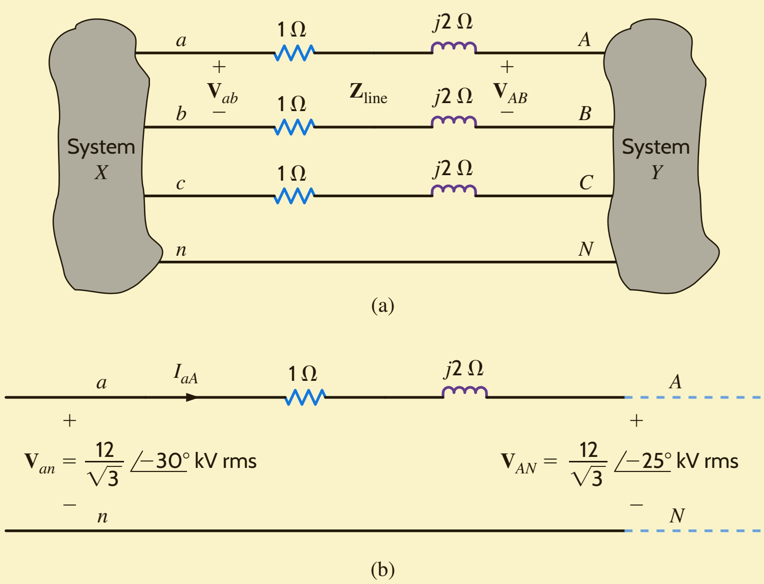

Figure 11.21 Circuits used in Example 11.10: (a) original three-phase system, (b) per-phase circuit.

The preceding example illustrates an interesting point. Note that the phase difference between the two ends of the power line determines the direction of the power flow. Since the numerous power companies throughout the United States are tied together to form the U.S. power grid, the phase difference across the interconnecting transmission lines reflects the manner in which power is transferred between power companies.

Capacitors for power factor correction are usually specified by the manufacturer in vars rather than in farads. Of course, the supplier must also specify the voltage at which the capacitor is designed to operate, and a frequency of 60 Hz is assumed. The relationship between capacitance and the var rating is

$$Q_R = \frac{V^2}{Z_C}$$

where Q_R is the var rating, V is the voltage rating, and Z_C is the capacitor's impedance at 60 Hz. Thus, a 500-V, 600-var capacitor has a capacitance of

$$C = \frac{Q_R}{\omega V^2} = \frac{600}{(377)(500)^2}$$

or

$$C = 6.37\ \mu\text{F}$$

and can be used in any application where the voltage across the capacitor does not exceed the rated value of 500 V.

11.5 Power Factor Correction

In Section 9.7 we illustrated a simple technique for raising the power factor of a load. The method involved judiciously selecting a capacitor and placing it in parallel with the load. In a balanced three-phase system, power factor correction is performed in exactly the same manner. It is important to note, however, that the $\mathbf{S}_{\text{cap}}$ specified in Eq. (9.37) is provided by three capacitors, and in addition, V_{rms} in the equation is the voltage across each capacitor. The following example illustrates the technique.

HINT

Major precautions for three-phase power factor correction:

Must distinguish P_T and P_p. Must use appropriate V_{rms} for Y- and Δ-connections.

EXAMPLE 11.11

In the balanced three-phase system shown in Fig. 11.22, the line voltage is 34.5 kV rms at 60 Hz. We wish to find the values of the capacitors C such that the total load has a power factor of 0.94 leading.

SOLUTION

Following the development outlined in Section 9.7 for single-phase power factor correction, we obtain

$$\begin{aligned}\mathbf{S}_{\text{old}} &= 24\underline{/\cos^{-1} 0.78} \text{ MVA} \\ &= 18.72 + j15.02 \text{ MVA}\end{aligned}$$

and

$$\begin{aligned}\theta_{\text{new}} &= -\cos^{-1} 0.94 \\ &= -19.95°\end{aligned}$$

Therefore,

$$\begin{aligned}\mathbf{S}_{\text{new}} &= 18.72 + j18.72 \tan(-19.95°) \\ &= 18.72 - j6.80 \text{ MVA}\end{aligned}$$

and

$$\begin{aligned}\mathbf{S}_{\text{cap}} &= \mathbf{S}_{\text{new}} - \mathbf{S}_{\text{old}} \\ &= -j21.82 \text{ MVA}\end{aligned}$$

However,

$$-j\omega C\, V_{\text{rms}}^2 = \frac{-j21.82 \text{ MVA}}{3}$$

and since the line voltage is 34.5 kV rms, then

$$(377)\left(\frac{34.5\text{k}}{\sqrt{3}}\right)^2 C = \frac{21.82}{3} \text{ M}$$

Hence,

$$C = 48.6 \ \mu\text{F}$$

HINT

The reactive power to be supplied by C is derived from the expression

$$jQ_{\text{cap}} = -j\omega C V_{\text{rms}}^2$$

The phase voltage for the Y connection is

$$V_Y = \frac{34.5\text{k}}{\sqrt{3}}$$

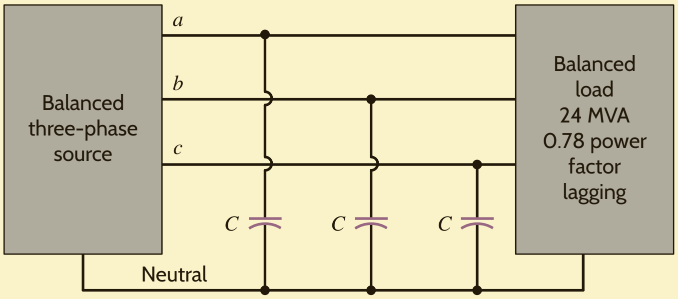

Figure 11.22

Network used in Example 11.11.

LEARNING ASSESSMENTS

E11.15 Find C in Example 11.11 such that the load has a power factor of 0.90 lagging.

ANSWER: $C = 13.26\ \mu\text{F}$.

E11.16 Find C in Fig. E11.16 such that the power factor of the source is 0.98 lagging.

ANSWER: $C = 14.2\ \mu\text{F}$.

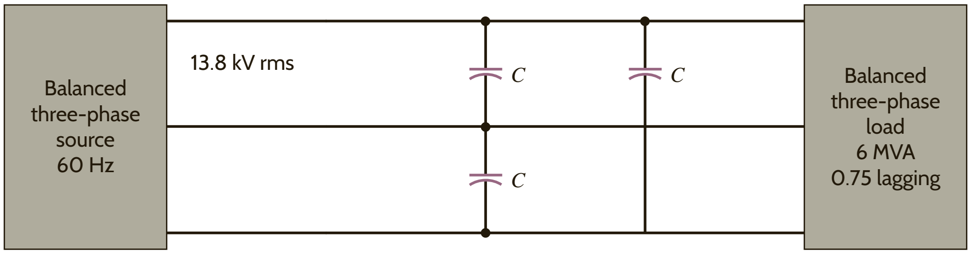

Figure E11.16

In the following example, we examine the selection of both the conductor and the capacitor in a practical power factor situation.

EXAMPLE 11.12

Two stores, as shown in Fig. 11.23, are located at a busy intersection. The stores are fed from a balanced three-phase 60-Hz source with a line voltage of 13.8 kV rms. The power line is constructed of a #4ACSR (aluminum cable steel reinforced) conductor that is rated at 170 A rms.

A third store, shown in Fig. 11.23, wishes to locate at the intersection. Let us determine (1) if the #4ACSR conductor will permit the addition of this store, and (2) the value of the capacitors connected in wye that are required to change the overall power factor for all three stores to 0.92 lagging.

SOLUTION

1. The complex power for each of the three loads is

$$\begin{aligned}\mathbf{S}_1 &= 700\underline{/36.9°} = 560 + j420 \text{ kVA}\\ \mathbf{S}_2 &= 1000\underline{/60°} = 500 + j866 \text{ kVA}\\ \mathbf{S}_3 &= 800\underline{/25.8°} = 720 + j349 \text{ kVA}\end{aligned}$$

Therefore, the total complex power is

$$\begin{aligned}\mathbf{S}_T &= \mathbf{S}_1 + \mathbf{S}_2 + \mathbf{S}_3\\ &= 1780 + j1635\\ &= 2417\underline{/42.57°} \text{ kVA}\end{aligned}$$

Since

$$S_T = \sqrt{3}\, V_L I_L$$

the line current is

$$\begin{aligned}I_L &= \frac{(2417)(10^3)}{\sqrt{3}(13.8)(10^3)}\\ &= 101.1 \text{ A rms}\end{aligned}$$

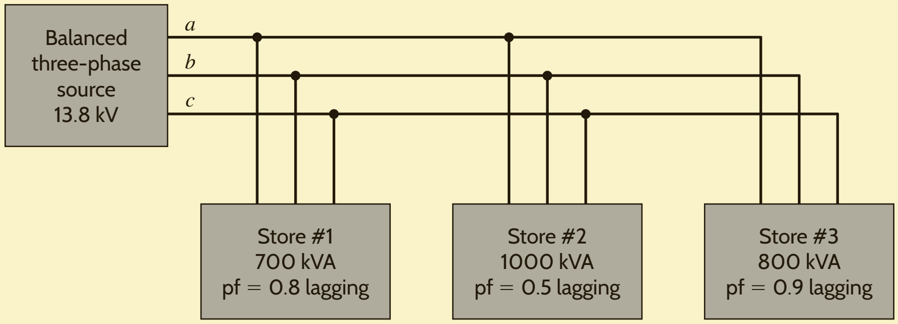

Figure 11.23 Circuit used in Example 11.12.

Since this value is well below the rated value of 170 A rms, the conductor is sized properly and we can safely add the third store.

2. The combined power factor for the three loads is found from the expression

$$\cos\theta = \text{pf} = \frac{1780}{2417} = 0.7365 \text{ lagging}$$

By adding capacitors we wish to change this power factor to 0.92 lagging. This new power factor corresponds to a θ_{new} of 23.07°. Therefore, the new complex power is

$$\begin{aligned}\mathbf{S}_{\text{new}} &= 1780 + j1780 \tan(23.07°)\\ &= 1780 + j758.28 \text{ kVA}\end{aligned}$$

As illustrated in Fig. 9.17, the difference between $\mathbf{S}_{\text{new}}$ and $\mathbf{S}_T$ is that supplied by the purely reactive capacitor and, therefore,

$$\mathbf{S}_{\text{cap}} = jQ_C = \mathbf{S}_{\text{new}} - \mathbf{S}_T$$

or

$$\begin{aligned}jQ_C &= j(758.28 - 1635)\\ &= -j876.72 \text{ kVA}\end{aligned}$$

Thus,

$$-j\omega C\, V_{\text{rms}}^2 = \frac{-j876.72\text{k}}{3}$$

and

$$377\left(\frac{13.8 \times 10^3}{\sqrt{3}}\right)^2 C = \frac{876.72}{3} \times 10^3$$

Therefore,

$$C = 12.2\ \mu\text{F}$$

Hence, three capacitors of this value connected in wye at the load will yield a total power factor of 0.92 lagging.

Finally, recall that our entire discussion in this chapter has focused on balanced systems. It is extremely important, however, to point out that in an unbalanced three-phase system the problem is much more complicated.