14.8 A three-phase 138 kVΔ/13.8 kV Y distribution substation transformer rated 40 MVA OA/50 MVA FA/65MVA FOA has an 8% impedance. (a) Determine the rated current on the primary distribution side of the transformer at its OA, FA, and FOA ratings. (b) Determine the per unit transformer impedance using a system base of 100 MVA and 13.8 kV on the primary distribution side of the transformer. (c) Calculate the short-circuit current on the primary distribution side of the transformer for a three-phase bolted fault on the primary distribution side. Assume that the prefault voltage is 13.8 kV.

14.12 Re-work Example 14.3 with $R_{Load} = 40\ \Omega$/phase, $X_{Load} = 60\ \Omega$/phase, and $X_C = 60\ \Omega$/phase.

EXAMPLE 14.3 Shunt Capacitor Bank at End of Primary Feeder

Figure 14.21 shows a single-line diagram of a 13.8-kV primary feeder supplying power to a load at the end of the feeder. A shunt capacitor bank is located at the load bus. Assume that the voltage at the sending end of the feeder is 5% above rated and that the load is Y-connected with $R_{Load} = 20\,\Omega$/phase in parallel with load $jX_{Load} = j\,40\,\Omega$/phase. (a) With the shunt capacitor bank out of service, calculate the following: (1) line current; (2) voltage drop across the line; (3) load voltage; (4) real and reactive power delivered to the load; (5) load power factor; (6) real and reactive line losses; and (7) real power, reactive power, and apparent power delivered by the distribution substation. (b) The capacitor bank is Y connected with a reactance $X_C = 40\,\Omega$/phase. With the shunt

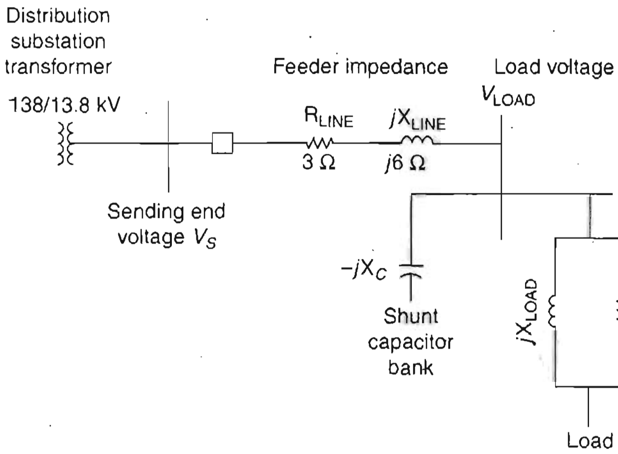

FIGURE 14.21 Single-line diagram of a primary feeder for Example 14.3 (J. D. Glover, "Electric Power Distribution," Encyclopedia of Energy Technology and The Environment, John Wiley & Sons, New York, NY, 1995. Reprinted with permission of John Wiley & Sons, Inc.)

capacitor bank in service, redo the calculations. Also calculate the reactive power supplied by the capacitor bank. (c) Compare the results of (a) and (b).

SOLUTION

a. Without the capacitor bank, the total impedance seen by the source is:

$$Z_{TOTAL} = R_{LINE} + jX_{LINE} + \frac{1}{\frac{1}{R_{LOAD}} + \frac{1}{jX_{LOAD}}}$$

$$Z_{TOTAL} = 3 + j6 + \frac{1}{\frac{1}{20} + \frac{1}{j40}}$$

$$Z_{TOTAL} = 3 + j6 + \frac{1}{0.0559\underline{/-26.57^\circ}}$$

$$= 3 + j6 + 17.89\underline{/26.56^\circ}$$

$$Z_{TOTAL} = 3 + j6 + 16 + j8 = 19 + j14$$

$$= 23.60\underline{/36.38^\circ}\ \Omega/\text{phase}$$

1. The line current is:

$$I_{LINE} = V_{SLN}/Z_{TOTAL} = \frac{1.05(13.8/\sqrt{3})\underline{/0^\circ}}{23.60\underline{/36.38^\circ}}$$

$$= 0.3545\underline{/-36.38^\circ}\ \text{kA/phase}$$

2. The voltage drop across the line is:

$$V_{DROP} = Z_{LINE}\, I_{LINE} = (3 + j6)(0.3545\underline{/-36.38^\circ})$$

$$= (6.708\underline{/63.43^\circ})(0.3545\underline{/-36.38^\circ})$$

$$= 2.378\underline{/27.05^\circ}\ \text{kV}$$

$$|V_{DROP}| = 2.378\ \text{kV}$$

3. The load voltage is:

$$V_{\text{LOAD}} = V_{\text{SLN}} - Z_{\text{LINE}} I_{\text{LINE}} = 1.05(13.8/\sqrt{3})\angle 0^\circ - 2.378\angle 27.05^\circ$$
$$= 8.366 - (2.117 + j1.081) = 6.249 - j1.081$$
$$= 6.342\angle -9.814^\circ \text{ kV}_{LN}$$
$$|V_{\text{LOAD}}| = 6.342\sqrt{3} = 10.98 \text{ kV}_{\text{LL}}$$

4. The real and reactive power delivered to the three-phase load is:

$$P_{\text{LOAD}3\varphi} = 3(V_{\text{LOADLN}})^2/R_{\text{LOAD}} = 3(6.342)^2/20 = 6.033 \text{ MW}$$
$$Q_{\text{LOAD}3\varphi} = 3(V_{\text{LOADLN}})^2/X_{\text{LOAD}} = 3(6.342)^2/40 = 3.017 \text{ Mvar}$$

5. The load power factor is:

$$\text{p.f.} = \cos[\tan^{-1}(Q/P)]$$
$$= \cos[\tan^{-1}(3.017/6.033)]$$
$$= 0.89 \text{ lagging}$$

6. The real and reactive line losses are:

$$P_{\text{LINELOSS}3\varphi} = 3\, I_{\text{LINE}}{}^2 R_{\text{LINE}} = 3(0.3545)^2(3) = 1.131 \text{ MW}$$
$$Q_{\text{LINELOSS}3\varphi} = 3\, I_{\text{LINE}}{}^2 X_{\text{LINE}} = 3(0.3545)^2(6) = 2.262 \text{ Mvar}$$

7. The real power, reactive power, and apparent power delivered by the distribution substation are:

$$P_{\text{SOURCE}3\varphi} = P_{\text{LOAD}3\varphi} + P_{\text{LINELOSS}3\varphi} = 6.033 + 1.131 = 7.164 \text{ MW}$$
$$Q_{\text{SOURCE}3\varphi} = Q_{\text{LOAD}3\varphi} + Q_{\text{LINELOSS}3\varphi} = 3.017 + 2.262 = 5.279 \text{ Mvar}$$
$$S_{\text{SOURCE}3\varphi} = \sqrt{(7.164^2 + 5.279^2)} = 8.899 \text{ MVA}$$

b. With the capacitor bank in service, the total impedance seen by the source is:

$$Z_{\text{TOTAL}} = R_{\text{LINE}} + jX_{\text{LINE}} + \frac{1}{\frac{1}{R_{\text{LOAD}}} + \frac{1}{jX_{\text{LOAD}}} - \frac{1}{jX_C}}$$

$$Z_{\text{TOTAL}} = 3 + j6 + \frac{1}{\frac{1}{20} + \frac{1}{j40} - \frac{1}{j40}}$$

$$Z_{\text{TOTAL}} = 3 + j6 + \frac{1}{0.05} = 23 + j6 = 23.77\angle 14.62^\circ \ \Omega/\text{phase}$$

1. The line current is:

$$I_{\text{LINE}} = V_{\text{SLN}}/Z_{\text{TOTAL}} = \frac{1.05(13.8/\sqrt{3})/0^\circ}{23.77\angle 14.62^\circ}$$
$$= 0.3520\angle -14.62^\circ \text{ kA/phase}$$

2. The voltage drop across the line is:

$$V_{DROP} = Z_{LINE}\, I_{LINE} = (6.708\angle 63.43^\circ)(0.3520\angle -14.62^\circ)$$
$$= 2.361\angle 48.81^\circ \text{ kV}$$
$$|V_{DROP}| = 2.361 \text{ kV}$$

3. The load voltage is:

$$V_{LOAD} = V_{SLN} - Z_{LINE}\, I_{LINE}$$
$$= 1.05(13.8/\sqrt{3})\angle 0^\circ - 2.361\angle 48.81^\circ$$
$$= 8.366 - (1.555 + j1.778)$$
$$= 6.81 - j1.778$$
$$= 7.038\angle -14.62^\circ \text{ kV}_{LN}$$
$$|V_{LOAD}| = 7.038\sqrt{3} = 12.19 \text{ kV}_{LL}$$

4. The real and reactive power delivered to the three-phase load is:

$$P_{LOAD3\varphi} = 3(V_{LOADLN})^2/R_{LOAD} = 3(7.038)^2/20 = 7.430 \text{ MW}$$
$$Q_{LOAD3\varphi} = 3(V_{LOADLN})^2/X_{LOAD} = 3(7.038)^2/40 = 3.715 \text{ Mvar}$$

5. The load power factor is:

$$\text{p.f.} = \cos[\tan^{-1}(Q/P)]$$
$$= \cos[\tan^{-1}(3.715/7.430)]$$
$$= 0.89 \text{ lagging}$$

6. The real and reactive line losses are:

$$P_{LINELOSS3\varphi} = 3\, I_{LINE}^2\, R_{LINE} = 3(0.3520)^2(3) = 1.115 \text{ MW}$$
$$Q_{LINELOSS3\varphi} = 3\, I_{LINE}^2\, X_{LINE} = 3(0.3520)^2(6) = 2.230 \text{ Mvar}$$

7. The reactive power delivered by the shunt capacitor bank is:

$$Q_C = 3(V_{LOADLN})^2/X_C = 3(7.038)^2/40 = 3.715 \text{ Mvars}$$

8. The real power, reactive power, and apparent power delivered by the distribution substation are:

$$P_{SOURCE3\varphi} = P_{LOAD3\varphi} + P_{LINELOSS3\varphi} = 7.430 + 1.115 = 8.545 \text{ MW}$$
$$Q_{SOURCE3\varphi} = Q_{LOAD3\varphi} + Q_{LINELOSS3\varphi} - Q_C$$
$$= 3.715 + 2.230 - 3.715$$
$$= 2.230 \text{ Mvar}$$
$$S_{SOURCE3\varphi} = \sqrt{(8.545^2 + 2.230^2)} = 8.675 \text{ MVA}$$

c. Comparing the results of (a) and (b), with the shunt capacitor bank in service, the real power delivered to the load increases by 23% (from 6.033 to 7.430 MW) while at the same time:

- The line current decreases
- The real and reactive line losses decrease
- The voltage drop across the line decreases
- The reactive power delivered by the source decreases
- The load voltage increases

The above benefits are achieved by having the shunt capacitor bank (instead of the distribution substation) deliver reactive power to the load. ■