Topics for Today:

- Project: Fun topic on course material
- Proposals due
- Work alone or in pairs

- Quick review of unsymmetric faults
- Sequence networks
- Transformers
  - Delta, wye, auto connections
  - Pos and Neg sequence phase shifts
  - Transfer of impedance (for cases with off-nominal turns)
- Thoughts on using $[Z]$ and/or $[Y]$ description of network
  - Zth from main diagonal of $[Z]$
  - $[Y]$ is sparse, $[Z]$ is not.
- Inclusion of Ref buses for zero, pos, neg networks
- Interconnection of sequence networks according to fault.
Closed Voltage Phasor Diagram.

\[ V_{AB} = V_A - V_B \]
Notes:
- Possible Δ-Y, Y-Δ Phase Shifts
  - ±30°, ±90°, ±150°?
- Nameplates: US (IEEE) [Δ-Δ], Europe (IEC) [Δ-Y, Y-Δ]

Diagram:
- Dyn1
  - Dyn5 = 150° Lag
  - Pri → sec

Diagram symbol: Δ-Δ
ANSI STANDARD 30-DEGREE SHIFT DELTA-WYE

ANSI STANDARD 30-DEGREE SHIFT WYE-DELTA
networks, as shown in Figure 3.10, where $Z_{ho} = Z_{h1} = Z_{h2} = Z_{H}$. Similarly, the leakage impedances of the low-voltage windings are symmetrical series impedances with $Z_{x0} = Z_{x1} = Z_{x2} = Z_{X}$. These series leakage impedances are shown in per-unit in the sequence networks of Figure 4.17(a).

The shunt branches of the practical $Y-Y$ transformer, which represent exciting current, are equivalent to the $Y$ load of Figure 3.3. Each phase in Figure 3.3 represents a core loss resistor in parallel with a magnetizing
the 0.08 per-unit voltage drop at the low-voltage three-phase short-circuit condition the rated transformer current, the design or specification of is desired to minimize voltage drop currents. Typical transformer the Appendix.

three-winding transformer. The 3 transformer, (4.1.8) and (4.1.14), ponding relations for an ideal

three-winding transformer. In actual units, these relations are:

\[ N_1 I_1 = N_2 I_2 + N_3 I_3 \]  \hspace{1cm} (4.6.1)
\[ \frac{E_1}{N_1} = \frac{E_2}{N_2} = \frac{E_3}{N_3} \]  \hspace{1cm} (4.6.2)

where \( I_1 \) enters the dotted terminal, \( I_2 \) and \( I_3 \) leave dotted terminals, and \( E_1 \), \( E_2 \), and \( E_3 \) have their + polarities at dotted terminals. In per-unit, (4.6.1) and (4.6.2) are:

\[ I_{1\text{p.u.}} = I_{2\text{p.u.}} + I_{3\text{p.u.}} \]  \hspace{1cm} (4.6.3)
\[ E_{1\text{p.u.}} = E_{2\text{p.u.}} = E_{3\text{p.u.}} \]  \hspace{1cm} (4.6.4)

where a common \( S_{\text{base}} \) is selected for all three windings, and voltage bases are selected in proportion to the rated voltages of the windings. These two per-unit relations are satisfied by the per-unit equivalent circuit shown in Figure.
The impedances of the per-unit negative-sequence network are the same as those of the per-unit positive-sequence network, which is always true for nonrotating equipment. Phase-shifting transformers, not shown in Figure 4.23(b), can be included to model phase shift between Δ and Y windings.

**Example 4.11**

**Three-phase transformer: per-unit sequence networks**

Three transformers, each identical to that described in Example 4.10, are connected as a three-phase bank in order to feed power from a 900-MVA, 13.8-kV generator to a 345-kV transmission line and to a 34.5-kV distribution line. The transformer windings are connected as follows:

- 13.8-kV windings (X): Δ, to generator
- 199.2-kV windings (H): solidly grounded Y, to 345-kV line
- 199.2-kV windings (M): grounded Y through $Z_n = j0.10\Omega$, to 34.5-kV line

![Diagram of per-unit sequence networks for Example 4.11](image)
Intro to Zbus methods for Unsymm Faults

Use rake equivalents - see page 328.

Ex: 125  Fig 12.16  Stevenson, 4th Ed.

\[
[Y]_{\text{pos}}
\]

\[
[Y]_{\text{neg}}
\]

\[
[Y]_{\text{zero}}
\]

form \( V_{\text{bus-1}} \)  \( V_{\text{bus-2}} = \mathbf{j} \begin{bmatrix} -13.3 & 10 \\ 10 & -20 \end{bmatrix} \)

\( V_{\text{bus-0}} = \mathbf{j} \begin{bmatrix} -6.67 & 0 \\ 0 & -15 \end{bmatrix} \)
**Aug. - Connections**
**Fault: S.C. Augmentation**
**or Large G to ref.?**

\[
\begin{array}{c|c|c|c}
\text{ Singular } & 0 & 0 & 0 \\
\hline
1 & 0 & 0 & 0 \\
\hline
0 & 2 & 0 & 0 \\
\hline
0 & 0 & 0 & 0 \\
\end{array}
\]
\[ Z_{bus-1} = Z_{bus-2} = J[0.12, 0.08] \]
\[ Z_{bus-0} = J[0.15, 0] \]

For a bus 1 L-G fault,
\[ I_f'' = \frac{3 \times 1.0}{j(0.12 + 0.12 + 0.15)} = -j \frac{17.692}{J} \text{ p.u.} \]

For a bus 2 L-G fault
\[ I_f'' = \frac{3 \times 1.0}{j(0.08 + 0.08 + 0.067)} = -j \frac{13.216}{J} \text{ p.u.} \]

Find \( V_1 \) voltage at bus 2 for bus 1 L-G fault
\[ I_{a1} = -j \frac{17.692}{3} = -j 2.564 \text{ p.u.} = I_{a2} = I_{a0} \]

Then we calculate voltage drop for each sequence voltage using respective transfer impedance & sequence current.

At bus 2,
\[ V_{a1} = V_f - I_{a1}Z_{21-1} = 1.0 - (-j2.564)(j0.06) \]
\[ = 1.0 - 0.1538 = 0.8462 \text{ p.u.} \]
\[ V_{a2} = - I_{a2}Z_{21-2} = -(j2.564)(j0.06) = -0.1538 \text{ p.u.} \]
\[ V_{a0} = - I_{a0}Z_{21-0} = 0 \]
Accounting for phase shift,

\[ V_{A1} = V_{A1} \cdot (10 \angle 30^\circ) = 0.8462 \angle 30^\circ \]
\[ V_{A2} = V_{A2} \cdot (1 \angle 30^\circ) = 0.1538 \angle 30^\circ \]
\[ V_A = V_{A1} + V_{A2} = 0.7328 + j0.4231 + 1.332 - j0.0769 \]
\[ = 0.866 + j3.462 = 0.9326 \angle 21.8^\circ \]

\[ V_B = a^2 V_{A1} + aV_{A2} = 0.8462 \angle 270^\circ + 0.1538 \angle 90^\circ \]
\[ = -j0.8462 + j0.1538 = -j0.6924 \]

\[ V_C = aV_{A1} + a^2 V_{A2} = 0.8462 \angle 150^\circ + 0.1538 \angle 210^\circ \]
\[ = -0.7328 + j0.4231 - 1.332 - j0.0769 \]
\[ = -0.866 + j3.462 = 0.9326 \angle 158.2^\circ \]

These are p.u. values on L-N base

No advantage for this method over hand calculation method, but better suited for computer application.
FAULTS THROUGH AN IMPEDANCE

See Fig 12.21, 12.22

$L-G$

$L-L$

$L-L-G$
Ex: \( \Delta \Delta \Delta \) \( I_a = \frac{V_f}{Z_1 + Z_f} \)

L-L \( I_a = \frac{V_f}{Z_1 + Z_2 + Z_0 + 3Z_f} \)

L-L-G \( I_a = \frac{V_f}{Z_1 + \frac{Z_2 (Z_0 + 3Z_f)}{Z_0 + Z_2 + 3Z_f}} \)

Normally, \( \Delta \Delta \) \& L-G faults are calculated for breaker ratings, rigid bus design, and protective relaying.

Although L-L-G faults many times cause larger fault current, they are very unlikely.

Calculation of current is done for all combinations of lines connected and unconnected from bus.
Phase Shifts & Impedances

\[ \vec{I}_{A1} \quad \vec{I}_{A1}^{*} (1, 30^\circ) \]

\[ \vec{V}_{A1} \quad \vec{V}_{A1}^{*} \]

\[ \vec{I}_{A2} \quad \vec{I}_{A2}^{*} (1, 30^\circ) \]

\[ \vec{V}_{A2} \quad \vec{V}_{A2}^{*} \]

\[ Z = \frac{\vec{V}_{A2}}{\vec{I}_{A2}} \]

\[ Z \text{ is same on either side.} \]
Fig. 4.17 Box sequence connections for shunt balanced and unbalanced conditions:
(a) balanced load or three-phase-to-ground fault with impedances; (b) three-phase fault;
(c) three-phase to ground fault; (d) shunt circuit open; (e) phase-to-ground fault through an impedance; (f) phase-to-ground fault; (g) phase-to-phase fault through impedance;
(h) phase-to-phase fault; (i) two-phase-to-ground fault through impedance; (j) two-phase to-ground fault; (k) three-phase-to-ground fault with impedance in phase a; (l) unbalanced load or three-phase-to-ground fault with impedance. (From E. L. Harder, Sequence Network Connections for Unbalanced Load and Fault conditions, The Electrical Journal, December 1937.)
Series unbalance in loads, connect.

Fig. 4.18: 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.)