Shunt faults

- phase to ground
- phase to phase
- phase to phase to ground
- 300

Series "faults" - abnormal unbalanced operating condition

- most common cases:

  1. 1 phase (pole) open
     (usually both ends intentionally open)
    - unintentionally: 1 breaker fails open
(2) 2 phases open
   - Breaker misoperation

(3) Series imbalance

Series caps

Bypass breaker

Triggered gap MOV

V I
Series unbalance does not include untransposed lines.
Analysis Techniques

1. Phasors $\rightarrow$ symmetrical components
2. Electromagnetic transients program
First need a Thevenin equivalent circuit (set of them) in sequence domain

2 port Thevenin equivalent (not the 1 port equivalent from before)

1 port equiv

\[ V_f = V_{TH} \]

Similar in neg & zero
Series Fault Examples

\[ pu := 1 \quad MVA := 1000kW \]

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

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

Single Phase Open Examples

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

![System one-line diagram](image)

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

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

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

\( S_{\text{Base}} := 100\text{MVA} \)
Check result by calculating power transfer between sources and current:

\[ P_{\text{trans}} := \frac{|E_1| \cdot |E_2| \cdot \sin(\phi_1 - \phi_2)}{2 \cdot X_{1\text{Mach}} + 2 \cdot X_T + X_{L1}} \quad P_{\text{trans}} - \text{Re}\left(S_{\text{pre}}\right) = 0 \]

\[ I_{\text{trans}} := \frac{E_1 - E_2}{j\left(2 \cdot X_{1\text{Mach}} + 2 \cdot X_T + X_{L1}\right)} \quad I_{\text{trans}} - I_{\text{load}} = 0 \]

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

- Negative sequence equivalent circuit:

Find total impedance counterclockwise around loop from F to F'

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

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

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

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

Find total impedance counterclockwise around loop from F to F'

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

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

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

\[
\begin{align*}
\text{j}0.08\text{pu} & \quad \text{F} \quad \text{F'} \quad \text{j}0.50\text{pu} \\
\text{j}0.04\text{pu} & \quad 3\text{j}0.05\text{pu} \quad \text{j}0.04\text{pu} \\
3\text{j}0.05\text{pu} & \quad 3\text{j}0.05\text{pu}
\end{align*}
\]

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

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

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

\[
|I_1| = 0.5\cdot \text{pu} \quad \text{arg}(I_1) = -31.79^{\circ}
\]

\[
I_2 := -I_1 \left( \frac{Z_{0FF'}}{Z_{2FF'} + Z_{0FF'}} \right)
\]

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

\[
|I_2| = 0.3\cdot \text{pu} \quad \text{arg}(I_2) = 148.21^{\circ}
\]

\[
I_0 := -I_1 \left( \frac{Z_{2FF'}}{Z_{2FF'} + Z_{0FF'}} \right)
\]

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

\[
|I_0| = 0.2\cdot \text{pu} \quad \text{arg}(I_0) = 148.21^{\circ}
\]

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

\[
Z_{\text{total}} := j\left(2\cdot X_{0\text{Mach}} + 2\cdot X_T + X_{L0} + 2\cdot 3\cdot X_{n\text{Mach}}\right)
\]

\[
Z_{\text{total}} = 1.04i\cdot \text{pu}
\]

\[
Z_{0FF'} := Z_{\text{total}}
\]
Getting 2 port Thevenin equivalent

- Simple case, no parallel path...

- Now add a line in parallel to one with series open
Top circuit - redraw slightly

- Transistor
- Zs1 + Zs2
- V1 - V2

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\[
\frac{V_{S1} - V_{R1}}{Z_{S1} + Z_{R1}} \quad \text{combine in parallel} \quad B1 \quad B2 \quad Z_{L1} \quad Z_{L2}
\]

\[
\frac{V_{S1} - V_{R1}}{Z_{S1} + Z_{R1}} \quad \text{Thevenin Equivalent} \quad B1 \quad B2 \quad Z_{L1} \quad Z_{L2}
\]
**Example 2**  For the system shown below, develop the sequence connection diagram for a single-phase open on Line 1.

![Diagram of symmetrical components](image)

- \( V_S = 1\text{pu @ 0 degrees} \)
- \( Z_{1S} = 0.1\text{pu @ 90 degrees} \)
- \( Z_{0S} = 0.3\text{pu @ 90 degrees} \)
- \( Z_{1L1} = 0.3\text{pu @ 90 degrees} \)
- \( Z_{0L1} = 1.2\text{pu @ 90 degrees} \)
- \( Z_{1L2} = 0.4\text{pu @ 90 degrees} \)
- \( Z_{0L2} = 1.5\text{pu @ 90 degrees} \)
- \( V_R = 1\text{pu @ 0 degrees} \)
- \( Z_{1R} = 0.05\text{pu @ 90 degrees} \)
- \( Z_{0R} = 0.2\text{pu @ 90 degrees} \)

\[
\begin{align*}
Z_{1S} & := j \cdot 0.1\text{pu} \\
Z_{1R} & := j \cdot 0.05\text{pu} \\
Z_{0S} & := j \cdot 0.3\text{pu} \\
Z_{0R} & := j \cdot 0.2\text{pu} \\
Z_{1L1} & := j \cdot 0.3 \\
Z_{1L2} & := j \cdot 0.4 \\
Z_{0L1} & := j \cdot 1.2 \\
Z_{0L2} & := j \cdot 1.5
\end{align*}
\]
\[ Z_{1\text{equiv}} = \frac{Z_{1L1}}{2} + \left( \frac{1}{\left( Z_{1S} + Z_{1R} + Z_{1L2} \right)^{-1}} \right) \]

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

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

\[ Z_{0\text{equiv}} = 1.58 \text{ pu} \]
Phase A open analysis:

Equivalent voltage source for phase A open analysis:
\[ V_{se} := V_s - V_R \]
\[ V_{se} = (0.06 - 0.34i) \cdot \text{pu} \]

Norton Equivalent Current:
\[ I_{se} := \frac{V_{se}}{Z_{1R} + Z_{1S}} \]
\[ I_{se} = (-2.28 - 0.4i) \cdot \text{pu} \]

Equivalent Parallel Impedance:
\[ Z_{eq} := \left( \frac{1}{Z_{1L2}} + \frac{1}{Z_{1S} + Z_{1R}} \right)^{-1} \]
\[ Z_{eq} = 0.11i \cdot \text{pu} \]

Convert back to Thevenin Equivalent Voltage:
\[ V_f := Z_{eq} I_{se} \]
\[ |V_f| = 0.25 \cdot \text{pu} \quad \text{arg}(V_f) = -80 \cdot \text{deg} \]

Positive sequence current in line 1:
\[ I_{1L1\_open} := \frac{V_f}{Z_{1\text{equiv}} + \left( \frac{1}{Z_{2\text{equiv}}} + \frac{1}{Z_{0\text{equiv}}} \right)^{-1}} \]
\[ |I_{1L1\_open}| = 0.34 \cdot \text{pu} \quad \text{arg}(I_{1L1\_open}) = -170 \cdot \text{deg} \]

Negative sequence current in line 1 (current divider on the line 1 current)
\[ I_{2L1\_open} := -I_{1L1\_open} \cdot \frac{Z_{0\text{equiv}}}{Z_{2\text{equiv}} + Z_{0\text{equiv}}} \]
\[ |I_{2L1\_open}| = 0.27 \cdot \text{pu} \quad \text{arg}(I_{2L1\_open}) = 10 \cdot \text{deg} \]
1-phase imbalance sequence connections

1-phase open would have $Z_A = \infty$

$Z_A$

$Z_B$

$Z_C = Z_B$
Phase domain relationship

\[
[VA_Gf - VB_Gf - VC_Gf]
\]

\[
[VA_Gf]
\]

\[
[VB_Gf]
\]

\[
[VC_Gf]
\]

\[
[v_{AA'} - v_{BB'} - v_{CC'}]
\]

\[
[v_{AA'}]
\]

\[
[v_{BB'}]
\]

\[
[v_{CC'}]
\]

\[
[0 0 Z_B 0 0 Z_B 0 0 Z_B]
\]

\[
[I_A]
\]

\[
[I_B]
\]

\[
[I_C]
\]

\[
[I_0]
\]

\[
[I_1]
\]

\[
[I_2]
\]

\[
[A_{012}]
\]

\[
[v_{AA'}]
\]

\[
[v_{BB'}]
\]

\[
[v_{CC'}]
\]

\[
[v_{AA'}]
\]

\[
[v_{BB'}]
\]

\[
[v_{CC'}]
\]

\[
[I_A]
\]

\[
[I_B]
\]

\[
[I_C]
\]

\[
[I_0]
\]

\[
[I_1]
\]

\[
[I_2]
\]

\[
[A_{012}]
\]
Rewrite as a premultiply both sides by $A_{012}$.

$$[V_{00}] = [Z_0 Z_0 Z_0 A_{012} I_0 Z_0 I_0 Z_0 Z_0 A_{012} I_0] [V_{ii}]$$

Multiply this out.
Series Unbalance Derivation

First step:

\[ V_{aa'} - V_{aa'}' = \frac{1}{3} \left[ I_0 \left[ (Z_A + 2Z_B) - (Z_A - Z_B) \right] + I_1 \left[ (Z_A - Z_B) - (Z_A + 2Z_B) \right] + I_2 \left[ (Z_A - Z_B) - (Z_A - Z_B) \right] \right] \]

- Simplifying

\[ V_{aa'} - V_{aa'}' = \frac{1}{3} \left[ Z_B \left( I_0 - 3I_1 \right) \right] = Z_B \left( I_0 - I_1 \right) \]

- Rearrange terms so all zero sequence terms on one side and positive sequence on the other:

\[ V_{aa'} - I_0 \cdot Z_B = V_{aa'}' - I_1 \cdot Z_B \]

- Similarly, using V0 - V2 we get:

\[ V_{aa'} - I_0 \cdot Z_B = V_{aa'} + I_2 \cdot Z_B = V_{aa'}' - I_1 \cdot Z_B \]

Second Step:

\[ V_{aa'} + V_{aa'}' = \frac{1}{3} \left[ I_0 \left[ (Z_A + 2Z_B) + (Z_A - Z_B) \right] + I_1 \left[ (Z_A - Z_B) + (Z_A + 2Z_B) \right] + I_2 \left[ (Z_A - Z_B) + (Z_A - Z_B) \right] \right] \]

- Simplifying

\[ V_{aa'} + V_{aa'}' = \frac{1}{3} \left[ (I_0 + I_1) \cdot (2Z_A + Z_B) + 2I_2 \cdot (Z_A - Z_B) \right] \]