

ECE 526

PROTECTION OF  
POWER SYSTEMS II

SESSION no. 16

## Single Pole Tripping

(Single pole reclosing)

- Three pole trip (3PT)
  - any fault trip all 3 phases
- Single Pole Trip (SPT)
  - SLC - open only faulted phase
  - (3PT for other faults) - ~~SLC~~

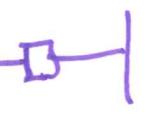
- If reclose SPT into a fault  
→ 3PT

Aside on reclose

- On overhead lines most (transmission)  
utilities do a single reclose  
after about 400-500ms
- (Not 3 phase)
  - ~~more~~ most common SLE, DLE, LL
  - Don't reclose into cables

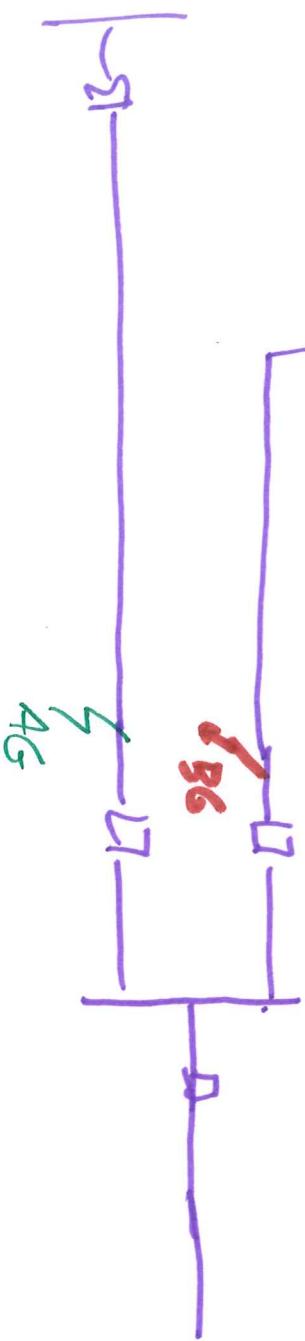
## Protection Challenges

- ① Correct fault type identification  
and faulted phase selection



→ directional challenges

- forward SLC vs reverse DUG
- zero sequence coupling
- cross country fault



Determine internal source voltages:

$$\text{magS}_{\text{pre}} := 80 \text{MVA} \quad \text{pf}_{\text{pre}} := 0.8 \quad \text{lagging} \quad \theta_{\text{pre}} := \text{acos}(0.85) \quad \theta_{\text{pre}} = 31.788 \cdot \text{deg}$$

$$\begin{aligned} S_{\text{pre}} &:= \frac{\text{magS}_{\text{pre}}}{S_{\text{Base}}} \cdot e^{j \cdot \theta_{\text{pre}}} & S_{\text{pre}} &= (0.68 + 0.421i) \text{pu} & |S_{\text{pre}}| &= 0.8 \text{pu} \end{aligned}$$

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

$$V_3 := 1.0$$

$$I_{\text{load}} := \overline{\left( \frac{S_{\text{pre}}}{V_3} \right)} \quad I_{\text{load}} = 0.68 - 0.421i \quad |I_{\text{load}}| = 0.8 \cdot \text{pu} \quad \arg(I_{\text{load}}) = -31.788 \cdot \text{deg}$$

Internal voltage on the motor (since we don't know steady-state synchronous reactance, use  $X_1$ ):

$$E_2 := V_3 - I_{\text{load}} \cdot j(X_T + X_{1\text{Mach}}) \quad |E_2| = 0.902 \quad \phi_2 := \arg(E_2) \quad \phi_2 = -12.182 \cdot \text{deg}$$

Generator internal voltage:

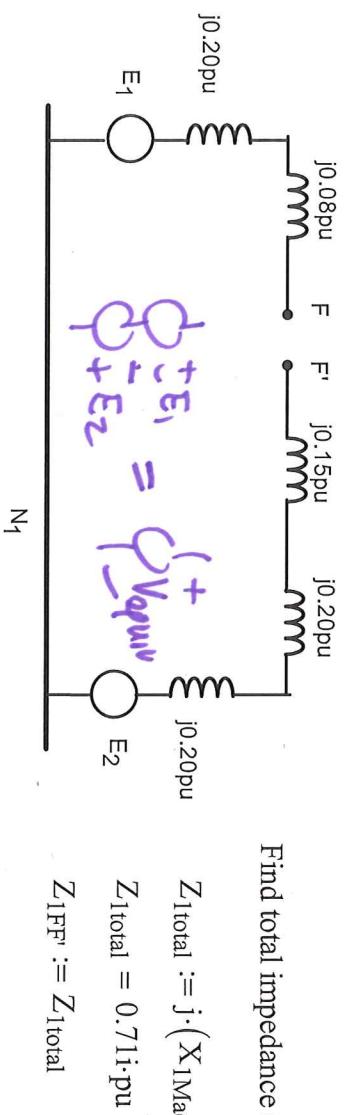
$$E_1 := V_3 + I_{\text{load}} \cdot (j \cdot X_{L1} + j \cdot X_T + j \cdot X_{1\text{Mach}}) \quad |E_1| = 1.217 \cdot \text{pu} \quad \phi_1 := \arg(E_1) \quad \phi_1 = 13.904 \cdot \text{deg}$$

Check result by calculating power transfer between sources and current:

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

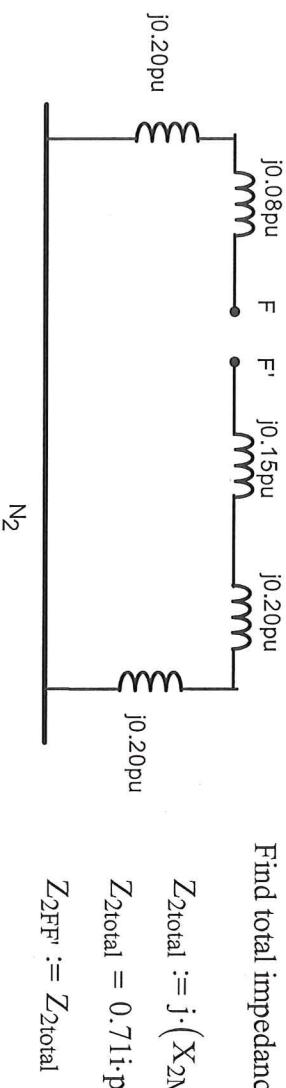
$$I_{\text{trans}} := \frac{E_1 - E_2}{j(2 \cdot X_{1\text{Mach}} + 2 \cdot X_T + X_{L1})} \quad I_{\text{trans}} - I_{\text{load}} = 0$$

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

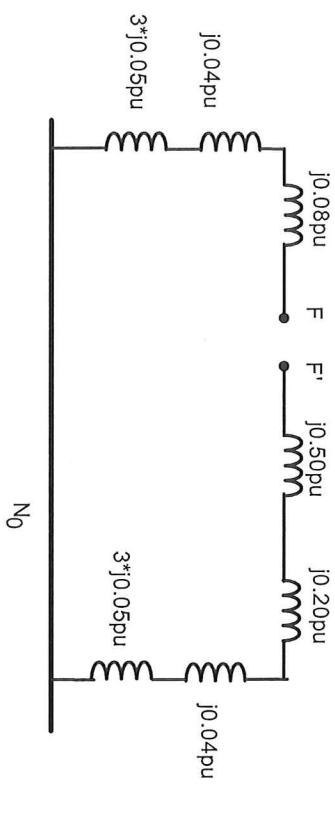


$$V_{\text{equiv}} := E_1 - E_2$$

- Negative sequence equivalent circuit:



- Zero sequence equivalent:



Find total impedance counterclockwise around loop from F to F'

$$Z_{0\text{total}} := j \cdot (2 \cdot X_{\text{Mach}} + 2 \cdot X_T + X_{L0} + 2 \cdot 3 \cdot X_{\text{nMach}})$$

$$Z_{0\text{total}} = 1.04i \text{ pu}$$

$$Z_{0FF'} := Z_{0\text{total}}$$

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

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

$$I_1 = (0.427 - 0.264i) \cdot \text{pu}$$

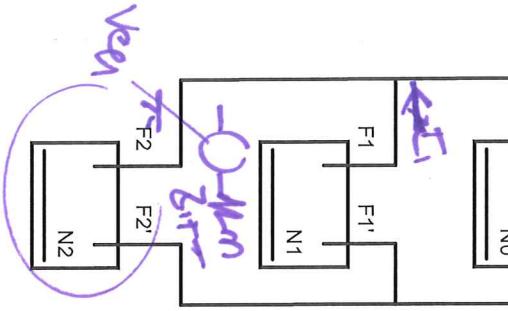
$$|I_1| = 0.502 \cdot \text{pu} \quad \arg(I_1) = -31.788 \cdot \text{deg}$$

$$I_2 = (-0.253 + 0.157i) \cdot \text{pu}$$

$$|I_2| = 0.298 \cdot \text{pu} \quad \arg(I_2) = 148.212 \cdot \text{deg}$$

$$I_0 = (-0.173 + 0.107i) \cdot \text{pu}$$

$$|I_0| = 0.204 \cdot \text{pu} \quad \arg(I_0) = 148.212 \cdot \text{deg}$$



$\omega_m$   
 $Z_2 + j0.05$

$$\overrightarrow{I_{abc}} = \begin{pmatrix} I_0 \\ I_1 \\ I_2 \end{pmatrix}$$

$$|I_{abc}| = \begin{pmatrix} 0 \\ 0.757 \\ 0.757 \end{pmatrix} \cdot \text{pu}$$

$$\arg(I_{abc_1}) = -145.575 \cdot \text{deg}$$

$$\arg(I_{abc_2}) = 81.998 \cdot \text{deg}$$

Using the right have the sequence equivalent circuits:

$$V_{3new1} := E_2 + I_1 \cdot j \cdot (X_{1Mach} + X_T)$$

$$|V_{3new1}| = 0.959 \cdot \text{pu}$$

$$\arg(V_{3new1}) = -4.246 \cdot \text{deg}$$

$$V_{3new2} := 0 + I_2 \cdot j \cdot (X_{2Mach} + X_T)$$

$$|V_{3new2}| = 0.083 \cdot \text{pu}$$

$$\arg(V_{3new2}) = -121.788 \cdot \text{deg}$$

$$V_{3new0} := 0 + I_0 \cdot j \cdot (X_{0Mach} + X_T + 3 \cdot X_{nMach})$$

$$|V_{3new0}| = 0.055 \cdot \text{pu}$$

$$\arg(V_{3new0}) = -121.788 \cdot \text{deg}$$

$$V_{3newABC} := A_{012} \cdot \begin{pmatrix} V_{3new0} \\ V_{3new1} \\ V_{3new2} \end{pmatrix}$$

$$= \begin{pmatrix} 0.903 \\ 0.971 \\ 1.014 \end{pmatrix} \cdot \text{pu}$$

$$\overrightarrow{|V_{3newABC}|} = \begin{pmatrix} -12.06 \\ -119.947 \\ 118.579 \end{pmatrix} \cdot \text{deg}$$

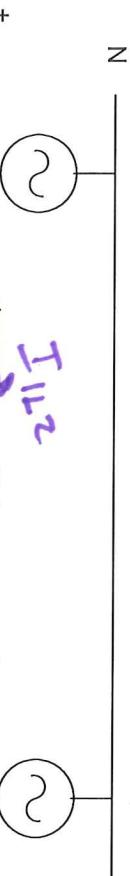
$$\Delta V_{ABC} := 1.0 \cdot \begin{pmatrix} 1 \\ a^2 \\ a \end{pmatrix} - V_{3newABC}$$

$$\overrightarrow{|\Delta V_{ABC}|} = \begin{pmatrix} 0.222 \\ 0.029 \\ 0.029 \end{pmatrix}$$

$$\overrightarrow{\arg(\Delta V_{ABC})} = \begin{pmatrix} 58.212 \\ -121.788 \\ -121.788 \end{pmatrix} \cdot \text{deg}$$

ATP simulation results: Currents

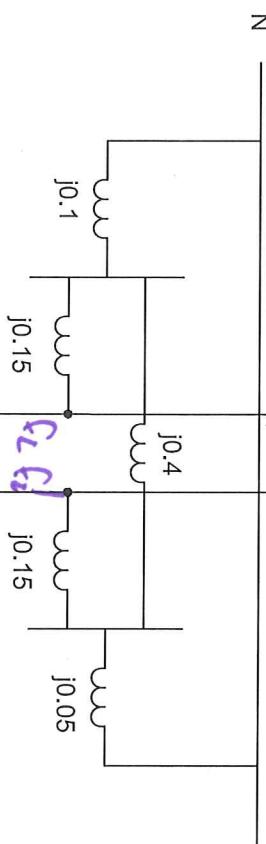
Voltages



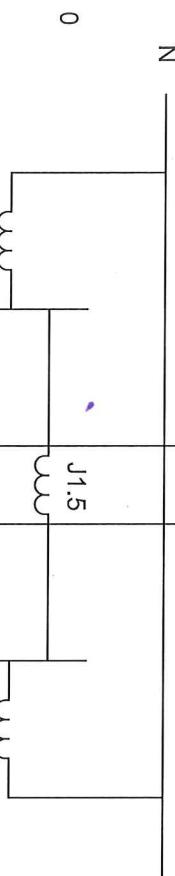
$$Z_{1\text{equiv}} := \frac{Z_{1L1}}{2} + \left( \frac{1}{Z_{1S} + Z_{1R}} + \frac{1}{Z_{1L2}} \right)^{-1} + \frac{Z_{1L1}}{2}$$

$$Z_{1\text{equiv}} = 0.409\text{i}\cdot\text{pu}$$

parallel



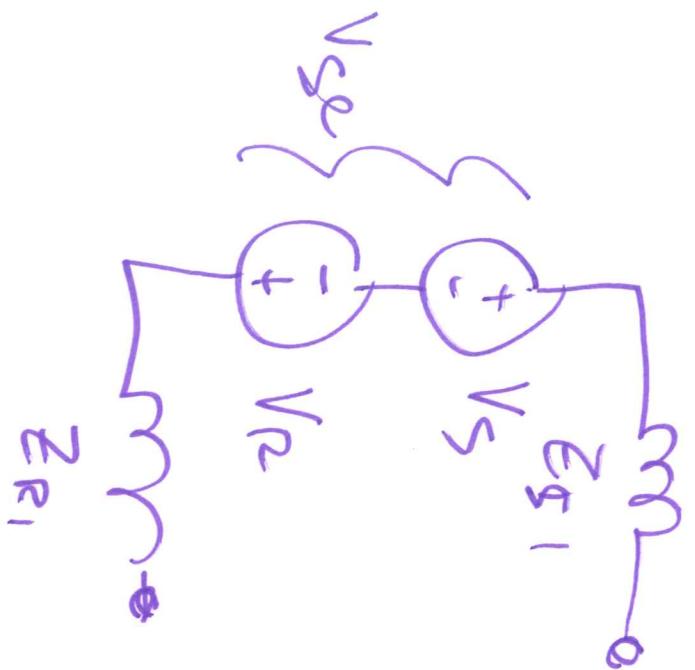
$$Z_{2\text{equiv}} := Z_{1\text{equiv}}$$



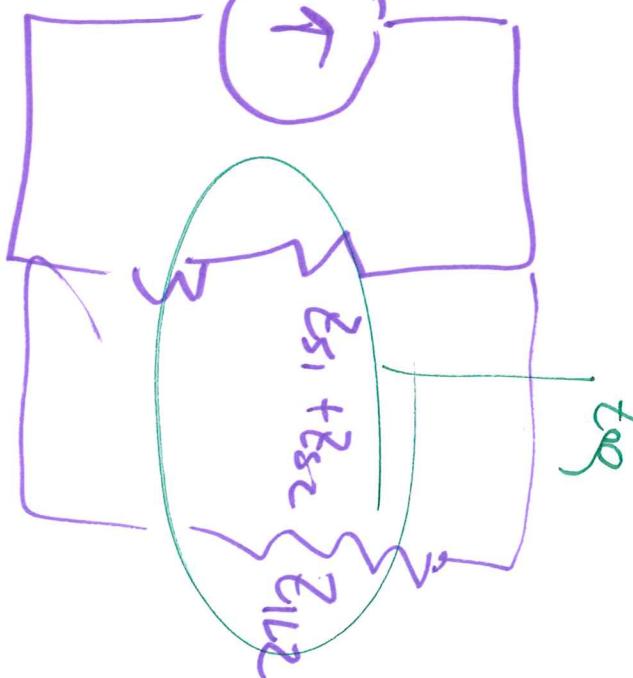
$$Z_{0\text{equiv}} := Z_{0L1} + \left( \frac{1}{Z_{0S} + Z_{0R}} + \frac{1}{Z_{0L2}} \right)^{-1}$$

$$Z_{0\text{equiv}} = 1.575\text{i}\cdot\text{pu}$$

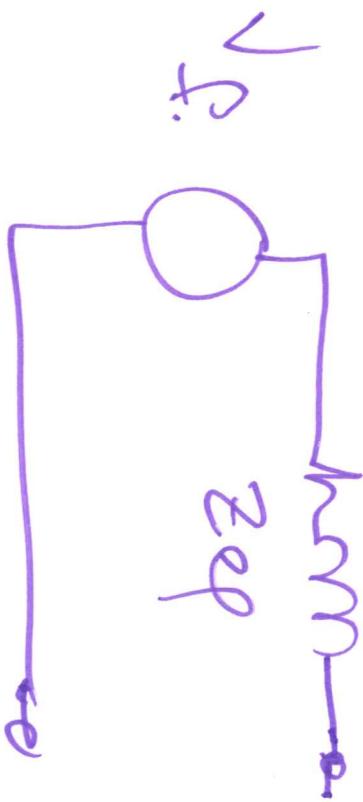
- Using the sequence diagrams above calculate the positive-, negative-, and zero-sequence currents on Line 2 with  $VR = 1\text{pu}$  @ 20 degrees.



Norton  
 $\frac{V_{se}}{Z_{s1} + Z_{s2}}$



↓ Ther



Equivalent voltage source for phase A open analysis:

$$V_{se} := V_S - V_R$$

$$V_{se} = (0.06 - 0.342i) \cdot pu$$

Norton Equivalent Current:

$$I_{se} := \frac{V_{se}}{Z_{1R} + Z_{1S}}$$

$$I_{se} = (-2.28 - 0.402i) \cdot pu$$

Equivalent Parallel Impedance:

$$Z_{eq} := \left( \frac{1}{Z_{1L2}} + \frac{1}{Z_{1S} + Z_{1R}} \right)^{-1}$$

$$Z_{eq} = 0.109i \cdot pu$$

Convert back to Thevenin Equivalent Voltage

$$V_f := Z_{eq} I_{se}$$

$$|V_f| = 0.253 \cdot pu \quad \arg(V_f) = -80 \cdot deg$$

Positive sequence current in line 1:

$$I_{LL\_open} := \frac{V_f}{Z_{1equiv} + \left( \frac{1}{Z_{2equiv}} + \frac{1}{Z_{0equiv}} \right)^{-1}}$$

$|I_{LL\_open}| = 0.344 \cdot pu$   
 $\arg(I_{LL\_open}) = -170 \cdot deg$

Negative sequence current in line 1 (current divider on the line 1 current)

$$I_{2L1\_open} := -I_{LL\_open} \cdot \frac{Z_{0equiv}}{Z_{2equiv} + Z_{0equiv}}$$

⋮ ⋮ ⋮

$$|I_{2L1\_open}| = 0.273 \cdot pu$$

$$\arg(I_{2L1\_open}) = 10 \cdot deg$$

Zero sequence current in line 1 (current divider on the line 1 current)

$$I_{0L1\_open} := -I_{LL1\_open} \cdot \frac{Z_{2\text{equiv}}}{Z_{2\text{equiv}} + Z_{0\text{equiv}}}$$

$$|I_{0L1\_open}| = 0.071 \cdot \text{pu} \quad \arg(I_{0L1\_open}) = 10 \cdot \text{deg}$$

$$I_{ABC\_Line1} := A_{012} \cdot \begin{pmatrix} I_{0L1\_open} \\ I_{LL1\_open} \\ I_{2L1\_open} \end{pmatrix} \xrightarrow{|I_{ABC\_Line1}|} = \begin{pmatrix} 0 \\ 0.545 \\ 0.545 \end{pmatrix} \cdot \text{pu} \quad \arg(I_{ABC\_Line1}) = 88.74 \cdot \text{deg}$$

$$\arg(I_{ABC\_Line1_2}) = -68.74 \cdot \text{deg}$$

Note that the magnitude on phase A is 0 and a little smaller on the unfaulted phases. There also a phase shift compared to prefault

Now to find the line 2 current, we need to do another current divider on each of the sequence currents from line 1, since the sequence currents could either pass through the sources or line to return to line 1.

Positive sequence load  
current in line two ignoring  
open line

$$I_{LineA2} := \frac{V_S - V_R}{Z_{1S} + Z_{1L2} + Z_{1R}}$$

$$|I_{LineA2}| = 0.631 \quad \arg(I_{LineA2}) = -170 \cdot \text{deg}$$

$$I_{1L2} := -I_{1L1\_open} \cdot \left( \frac{Z_{1S} + Z_{1R}}{Z_{1S} + Z_{1R} + Z_{1L2}} \right) + I_{LineA2}$$

$$|I_{1L2}| = 0.538 \cdot \text{pu}$$

$$\arg(I_{1L2}) = -170 \cdot \text{deg}$$

$$I_{2L2} := -I_{2L1\_open} \cdot \left( \frac{Z_{1S} + Z_{1R}}{Z_{1S} + Z_{1R} + Z_{1L2}} \right)$$

$$|I_{2L2}| = 0.075 \cdot \text{pu}$$

$$\arg(I_{2L2}) = -170 \cdot \text{deg}$$

(2) correct response ~~from~~ from relays  
on the line & parallel lines  
due to imbalance.

→ ~~if~~ Lines "parallel" - port  
of conductors ~~path~~ path for  
 $I_0 + I_2$  will see unbalance  
currents

→ Reclose time issue...

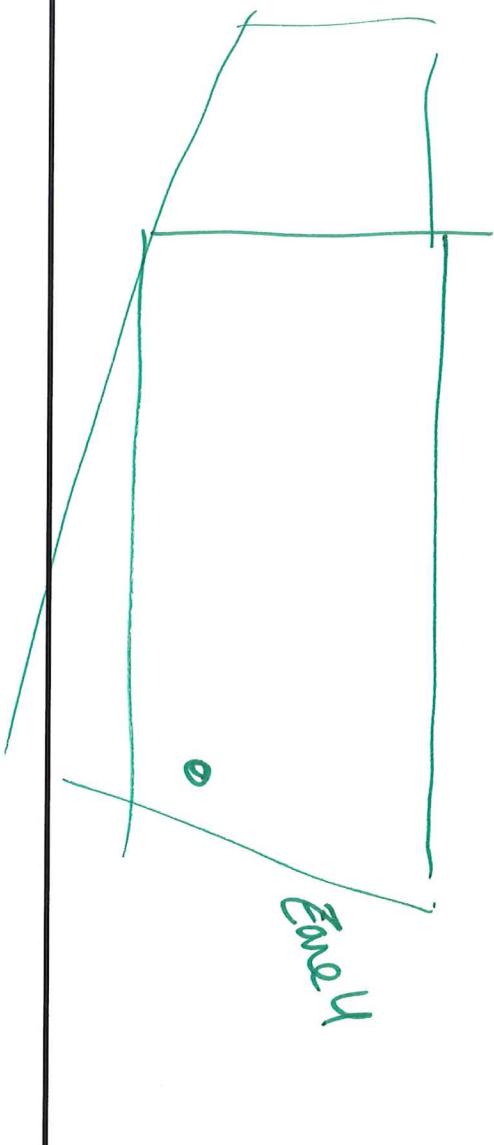
either detect desired  
secondary or predetermined  
want pre-determined  
want time - typically  
about 1 sec  
- Secondary Arc (not fed by  
breakers)

- long duration of  $I_z$  &  $I_0$  needs to accounted for, even at low levels

- Long over reaching  $\Rightarrow$  distance zones - especially quad elements as discussed earlier

$$\rightarrow \text{replace } I_A \rightarrow \frac{3}{2}(I_0 + I_z)$$

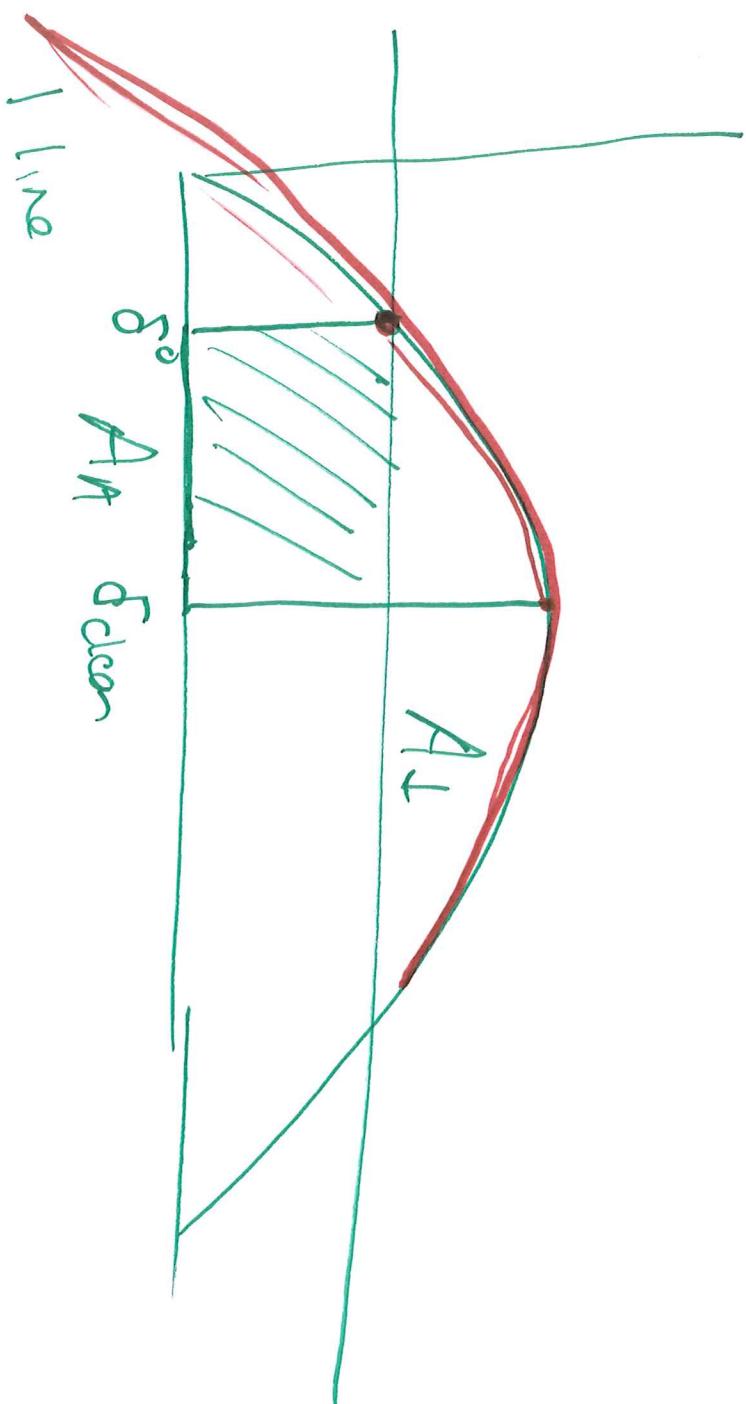
↓  
sets initial pos  
sep load current

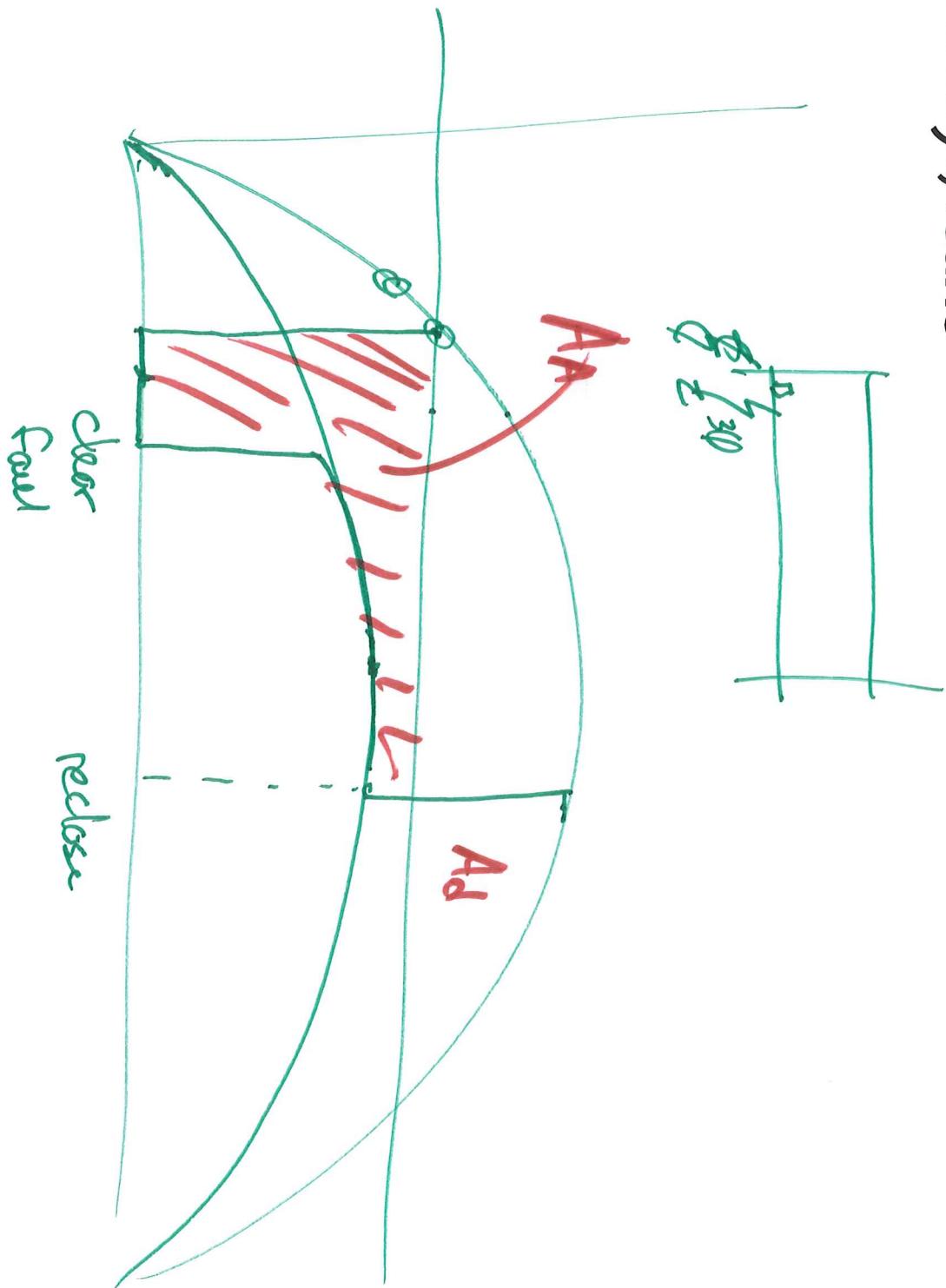


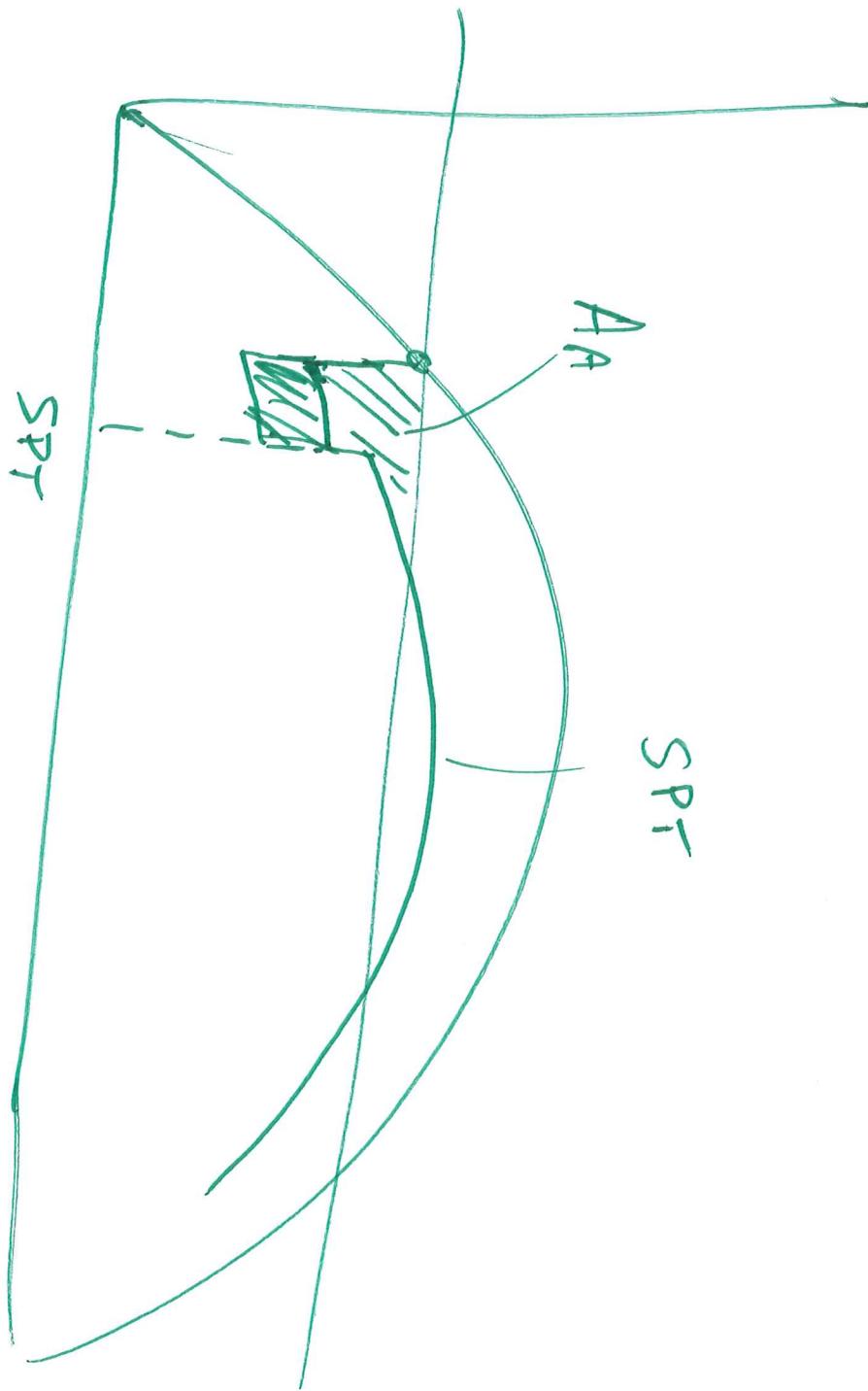
- ③ Correct behavior if a  
second fault occurs  
during single pole open condit.m

Why do single trip?

- ~~Best~~ Better stability margin





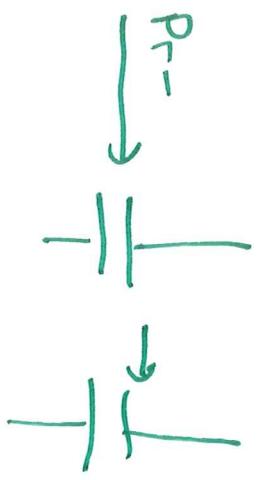


## Breaker modification's

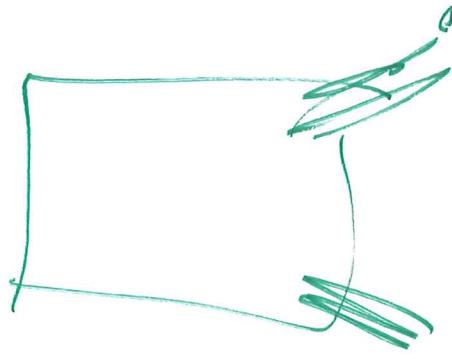
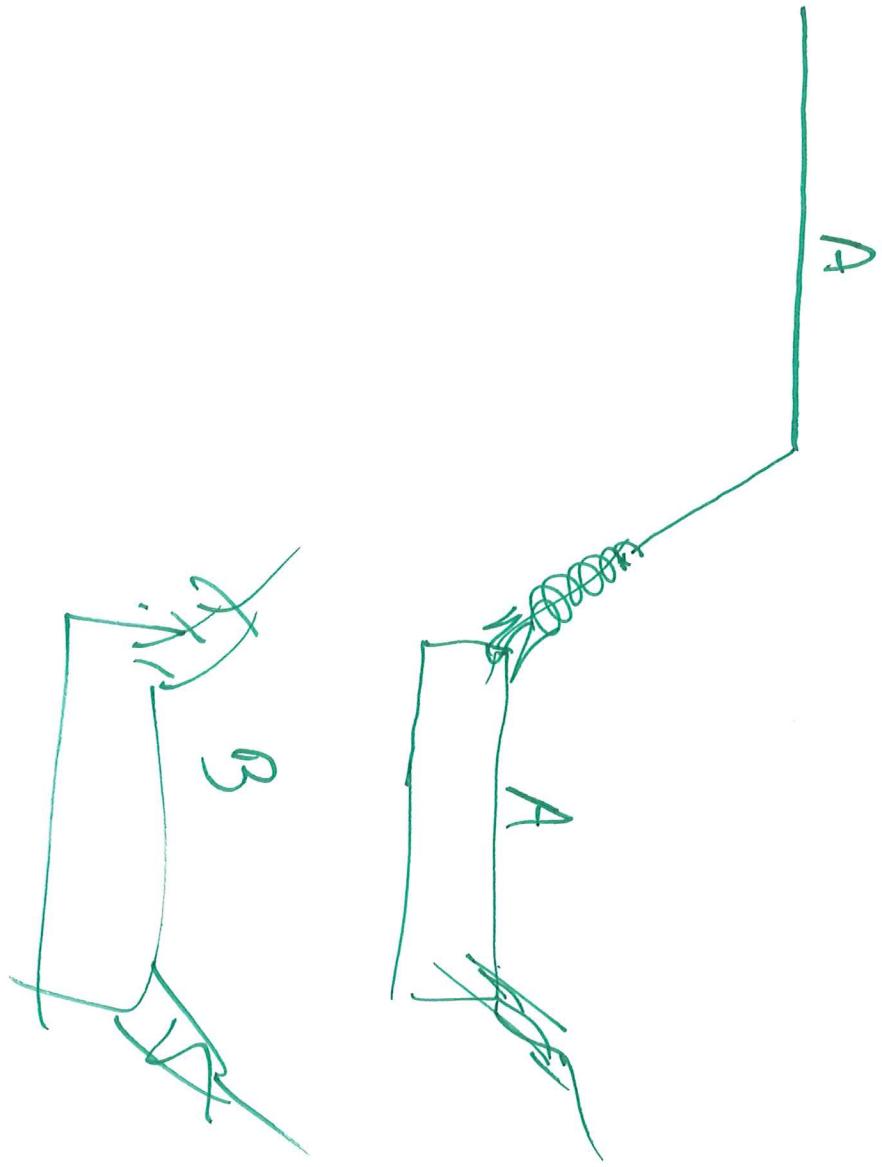
- Not all substations - are set up for single pole tripping.

- Additional trip outputs

from relay(s)

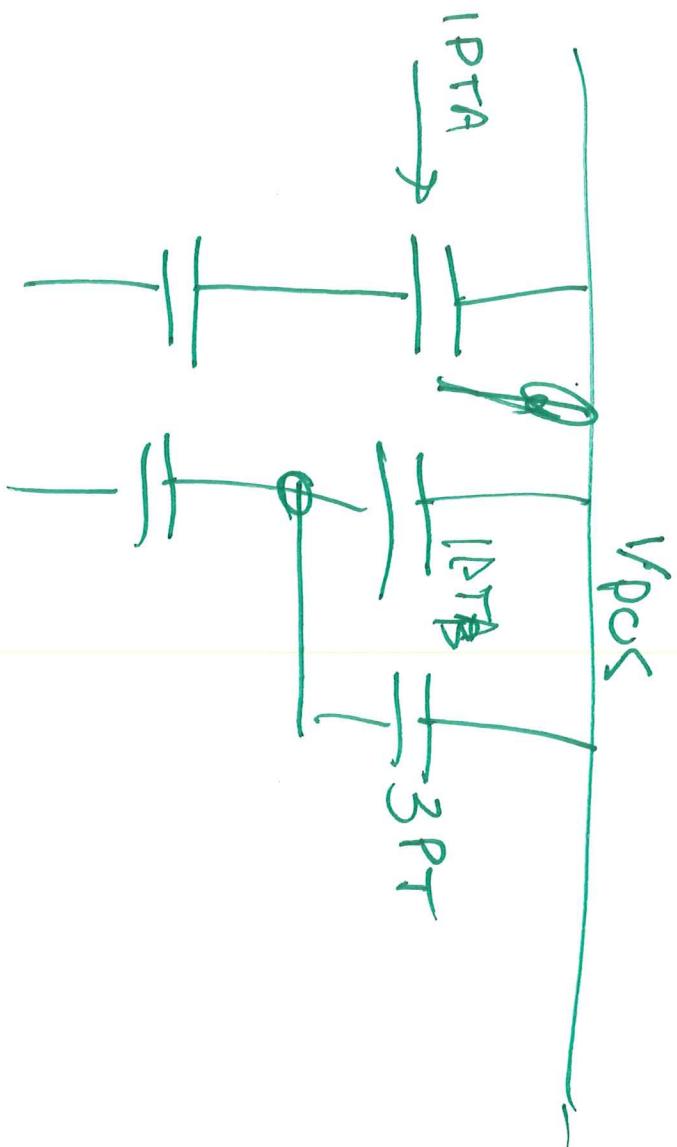


} traditional substation  
with all dc contacts



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11.6 20/20



V<sub>NGG</sub>