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Series and Simultaneous Unbalance Sequence Network Interconnections

7.1 INTRODUCTION

A general representation of power systems and their sequence networks was introduced in Section 5.2. The right-hand representations of Fig. 5.1 represent, at the top, the power system, which is assumed symmetrical up to the area or point of unbalance, which can be documented between the phases a, b, c and n (neutral) terminals shown. Below these are the three sequence networks with their terminal points: the neutral or zero potential bus (n), (x) the left side, and (y) the right side of the unbalance point or area.

7.2 SERIES UNBALANCE SEQUENCE INTERCONNECTIONS

A variety of potential series unbalances that can occur in a power system is shown in Fig. 7.1. A common one is a blown fuse or broken conductor, represented by Fig. 7.1j. Other problems are:

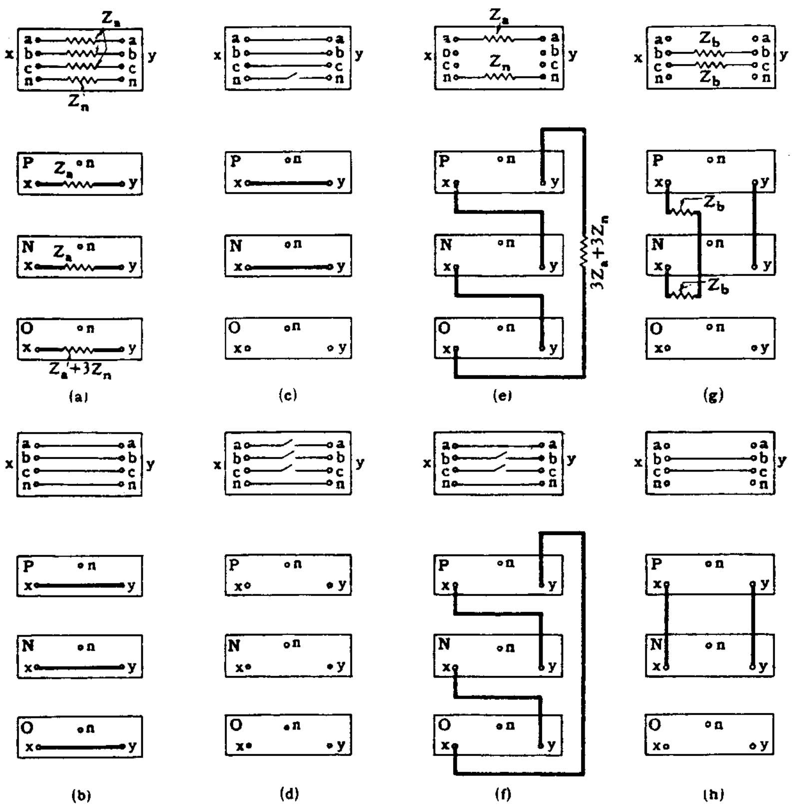
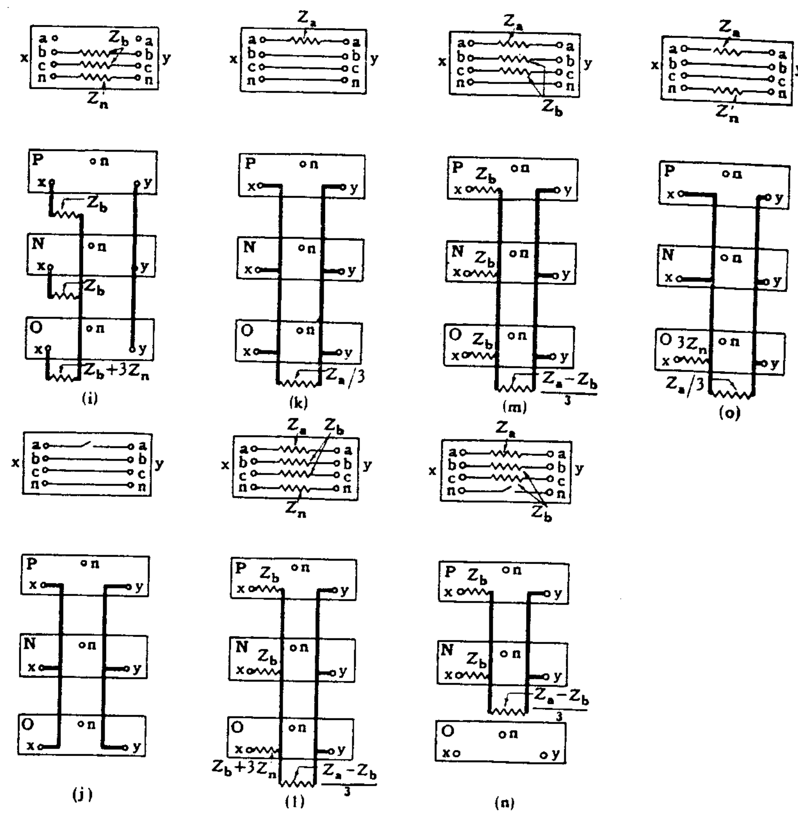


Figure 7.1 Box sequence connections for series unbalanced conditions: (a) equal impedances in three phases; (b) normal balanced conditions; (c) neutral circuit open; (d) any three or four phases open; (e) phases *b* and *c* open and impedances in phase *a* and neutral; (f) phases *b* and *c* open; (g) phases *a* and neutral open and impedances in phases *b* and *c*; (h) phase *a* and neutral open; (i) phase *a* open and impedances



in phases *b*, *c*, and neutral; (j) phase *a* open; (k) impedance in phase *a*; (l) equal impedances in phases *b* and *c*, impedance in neutral; (m) equal impedances in phases *b* and *c*; (n) equal impedances in phases *b* and *c*, neutral open; (o) impedances in phase *a* and neutral. (From E. L. Harder, Sequence Network Connections for Unbalanced Load and Fault Conditions, *The Electrical Journal*, December 1937.)

two blown fuses or open conductors (Figure 7.1f); unequal impedances in the phases in several combinations (Figure 7.1k through o), and so on. Applications of these are best discussed with examples.

7.3 ONE PHASE OPEN: BROKEN CONDUCTOR OR BLOWN FUSE

This is Fig. 7.1j. The application to a power system is shown in Fig. 7.2. Load or the equivalent represented by a difference between the source voltages must be included for these series unbalances, as the current is dependent on the load or difference between the system voltages on either side of the open. If load (Z_L) was omitted as is common for the shunt faults, no current can flow in the networks in Fig. 7.2. This makes sense, as opening a unloaded circuit does not change the current. Such opening will cause a transient arc as the system capacitance current is interrupted. This also indicates that the current flow during the open will be on the order of the load current.

Including load now indicates that impedance values should be used rather than reactance only as for the shunt faults. The system impedances will be mostly reactance except for low voltage lines, while the load will be mostly resistance. Thus $(r + jx)$ calculations are required.

The system shown in Fig. 7.2 is grounded on both sides of the open. If one side is ungrounded, it will be seen that the zero-sequence network is open. Thus no zero-sequence current can flow. This is typical of a motor load. This type of unbalance is shown in Fig. 7.1g or h.

7.4 EXAMPLE: OPEN PHASE CALCULATION

7.4.1 Power System Grounded on Both Sides of the Open Conductor

Using the power system of Fig. 6.10 with the fault now being the phase a conductor open in the line at bus H, the sequence

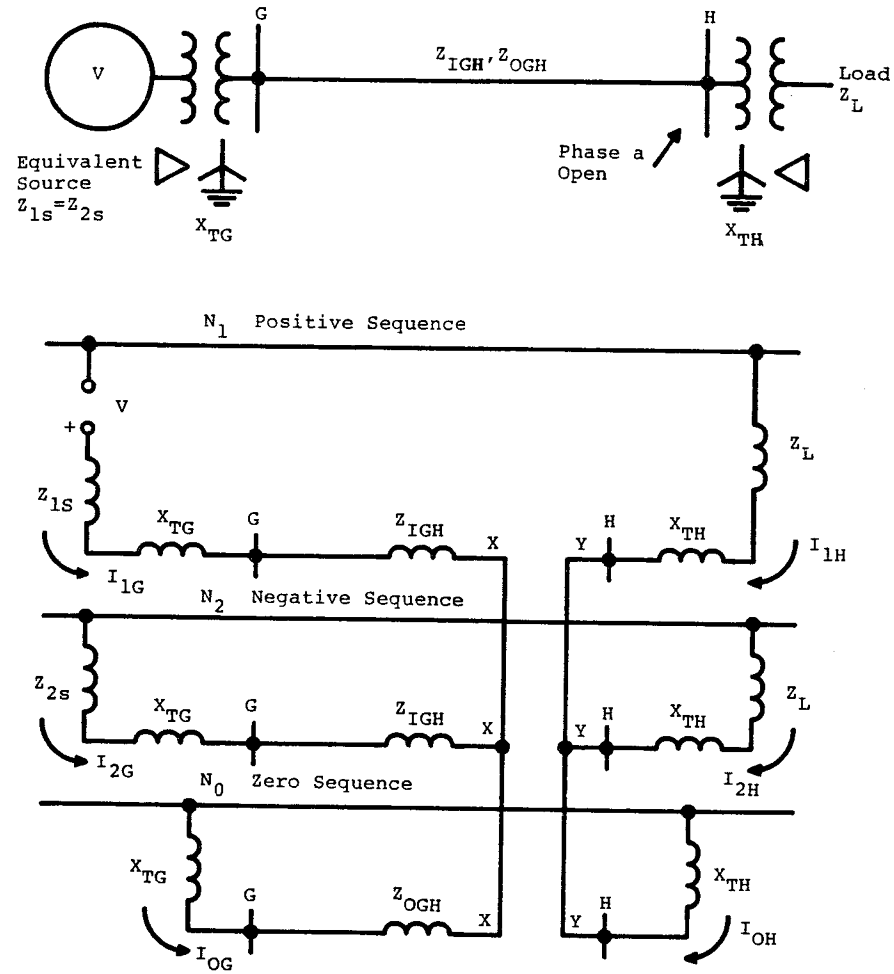


Figure 7.2 Example of the sequence interconnections for phase a open at bus H for a typical power system.

networks and interconnections of Fig. 7.1j are shown in Fig. 7.3. The values are those of Eqs. (6.52). With induction motors their negative-sequence impedance is less than the positive-sequence impedance, so $Z_{1\text{Load}}$ and $Z_{2\text{Load}}$ are not equal. This is discussed in Chapter 10. From the interconnections, $Z_{1G} + Z_{2H} = Z_2$ is in parallel with $Z_{0G} + Z_{0H} = Z_0$. Thus

$$Z_2 = 0.5932 + j0.7015 = 0.9187\underline{/49.78^\circ}$$

$$Z_0 = 0.250 + j0.711 = 0.7537\underline{/70.63^\circ}$$

$$\frac{Z_2 Z_0}{Z_2 + Z_0} = \frac{0.9187 \times 0.7537\underline{/49.78^\circ + 70.63^\circ}}{0.8432 + j1.4125}$$

$$= 0.4209\underline{/61.245^\circ} = 0.2025 + j0.3690$$

The total impedance is

$$Z_{1G} + \frac{Z_2 Z_0}{Z_2 + Z_0} + Z_{1H} = 1.171 + j1.216 = 1.688\underline{/46.08^\circ} \tag{7.1}$$

The equivalent system voltage to provide a voltage at the load of $1.0\underline{/0^\circ}$ with I in the load of $1.0\underline{/-25.84^\circ}$ would be

$$-V + I(Z_{1G} + X_{TH}) + 1.0 = 0$$

$$V = 1.0 + 1.0\underline{/-25.84^\circ}\,(0.0684 + j0.4106)$$

$$= 1.0 + 1 \times 0.4163\underline{/-25.84^\circ + 80.54^\circ} \tag{7.2}$$

$$= 1.0 + 0.4163\underline{/54.70^\circ} = 1.286\underline{/15.315^\circ}\text{ pu}$$

From Eqs. (7.1) and (7.2),

$$I_{1G} = \frac{1.286\underline{/15.315^\circ}}{1.688\underline{/46.08^\circ}} = 0.762\underline{/-30.765^\circ}\text{pu} = 0.655 - j0.390\text{pu} \tag{7.3}$$

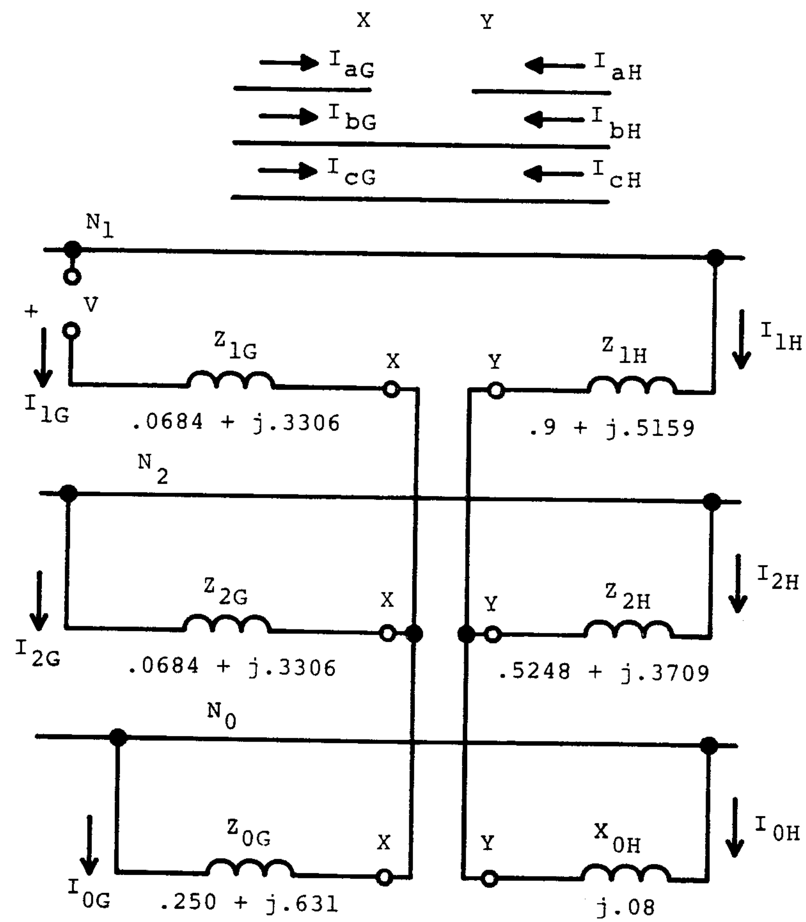


Figure 7.3 Sequence interconnections for a phase *a* open on the line at bus *H* of the power system of Fig. 6.10. Values are in per unit at 30 MVA, 34.5 kV.

$$I_{2G} = -I_{1G}\frac{Z_0}{Z_2 + Z_0} = -0.762\underline{/-30.76^\circ}\frac{0.7537\underline{/70.63^\circ}}{1.645\underline{/59.165^\circ}}$$

$$= 0.349\underline{/160.70^\circ} = -0.329 + j0.115\,\text{pu} \tag{7.4}$$

$$I_{0G} = -I_{1G}\frac{Z_2}{Z_2 + Z_0} = -0.762\underline{/-30.76^\circ}\frac{0.9187\underline{/49.78^\circ}}{1.645\underline{/59.165^\circ}}$$

$$= 0.426\underline{/139.85^\circ} = -0.325 + j0.274\,\text{pu} \tag{7.5}$$

From these,

$$I_{aG} = I_{1G} + I_{2G} + I_{0G} = 0 \tag{7.6}$$

$$I_{bG} = a^2 I_{1G} + aI_{2G} + I_{0G}$$

$$= 0.762\underline{/209.24^\circ} + 0.349\underline{/280.7^\circ} + 0.426\underline{/139.85^\circ} \tag{7.7}$$

$$= -0.925 - j0.441 = 1.025\underline{/-154.53^\circ}\,\text{pu}$$

$$I_{cG} = aI_{1G} + a^2 I_{2G} + I_{0G}$$

$$= 0.762\underline{/89.24^\circ} + 0.349\underline{/40.7^\circ} + 0.426\underline{/139.85^\circ} \tag{7.8}$$

$$= -0.050 + j1.264 = 1.265\underline{/92.285^\circ}\,\text{pu}$$

These per unit currents as they flow in the power system are shown in Fig. 7.4a. Their magnitudes are around load current with the open phase *a* current essentially flowing through the ground. Figure 6.12 shows the currents for ground faults on this same system for comparison.

7.4.2 Power System Ungrounded on One Side of the Open Conductor

If the 30-MVA transformer at station H (Fig. 6.10) is not grounded, the zero-sequence X_{TH} circuit is open in Fig. 7.2, and neither I_{0G} nor I_{0H} can flow. Then only the total negative-sequence impedance is across X and Y. From the previous cal-