SO Few: Shunt faults

- phase to ground
- phase to phase
- or combinations

Series faults
- abnormal operation

- in series with line, transformer, etc.
- large imbalance (not like untransposed line)
most common cases

1) 1 phase (pole) open
   (single pole open)
   - If intentional, breakers at both ends of a line

   Single pole trip - both ends

   Intentional single pole open
UNINTENTIONAL SINGLE POLE OPEN

- Breaker fails to close

(POLE)

2 PHASES (POLES) OPEN

- Breaker misoperation

- Fault
3. Series \textit{imbalance} with two phases matching (often two phases normal)

One example:

- Series capacitors

\textbf{Bus}
Large enough imbalance that isn't approximated like untransposed line.
Analysis Techniques

Solution approaches:  
1. Phasors (symmetrical components)
2. Electromagnetic Transients Simulation (ATP, EMTP, EMTP-RV, PSCAD, OpenRT etc.)
Phasor based approach

- First need all Thévenin Equivalent circuits in pos, neg, zero

- However, this requires a 2 port Thévenin equivalent (not a single port)
Single port equivalent
Two port equivalent \( \mathcal{E}_A, \mathcal{E}_B, \mathcal{E}_C \) unbalanced condition

\[ V_s \hspace{2cm} f_i \hspace{2cm} f_i' \hspace{2cm} Z_{\text{LH}} \hspace{2cm} V_r \]

\[ Z_{\text{s1}} \hspace{2cm} Z_{\text{L2}} \hspace{2cm} Z_{\text{L1}} \]

\[ f_i' \downarrow M \hspace{2cm} f_i \]

\( Z_{\text{TH1}} \), \( V_{\text{TH2}} \)
Series Fault Examples

\[ pu := 1 \quad MVA := 1000\text{kW} \]

\[ a := 1e^{j\cdot120\text{deg}} \]

\[ A_{012} := \begin{pmatrix}
1 & 1 & 1 \\
1 & a & a^2 \\
1 & a^2 & a \\
\end{pmatrix} \]

Single Phase Open Examples

**Example 1:**
- System one-line diagram:

![System One-Line Diagram](image)

- Machines 1 and 2:
  - \( S_{\text{Mach}} := 100\text{MVA} \)
  - \( V_{\text{machine}} := 20\text{kV} \)
  - \( X_{d\text{Mach}}' := 20\% \)
  - \( X_{1\text{Mach}} := X_{d\text{Mach}}' \)
  - \( X_{2\text{Mach}} := X_{1\text{Mach}} \)
  - \( X_{0\text{Mach}} := 4\% \)
  - \( X_{n\text{Mach}} := 5\% \)

- Transformers T1 and T2:
  - \( S_{\text{Tran}} := 1000\text{MVA} \)
  - \( V_{HV} := 345\text{kV} \)
  - \( V_{LV} := 20\text{kV} \)
  - \( X_T := 8\% \)

- Transmission Line:
  - \( X_{L1} := 15\% \)
  - \( X_{L2} := X_{L1} \)
  - \( X_{L0} := 50\% \)

- \( S_{\text{Base}} := 100\text{MVA} \)
$V_{\text{B Line}} := 345\text{kV}$  
$V_{\text{B mach}} := V_{\text{B Line}} \left( \frac{V_{LV}}{V_{HV}} \right)$  
$V_{\text{B mach}} = 20\cdot\text{kV}$

No change of base calculations are needed for this system.

Determine internal source voltages:

$$\text{mag} S_{\text{pre}} := 80\text{MVA} \quad \text{pf}_{\text{pre}} := 0.85 \text{ lagging} \quad \theta_{\text{pre}} := \text{acos}(\text{pf}_{\text{pre}}) \quad \theta_{\text{pre}} = 31.79\cdot\text{deg}$$

$$S_{\text{pre}} := \frac{\text{mag} S_{\text{pre}}}{S_{\text{Base}}} \cdot e^{j \cdot \theta_{\text{pre}}} \quad S_{\text{pre}} = (0.68 + 0.42i)\cdot\text{pu} \quad |S_{\text{pre}}| = 0.8\cdot\text{pu}$$

Assume bus 3 voltage is 1.0 pu at and angle of 0 degrees.

$$V_3 := 1.0$$

$$I_{\text{load}} := \left( \frac{S_{\text{pre}}}{V_3} \right)^+ \quad I_{\text{load}} = 0.68 - 0.42i \quad |I_{\text{load}}| = 0.8\cdot\text{pu} \quad \text{arg}(I_{\text{load}}) = -31.79\cdot\text{deg}$$

Internal voltage on the motor (since we don't know steady-state synchronous reactance, use X1):

$$E_2 := V_3 - I_{\text{load}} \cdot j (X_T + X_{1 \text{Mach}}) \quad |E_2| = 0.9 \quad \phi_2 := \text{arg}(E_2) \quad \phi_2 = -12.18\cdot\text{deg}$$

Generator internal voltage:

$$E_1 := V_3 + I_{\text{load}} \cdot (j \cdot X_{L1} + j \cdot X_T + j \cdot X_{1 \text{Mach}}) \quad |E_1| = 1.22\cdot\text{pu} \quad \phi_1 := \text{arg}(E_1) \quad \phi_1 = 13.9\cdot\text{deg}$$
Check result by calculating power transfer between sources and current:

\[
P_{\text{trans}} := \frac{|E_1| \cdot |E_2| \cdot \sin(\phi_1 - \phi_2)}{2 \cdot X_{1Mach} + 2 \cdot X_T + X_{L1}} \]

\[
P_{\text{trans}} - \text{Re}(S_{\text{pre}}) = 0
\]

\[
I_{\text{trans}} := \frac{E_1 - E_2}{j(2 \cdot X_{1Mach} + 2 \cdot X_T + X_{L1})}
\]

\[
I_{\text{trans}} - I_{\text{load}} = 0
\]

- Positive sequence equivalent circuit (with phase open point indicated).

- Negative sequence equivalent circuit:

Find total impedance counterclockwise around loop from F to F':

\[
Z_{1\text{total}} := j \cdot (X_{1Mach} + X_T + X_{L1} + X_T + X_{1Mach})
\]

\[
Z_{1\text{total}} = 0.71\text{pu}
\]

\[
Z_{1\text{FF}} := Z_{1\text{total}}
\]

\[
V_{\text{equiv}} := E_1 - E_2
\]

Find total impedance counterclockwise around loop from F to F':

\[
Z_{2\text{total}} := j \cdot (X_{2Mach} + X_T + X_{L2} + X_T + X_{2Mach})
\]

\[
Z_{2\text{total}} = 0.71\text{pu}
\]

\[
Z_{2\text{FF}} := Z_{2\text{total}}
\]
Zero sequence equivalent:

$\begin{align*}
\text{Find total impedance counterclockwise around loop from F to F'} \\
Z_{0\text{total}} &:= j (2 \cdot X_{0\text{Mach}} + 2 \cdot X_T + X_{L0} + 2 \cdot 3 \cdot X_{n\text{Mach}}) \\
Z_{0\text{total}} &= 1.04 \cdot \text{pu} \\
Z_{0\text{FF'}} &:= Z_{0\text{total}}
\end{align*}$

**Now solve for the single phase open circuit currents and voltages:**

$I_1 := \frac{V_{\text{equiv}}}{Z_{1\text{FF'}} + \left( \frac{1}{Z_{2\text{FF'}}} + \frac{1}{Z_{0\text{FF'}}} \right)^{-1}}$

$I_1 = (0.43 - 0.26i) \cdot \text{pu}$

$|I_1| = 0.5 \cdot \text{pu} \\
\text{arg}(I_1) = -31.79 \cdot \text{deg}$

$I_2 := -I_1 \cdot \left( \frac{Z_{0\text{FF'}}}{Z_{2\text{FF'}} + Z_{0\text{FF'}}} \right)$

$I_2 = (-0.25 + 0.16i) \cdot \text{pu}$

$|I_2| = 0.3 \cdot \text{pu} \\
\text{arg}(I_2) = 148.21 \cdot \text{deg}$

$I_0 := -I_1 \cdot \left( \frac{Z_{2\text{FF'}}}{Z_{2\text{FF'}} + Z_{0\text{FF'}}} \right)$

$I_0 = (-0.17 + 0.11i) \cdot \text{pu}$

$|I_0| = 0.2 \cdot \text{pu} \\
\text{arg}(I_0) = 148.21 \cdot \text{deg}$
Example 2: For the system shown below, develop the sequence connection diagram for a single-phase open on Line 1.

\[ Z_{1S} := j \cdot 0.1 \text{pu} \]
\[ Z_{1L} := j \cdot 0.3 \]
\[ Z_{1L1} := j \cdot 0.3 \]
\[ Z_{1R} := j \cdot 0.05 \text{pu} \]
\[ Z_{L1} := j \cdot 0.4 \]
\[ Z_{0S} := j \cdot 0.3 \text{pu} \]
\[ Z_{0L1} := j \cdot 1.2 \]
\[ Z_{0L} := j \cdot 1.5 \]
\[ Z_{0L2} := j \cdot 1.5 \]

VS = 1pu @ 0 degrees

VR = 1pu @ 0 degrees

Z1L1 = 0.3pu @ 90 degrees
Z0L1 = 1.2pu @ 90 degrees

Z1L = 0.4pu @ 90 degrees
Z0L2 = 1.5pu @ 90 degrees

Z1R = 0.05pu @ 90 degrees
Z0R = 0.2pu @ 90 degrees
\[
Z_{1\text{equiv}} := \frac{Z_{1L1}}{2} + \left( \frac{1}{Z_{1S} + Z_{1R}} + \frac{1}{Z_{1L2}} \right)^{-1} \frac{Z_{1L1}}{2}
\]

\[
Z_{1\text{equiv}} = 0.41 \text{i-pu} \left( \frac{Z_{1S} + Z_{1R}}{Z_{1L2}} \right)
\]

\[
Z_{2\text{equiv}} := Z_{1\text{equiv}}
\]

\[
Z_{0\text{equiv}} := Z_{0L1} + \left( \frac{1}{Z_{0S} + Z_{0R}} + \frac{1}{Z_{0L2}} \right)^{-1}
\]

\[
Z_{0\text{equiv}} = 1.58 \text{i-pu}
\]
Alternate notation (no effect on results)
calculating $V_{TH}$ when we have parallel lines

- Can't simply take differences of source voltages now

---

Top circuit & redraw

\[ Z_{S1} + Z_{R1} \]

\[ V_{S1} - V_{R1} \]
Simplify to

\[ E_0 \quad \text{to} \quad V_{TH} \quad \text{and} \quad Z_{TH} \quad \text{(same as we calculated)} \]