ECE 525
POWER SYSTEM PROTECTION AND RELAYING
SESSION no. 21
- Negative Sequence and Ground Elements

Note, this uses sine filters so does not fully remove decaying dc offset.

Ground Element (3*10 based)

Enter your trip settings as Is in the Level1G and Level2G icons.

A = zero sequence, same current on all three phases.
B = positive sequence,
C = negative sequence

Negative Sequence Element

Enter your trip settings as Is in the Level1Q and Level2Q icons.
These use I0, not 3*I0
High Impedance Ground: Peterson Coil

- Normal unbalanced operation on distribution line poses problems
- Still need line to line rating on insulation
  - Ground fault neutralized
  - Resonant ground

Impact of Grounding
Fall 2018

Impedance Ground

- Resistance Ground
  » High R: \( I_f < 10 \text{ A} \)
  » Low R: \( 10 \text{A} < I_f < 1000\text{A} \)
- Inductive Ground
  » Zig-zag transformer
  » Poor performance in general
- Resonant Ground (ground fault neutralizer)

Impact of Grounding
Fall 2018
Low impedance ground configurations

No load (pos sep)

2 Broken Delta

Grounding Xfmr
Low Impedance Ground:

- Limit fault current to 50-600 A
- Current sensing used for relaying and can do direction sensing
- Limit over voltages nearly as well as effective ground
- Sometimes use zig-zag transformer with resistor on neutral (if no R, then magnetizing branch is ground path)

Solid Effective Grounding

- Most popular in North America
- $X_0/X_1 \leq 3$ and $R_0/X_1 \leq 1$ and are positive
- Uni-grounded (Europe) versus multi-grounded (U.S.)
- Best for detecting faults, sensing direction, and fault locating
Grounding Examples

\[ a := 1 \cdot e^{j120\text{deg}} \]
\[ \mathbf{A}_{012} := \begin{pmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{pmatrix} \]
\[ \text{MVA} := 1000\text{kW} \quad \text{pu} := 1 \]

A 4160 V feeder is supplied by the WYE connected side of a 75 MVA transformer. The system MVA_{sc} supplying the delta side of the transformer is 650 MVA. The transformer has a leakage reactance of 10%. A ground impedance will be connected in the neutral of 4.16kV side of the transformer to limit fault currents.

**A** Sketch the per unit diagram for the system

\[ \text{MVA}_{\text{base}} := 100\text{MVA} \]
\[ \text{Srated} := 75\text{MVA} \]
\[ V_{\text{LL}} := 4.16\text{kV} \]
\[ V_{\text{ln}} := \frac{V_{\text{LL}}}{\sqrt{3}} \]
\[ V_{\text{ln}} = 2.402\cdot\text{kV} \]

\[ \text{MVAsc} := 650\text{MVA} \]

\[ X_{\text{src}}_{\text{pu}} := \frac{1.0^2}{\left(\frac{\text{MVAsc}}{\text{MVA}_{\text{base}}}\right)} \quad X_{\text{src}}_{\text{pu}} = 0.154\cdot\text{pu} \]

\[ X_{\text{xfmr}} := 0.1 \cdot \left(\frac{4160\text{V}}{4160\text{V}}\right)^2 \left(\frac{\text{MVA}_{\text{base}}}{\text{Srated}}\right) \]
\[ X_{\text{xfmr}} = 0.133\cdot\text{pu} \]

\[ \text{V}_{\text{src}} \quad \text{Xsrc} \quad \text{Xfmr} \]

or
\[ X_{\text{gndpu}} := \text{Im}(Z_{\text{gnd}}) \quad X_{\text{gndpu}} = 2.077 \text{ per unit} \]

\[ X_{\text{gnd}} := X_{\text{gndpu}} \cdot Z_{\text{base}} \quad X_{\text{gnd}} = 0.359 \Omega \]

\[ L_{\text{gnd}} := \frac{X_{\text{gnd}}}{2 \cdot \pi \cdot 60 \text{Hz}} \quad L_{\text{gnd}} = 0.954 \text{ mH at 60Hz} \]

**D**: If the feeder is largely underground, the capacitance cannot be neglected. If the total per phase capacitance to ground is 1.5 \( \mu \text{F} \), determine the grounding resistance needed to limit the single line to ground fault current to 20 A.

\[ C_{\text{parasitic}} := 1.5 \mu \text{F} \quad X_c := \frac{1}{2 \cdot \pi \cdot 60 \text{Hz} \cdot C_{\text{parasitic}}} \quad X_c = 1.768 \text{ k}\Omega \]

\[ X_{c \_pu} := \frac{X_c}{Z_{\text{base}}} \quad X_{c \_pu} = 10218.6 \text{ pu} \]

\[ I_{\text{slg \_max}} := 20 \text{A} \quad I_{\text{slgpu}} := \frac{I_{\text{slg \_max}}}{I_{\text{base}}} \quad I_{\text{slgpu}} = 1.441 \times 10^{-3} \text{ pu} \]

The sequence networks will now change with the addition of the capacitance as shown.

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Alternate selection for \( R_{\text{gnd}} \):

- If capacitance is known:
  \[ 3R_{\text{gnd}} = X_{co} \]
  - Limits SLG current to \( \approx \) charging current

\[ I_0 \]
B Determine sequence networks for the system

Positive Sequence:

Negative Sequence:

Zero Sequence:

Note that this is a Δ-Y grounded transformer. Also, assuming that zero sequence leakage impedance equal to positive and negative sequence values.

C Assume that the feeder is all overhead lines with negligible capacitance. Determine the ground reactance needed to limit the single line to ground fault current to 6000A.

If\_slgmax := 6000A

\[ I_{base} := \frac{MVA\_base}{\sqrt{3} \cdot V\_LL} \]

\[ I_{base} = 13.88 \cdot kA \]

\[ Z_{base} := \frac{V\_LL^2}{MVA\_base} \]

\[ Ifpu := \frac{If\_slgmax}{I_{base}} \]

\[ Ifpu = 0.432\cdot pu \]

For a SLG fault we have (connect positive, negative and zero sequence circuits in series):

\[ I_0 = \frac{V_{fault}}{Z1 + Z2 + Z0 + 3 \cdot jX_{gnd}} \]

where

\[ V_{fault} := 1.0 \cdot e^{j\cdot 90\text{deg}} \]

\[ Z1 := jX_{src\_pu} + jX_{xfmr} \]

\[ Z2 := Z1 \]

\[ Z0 := jX_{xfmr} \]

and we know for a SLG fault:

\[ I_0 := \frac{Ifpu}{3} \]

Solve for Zgnd

\[ Z_{gnd} := \frac{1}{3} \left( \frac{V_{fault}}{I_0} - (Z1 + Z2 + Z0) \right) \]

\[ Z_{gnd} = 2.0772i \] per unit
E Calculate the line to ground voltages on the unfaulted phases in parts C and D and calculate the zero sequence voltages and currents.

Part C:
\[
I_{0\_partC} := \frac{V_{\text{fault}}}{Z_0 + 3\cdot jX_{\text{gnd pu}} + Z_1 + Z_2}
\]
\[I_{0\_partC} = 0.144\]
\[I_{1\_partC} := I_{0\_partC}\]
\[I_{2\_partC} := I_{0\_partC}\]

as a check: \[I_{a\_partC} := 3\cdot I_{0\_partC}\]
\[|I_{a\_partC}| = 0.432 \text{ pu} \quad |I_{a\_partC}| \cdot I_{\text{base}} = 6 \text{ kA}\]
\[V_{1\_partC} := V_{\text{fault}} - I_{1\_partC} \cdot Z_1\]
\[V_{2\_partC} := -I_{2\_partC} \cdot Z_2\]
\[V_{0\_partC} := -I_{0\_partC} \cdot (Z_0 + 3\cdot j\cdot X_{\text{gnd pu}})\]
\[
V_{\text{abc part C}} := A_{012} \begin{pmatrix}
V_{0\_partC} \\
V_{1\_partC} \\
V_{2\_partC}
\end{pmatrix}
\]
\[
V_{\text{abc part C}} = \begin{pmatrix}
0 \\
0.866 - 1.376i \\
-0.866 - 1.376i
\end{pmatrix}
\]

\[
|V_{\text{abc part C}}| = \begin{pmatrix}
1.626 \\
1.626
\end{pmatrix}
\]
\[
\begin{pmatrix}
0 \\
90
\end{pmatrix}
\]
\[
\text{arg}(V_{\text{abc part C}}) = \begin{pmatrix}
57.812 \\
-122.188
\end{pmatrix} \text{ deg}
\]

\[
V_{\text{in}} \cdot |V_{\text{abc part C}}| = \begin{pmatrix}
3.905 \\
3.905
\end{pmatrix} \text{ kV}
\]

Part D:
\[
Z_{\text{gnd D}} := \frac{(3\cdot R_{\text{gnd pu}} + Z_0) \cdot (-j\cdot X_{\text{c pu}})}{(3\cdot R_{\text{gnd pu}} + Z_0) - j\cdot X_{\text{c pu}}}
\]
\[
I_{0\_partD} := \frac{V_{\text{fault}}}{Z_{\text{gnd D}} + Z_1 + Z_2}
\]
\[I_{0\_partD} = -9.771 \times 10^{-5} + 4.703i \times 10^{-4}\]
\[I_{1\_partD} := I_{0\_partD}\]
\[I_{2\_partD} := I_{0\_partD}\]
\[|I_{0\_partD}| = 4.804 \times 10^{-4}\]
as a check: \[ I_{a\_partD} := 3 \cdot I_{0\_partD} \quad |I_{a\_partD}| = 1.441 \times 10^{-3} \text{ pu} \]

\[ |I_{a\_partD}| \cdot I_{\text{base}} = 20.001 \cdot \text{A} \]

\[ V_{1\_partD} := V_{\text{fault}} - I_{1\_partD} \cdot Z_{1} \]
\[ V_{2\_partD} := -I_{2\_partD} \cdot Z_{2} \]
\[ V_{0\_partD} := -I_{0\_partD} \cdot (Z_{\text{gndD}}) \]

\[ V_{\text{abc\_partD}} := A_{012} \begin{pmatrix} V_{0\_partD} \\ V_{1\_partD} \\ V_{2\_partD} \end{pmatrix} \]

\[ \begin{bmatrix} |V_{\text{abc\_partD}}| \\ \text{arg}(V_{\text{abc\_partD}}) \end{bmatrix} = \begin{bmatrix} 0 \\ 0.866 - 1.5i \\ -0.866 - 1.5i \end{bmatrix} \frac{\text{deg}}{} \]

\[ V_{\text{in}} \cdot |V_{\text{abc\_partD}}| = \begin{pmatrix} 0 \\ 4.16 \\ 4.161 \end{pmatrix} \text{ kV} \]

\[ F \text{ Compute the single line to ground fault current and the voltage on the unaftaulted phases if the transformer is solidly grounded. Calculate the zero sequence voltages and currents.} \]

\[ I_{0\_\text{gnd}} := \frac{V_{\text{fault}}}{Z_{0} + Z_{1} + Z_{2}} \]
\[ I_{0\_\text{gnd}} = 1.413 \quad I_{1\_\text{gnd}} := I_{0\_\text{gnd}} \]
\[ I_{2\_\text{gnd}} := I_{0\_\text{gnd}} \]

\[ I_{a\_\text{gnd}} := 3 \cdot I_{0\_\text{gnd}} \]
\[ I_{a\_\text{gnd}} = 4.239 \text{ per unit} \]
\[ I_{a\_\text{gnd}} \cdot I_{\text{base}} = 58.833 \text{ kA} \]

\[ V_{1\_\text{gnd}} := V_{\text{fault}} - I_{1\_\text{gnd}} \cdot Z_{1} \]
\[ V_{1\_\text{gnd}} = 0.594i \]
\[ V_{2\_\text{gnd}} := -I_{2\_\text{gnd}} \cdot Z_{2} \]
\[ V_{2\_\text{gnd}} = -0.406i \]
\[ V_{0\_\text{gnd}} := -I_{0\_\text{gnd}} \cdot Z_{0} \]
\[ V_{0\_\text{gnd}} = -0.18841i \]
Fault Detection & Direction Determination
as impacted by grounding

(1) Solidly grounded:

Detection: overcurrent protection
- phase elements
- ground elements
- negative sequence elements

⇒ If fault typically much larger than load current (can use phase elements)
Direction Sensing:

- voltage + current
  - Torque elements
    - phase quantities
    - negative sequence
    - positive sequence

2) Low impedance grounded

Detection:

- SLG: limits I_o - can still use over current elements
  - ground over current
- DLG 30, LL: overcurrent as above

Direction - largely same as above, zero seq directional
- caution with zero sep direction

→ mutual coupling to parallel line - can fool element
High Resistance Grounded

Fault Detection

SLG: Vng = 3\(V_o\) - else for ungrounded

LL, DLG, 3G: Overcurrent - same as earlier

2 Direction determination - same as earlier