watt mercury lamp	50
40 Watt fluorescent lamp	70
400 Watt metal halide lamp	75
400 Watt high-pressure sodium lamp	110

ELECTRICAL LIGHTING CIRCUITS

There are several types of electrical circuits that are used for electrical lighting control. We will study some of the circuits used for incandescent and fluorescent lighting systems. Electrical lighting circuits for different areas of a building must be wired properly. Some lighting fixtures are controlled from one point by one switch, while other fixtures may be controlled from two or more points by a switch at each point.

Incandescent lighting circuits are a typical type of branch circuit. The most common type of incandescent lighting circuit is a 120-volt branch that extends from a power distribution panel to a light fixture or fixtures in some other area of a building. The path for the electrical distribution is controlled by one or more switches that are usually placed in small metal or plastic enclosures inside a wall. These switches are then covered by rectangular plastic plates to prevent possible shock hazards.

Switches are always placed in a wiring circuit so that they can open or close a hot wire. This hot wire distributes electrical power to the lighting fixtures that the switches control. These switches are referred to as "T-rated" switches. They are designed to handle the high, instantaneous current drawn by lights when they are turned on. A switch that accomplishes control from a single location is a simple, single-pole, single-throw (spst) switch, such as that shown in Figure 13-8. A pictorial view of the same circuit is shown in Figure 13-9.

Control from two locations, such as near the kitchen door and inside the garage door, is accomplished by two 3-way switches. This circuit is

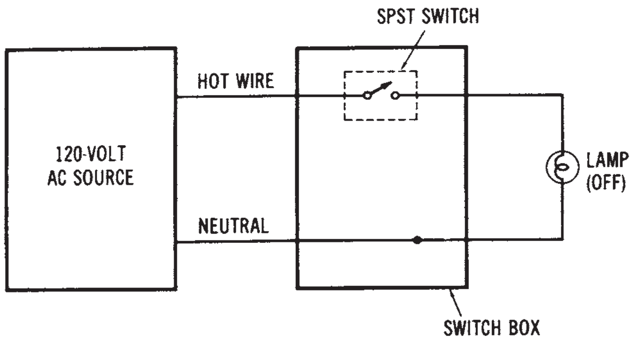

Figure 13-8. Schematic diagram for the control of a light from one location

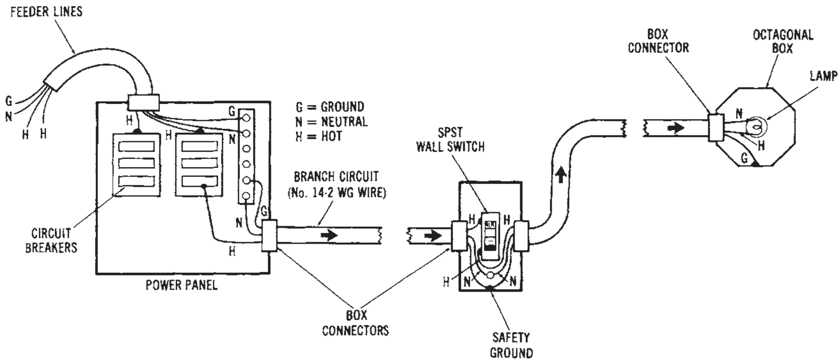

Figure 13-9. Pictorial view of the circuit shown in Figure 13-8

shown in Figure 13-10A, while Figure 13-11 presents a pictorial view of the same circuit. When control of a lighting fixture from more than two points is desired, two 3-way switches and one or more 4-way switches are used. For instance, control of one light from five points could be accomplished by using a combination of two 3-way switches and three 4-way switches. Figure 13-12 and 13-13 show a circuit for controlling a light from three locations. The 3-way switches are always connected to the power panel and to the light fixture, with the 4-way switch between them. The use of 3-way and 4-way switch combinations makes it possible to achieve control of a light from any number of points.

Each lighting-control circuit requires an entirely different type of switching combination to adequately accomplish control of a lighting fixture. These circuits are usually wired into buildings during construction, in order to provide the type of lighting control desired for each room. You should study the diagrams of Figures 13-8 through 13-13 to fully understand how these lighting circuits operate.

BRANCH CIRCUIT DESIGN

The design of lighting branch circuits involves the calculation of the maximum current that can be drawn by the lights that are connected to the branch circuit. Many times, particularly in homes, a lighting branch circuit also has duplex receptacles for portable appliances. This makes the exact current calculation more difficult, since not all the lights or the appliances will be in use at the same time.

The National Electrical Code (NEC) specifies that there should be at least one branch circuit for each 500 square feet of lighting area. The NEC further specifies a minimum requirement for lighting for various types of buildings. Table 13-3 lists the number of watts of light per square foot required in some buildings.

The solution of a typical branch circuit lighting problem follows.

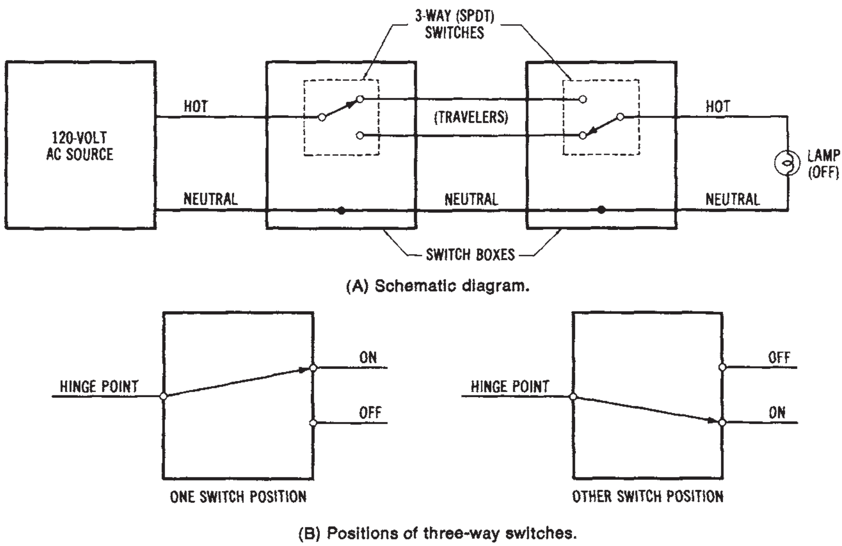

Figure 13-10. Circuit for controlling a light from two locations: (A) Schematic diagram, (B) Positions of three-way switches

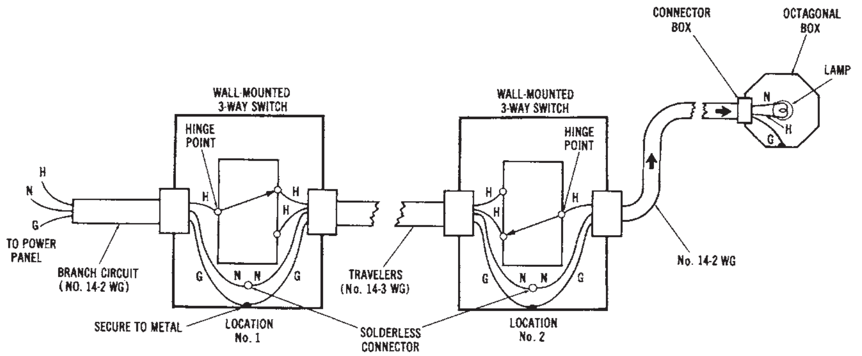

Figure 13-11. Pictorial view of the circuit of Figure 13-10 (A)

Table 13-3. Building Lighting Requirements in Wattage per Square Foot

Type of Building	*Watts*
Armories and Auditoriums	1
Banks	2
Churches	1
Dwellings (other than hotels)	3
Garages (for commercial storage)	1/2
Hospitals	2
Hotels and Motels	2
Industrial or Commercial Buildings	2
Office Buildings	5
Restaurants	2
Schools	3
Stores (grocery)	3
Warehouses (storage)	1/4

Sample Problem:

Given: a room in a commercial building is 70 feet × 120 feet (21.34 × 36.58 meters). It will use 125 fluorescent lighting units that draw 3 amperes each. Also, 20-ampere branch circuits will be used. The power factor of the units is 0.75. The operating voltage is 120 volts.

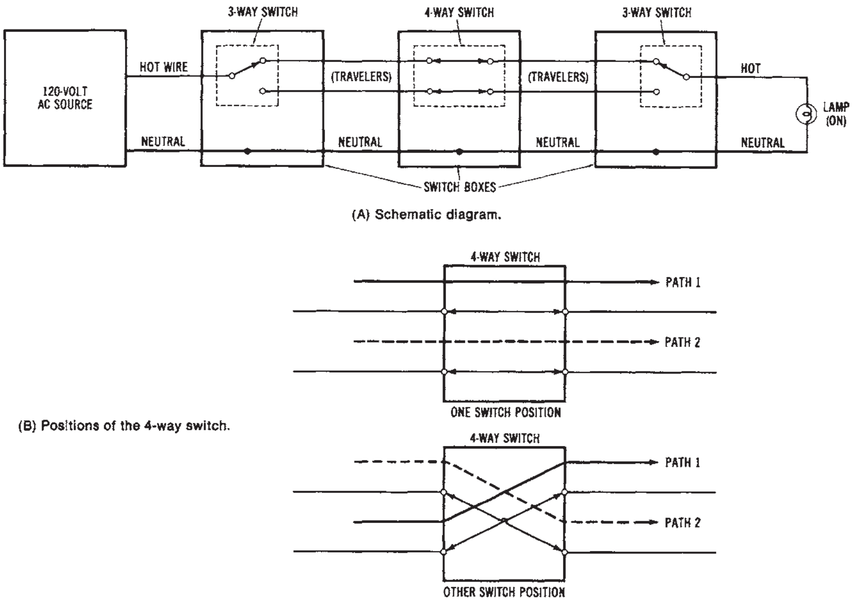

Figure 13-12. Circuit for controlling a light from three locations: (A) Schematic diagram, (B) Positions of the four-way switch

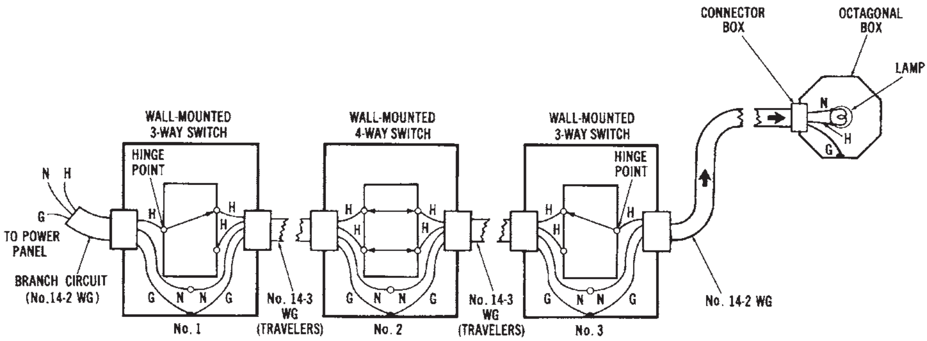

Figure 13-13. Pictorial view of the circuit shown in Figure 13-12(A)

Find: the minimum number of branch circuits needed, and the total power requirement for the lighting units.

Solution for the branch circuits:

1. Find the number of units that should be installed on each branch circuit.

$$\text{units} = \frac{\text{branch current}}{\text{load current}}$$

$$= \frac{\text{20 amperes}}{\text{3 amperes}}$$

$$= \text{6.67 units (round off at 6)}$$

2. Find the number of branch circuits needed.

$$\text{circuits} = \frac{\text{lighting units}}{\text{No. units per branch circuit}}$$

$$= \frac{125}{6}$$

$$= \text{20.8 (round up to 21)}$$

Twenty-one 20-ampere branch circuits will be needed.

Solution for total power:

1. Find the total current drawn by the lights.

$$\begin{aligned} I &= \text{125 units} \times \text{3 amperes} \\ &= \text{375 amperes} \end{aligned}$$

2. Calculate the total power.

$$\begin{aligned} p &= V \times I \times pf \\ &= 120 \times 375 \times 0.75 \\ &= \text{33,750 watts (33.75 kW)} \end{aligned}$$

An even more common type of branch circuit lighting problem is given in the following discussion. This problem begins with the minimum number of lights required in a room. The number of branch circuits that are required must be determined.

<u>Sample Problem</u>:

Given: a large room in an industrial building needs to have 40,000 watts of incandescent lighting. It is decided that 120-volt 20-ampere branch circuits will be used. The lights will use 200-watt bulbs.

Find: the number of branch circuits required for the lighting.

Solution:

1. Find the amount of current each lamp will draw.

$$I = \frac{P}{V}$$

$$= \frac{200 \text{ watts}}{120 \text{ volts}}$$

$$= 1.67 \text{ amperes}$$

2. Find the maximum number of lamps in each branch circuit.

$$\text{lamps} = \frac{\text{amperage of circuit}}{\text{amperage of lamps}}$$

$$= \frac{20 \text{ amperes}}{1.67 \text{ amperes}}$$

$$= 11.97 \text{ (round down to 11)}$$

3. Find the total number of bulbs (lamps needed.

$$\text{bulb required} = \frac{\text{wattage of room}}{\text{wattage of bulbs}}$$

$$= \frac{40{,}000 \text{ watts}}{200 \text{ watts}}$$

$$= 200 \text{ bulbs required}$$

4. Find the minimum number of branch circuits needed.

$$\text{branch circuits} = \frac{\text{total bulbs required}}{\text{number of bulbs per circuit}}$$

$$= \frac{200}{11}$$

$$= 18.18 \text{ (round up to 19)}$$

Nineteen branch circuits will be needed.

It should be pointed out that, in these problems, we determined the minimum number of branch circuits. But room for flexibility should be provided for each branch circuit. This can be done by designing the circuit to handle only 16 amperes (80 percent) rather than 20 amperes. Also, room should be provided on the power distribution panel to allow for connecting some additional lighting branch circuits. This will allow additional loads to be connected at a later time.

LIGHTING FIXTURE DESIGN

Lighting fixtures are the devices that are used to hold lamps in place. They are commonly referred to as luminaires. Luminaires are used to efficiently transfer light from its source to a work surface. The proper design of luminaires allows a more efficient transfer of light. It is important to keep in mind that light intensity varies inversely as the square of the distance from the light source. Thus, if the distance is doubled, the light intensity will be reduced four times.

Many factors must be considered in determining the amount of light that is transferred from a light bulb to a work surface. Some light is absorbed by the walls and by the light fixture itself; thus, not all light is efficiently transferred. The manufacturers of lighting systems develop charts that are used to predict the amount of light that will be transferred to a work surface. These charts take into consideration the necessary variables for making a prediction of the quantity of light falling onto a surface.

Each luminaire has a rating, which is referred to as its *coefficient of utilization.* The coefficient of utilization is a factor that expresses the percentage of light output that will be transferred from a lamp to a work area. The coefficient of a luminaire is determined by laboratory tests made by the manufacturer. These coefficiency charts also take into consideration the light absorption characteristics of walls, ceilings, and floors, when the coefficient of utilization of a luminaire is to be determined.

Another factor used for determining the coefficient of utilization is the *room ratio.* Room ratio is very simply determined by the formula:

$$\text{room ratio} = \frac{W \times L}{H\,(W + L)}$$

where:

W = the room width in feet,
L = the room length in feet, and
H = the distance in feet from the light source to the work surface.

Note: Work surfaces are considered to be 2.5 feet from the floor, unless otherwise specified.

FACTORS IN DETERMINING LIGHT OUTPUT

There are several other factors that must be considered in order to determine the amount of light transferred from a light source to a work surface. We know, for instance, that the age of a lamp has an effect on its light output. Lamp manufacturers determine a *depreciation factor* or *maintenance factor* for luminaires. This factor expresses the percentage of light output available from a light source. A depreciation factor of 0.75 means that in the daily use of a light source, only 75 percent of the actual light output is available for transfer to the work surface. The depreciation factor is an average value. It takes into consideration the reduction of light output with age, and the accumulation of dust and dirt on the luminaires. Some collect dust more easily than others.

The following problem shows the effect of the coefficient of utilization (CD) and the depreciation factor (OF) on the light output transferred to a work surface.

Sample Problem:

Given: a lighting system for a building has 16 luminaries. Each luminaire has two fluorescent lamps. Each lamp has a light output of 3000 lumens. The CD and OF found in the chart developed by the manufacturer are 0.45 and 0.90, respectively.

Find: the total light output from the lighting system.

Solution:

1. Find the total light output from the lamps.

$$3000 \text{ lumens per lamp} \times 16 \text{ luminaires} \times 2 \text{ lamps per luminaire} = 96{,}000 \text{ lumens}$$

2. Find the total light output:

$$\begin{aligned} \text{light output} &= \text{total lumens} \times CD \times DF \\ &= 96{,}000 \times 0.45 \times 0.90 \\ &= 38{,}880 \text{ lumens} \end{aligned}$$

The distribution of light output onto work surfaces must also be considered. The CD and the DF are used to find the total light output of a lighting system. A greater light output is required for larger areas. The light output to a work surface is expressed as lumens per square foot, or footcandles. A light meter is used to measure the quantity of light that reaches a surface.

The following two formulas are useful for finding the required lumens for a work area, or the light output available from a particular lighting system:

$$\text{total lumens} = \frac{\text{desired footcandles} \times \text{room area in ft.}}{CD \times DF}$$

and

$$\text{footcandles available} = \frac{\text{total lumens} \times CD \times DF}{\text{room area in feet}}$$

<u>Sample Problem</u>:

Given: a lighting system with 12,000 total lumen output, luminaire CD = 0.83 and DF = 0.85, is installed in a 600 sq. ft. room.

Find: the footcandles of light available on the work surface.

Solution:

$$FC = \frac{\text{lumens} \times CD \times DF}{\text{room area}}$$

$$= \frac{12{,}000 \times 0.83 \times 0.85}{600}$$

$$FC = 14.11 \text{ footcandles}$$

Considerations for Electrical Lighting Loads

Incandescent lamps produce light by the passage of electrical current through a tungsten filament. The electrical current heats the filament to the point of incandescence, which causes the lamp to produce light. The primary advantage of incandescent lights is their low initial cost. However, they have a very low efficacy (lumen/watt) rating. They also have a very high operating temperature and a short life expectancy. Incandescent lights are usually not good choices of light sources for commercial, industrial, or outdoor lighting applications; their primary applications are for residential use.

Fluorescent light sources have a higher efficacy (lumens/watt) than incandescent lights. They have a much longer life, and lower brightness and operating temperature. Fluorescent lights are used for residential (120-volt applications) and for general-purpose commercial and industrial lighting (120-volt and 277-volt systems). Disadvantages of fluorescent lights include the necessity for a ballast and a rather large luminaire. They also have a higher initial cost than incandescent lamps. It is estimated that fluorescent light sources provide approximately 70 percent of the lighting in the United States.

Vapor light sources also have very good efficacy ratings and long life expectancies. They have a high light output for their compact size. They are typically used for industrial, commercial, and outdoor applications, since they can be operated economically on higher-voltage systems. The initial cost of vapor lights is high, they require a ballast, and they are a very bright light source. Their very high efficacy ratings have led to increased use of vapor light sources.

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