

ECE 526

PROTECTION OF
POWER SYSTEMS II

SESSION no. 23

Fault Location (for Lines)

2 types of decisions :-

① Tripping related

→ Zone Selection

- direction

- Speed, sensitivity, security

→ NOT PRECISE LOCATION
OF FAULT

(2) Fault Location for

Line crews & in some cases auto reclosing

- Some utilities will auto reclose for SLG, but not for DLG or 3Ø without inspection
 - for sending out crews ~~need~~ prefer accurate location
 - down to a few towers

Challenges

① Fault challenge

→ remote infeed

② Tapped line with remote infeed

③ Source impedance variation

④ Series compensation

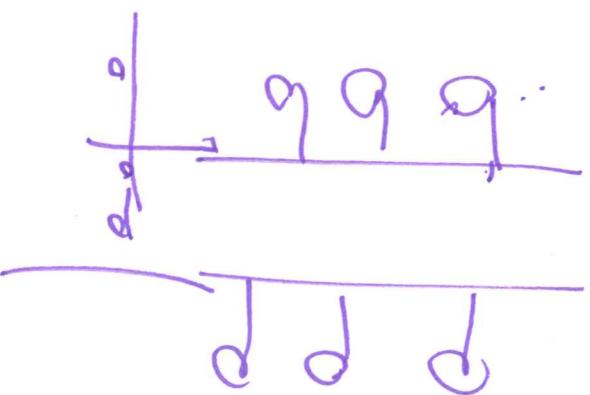
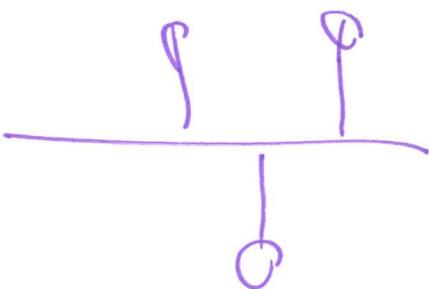
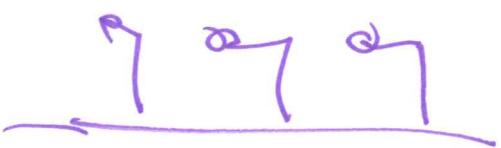
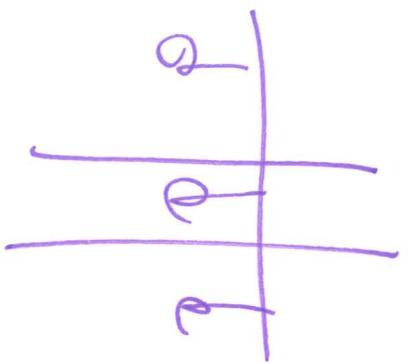
⑤ Mutual coupling

⑥ Accuracy of line model

- Earth resistivity $\rightarrow Z_0$

- Tower configurations

- Mutual coupling



⑦ Mixed Overhead/Underground

⑧ Time window for measurement

- a few cycles before breaker opens

⑨ - relay measurements

CT/PT Error - transient response

Options for determining fault location

- ① Nomographs
 - compare waveforms from event file with fault signatures from off-line studies
- ② Impedance based schemes \Rightarrow single ended
(using $V + I$ current measurements)
- ③ Double ended (multi) impedance based
(V, I phasors)

④ Travelling wave schemes

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⑤ ~~Waves~~ Signal injection Methods

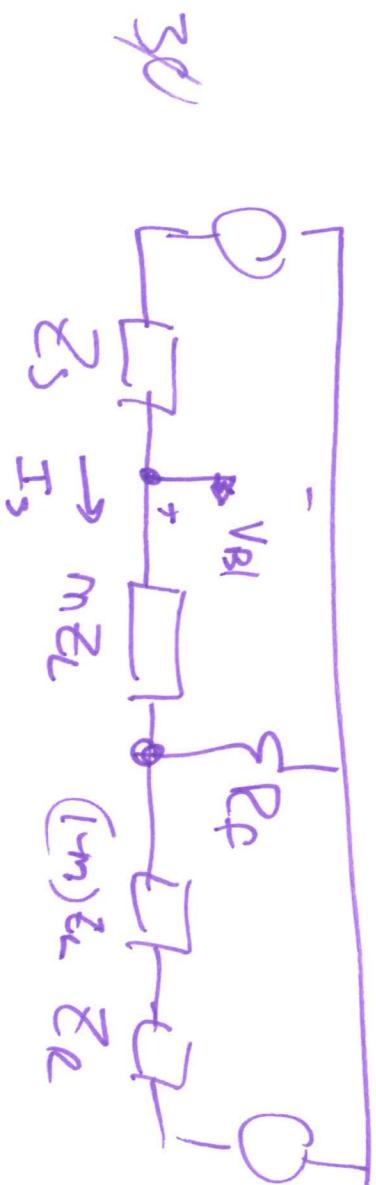
(more common ~~use~~. underground cables)

- Phasor based methods

- ① Single ended "impedance based"

$$V_A, V_B, V_C, I_{A_1}, I_{B_1}, I_C$$

(A) Reactance Method



$$V_{BI} = I_S \cdot \text{m}Z_L + \bar{I}_F R_F$$

$$Z_{\text{eff}} = \frac{V_{B1}}{I_s} = m Z_L + \left(\frac{I_f}{I_s} \right) R_f$$

error term

Imaginary part ...

$$m = \frac{I_m \left(\frac{V_{B1}}{I_s} \right) - R_f I_m \left(\frac{I_f}{I_s} \right)}{I_m (\bar{Z}_L)}$$

- $I_f : \angle I_f = \angle I_s$ works well

$$\sigma_{I_f} R_f = 0$$

- Also has problem if ~~prefilter~~ power flow
is low

Takagi Fault Location Method

$$\bar{I}_S = \bar{I}_{S_{\text{fault}}} - \bar{I}_{S_{\text{prefault}}}$$

measured
recorded

used in
fault
location
calc

- Reduces R_f effect on non homogeneous system
- Reduced sensitivity to load flow

$$V_{B1} = m \bar{z}_L I_{\text{factual}} + R_f I_f$$

- multiply both sides by $I_s^* = (I_{fs} - I_{pres})^*$

- Imaginary

$$\begin{aligned} \text{Im}(V_{B1} \cdot I_s^*) &= m \text{Im}(\bar{z}_L \bar{I}_{fs} \bar{I}_s^*) \\ &\quad + R_f \text{Im}(I_f \bar{I}_s^*) \end{aligned}$$

*Actual
equation
(w/m)*

$$m = \frac{\text{Im}(V_{B1} I_s^*)}{\text{Im}(\bar{z}_L \bar{I}_{fs} \bar{I}_s^*)} - R_f \frac{\text{Im}(I_f \bar{I}_s^*)}{\text{Im}(\bar{z}_L \bar{I}_{fs} \bar{I}_s^*)}$$

what relay calculates

Improved version: Modified Takagi Method

2 versions

(A)

Instead of I_S we use $3 I_{OS}$
measured

- need to rotate with tilt angle like quad element
- u non-homogeneous

$$n = \frac{I_m(V_B \cdot (3I_{OS})^* e^{-jT}) - R_F I_m(I_F (3I_{OS})_0^* e^{-jT})}{I_m(2I_{FS} (3I_{OS})^* e^{-jT})}$$

- tilt angle requires info on source impedances
- good for SLG, DLG, not LL, 3Ø
- zero sequence mutual effects...

(B) modified Takagi with

- I_S replaced by I_{ZS}
- use this for SLC, U, DLG
- use regular Takagi for 30

- doesn't need a fit angle

$$\omega = \frac{Im(V_B \cdot I_{ZS}^*) - R_F Im(I_F \cdot I_{ZS}^*)}{Im(Z_L I_S (I_{ZS})^*)}$$

What are V_{B1} and I_{fs} ? fault current

| | V_{BL} | I_{fs} |
|----------|-------------------|------------------------|
| m_{AG} | V_{AG} | $I_{AS} + k_0 3I_{os}$ |
| m_{BG} | V_{BG} | |
| m_{CG} | V_{CG} | |
| m_{AB} | $V_{AG} - V_{BG}$ | $I_{AS} - I_{BS}$ |
| m_{BC} | $V_{BG} - V_{CG}$ | |
| m_{CA} | $V_{CG} - V_{AG}$ | |

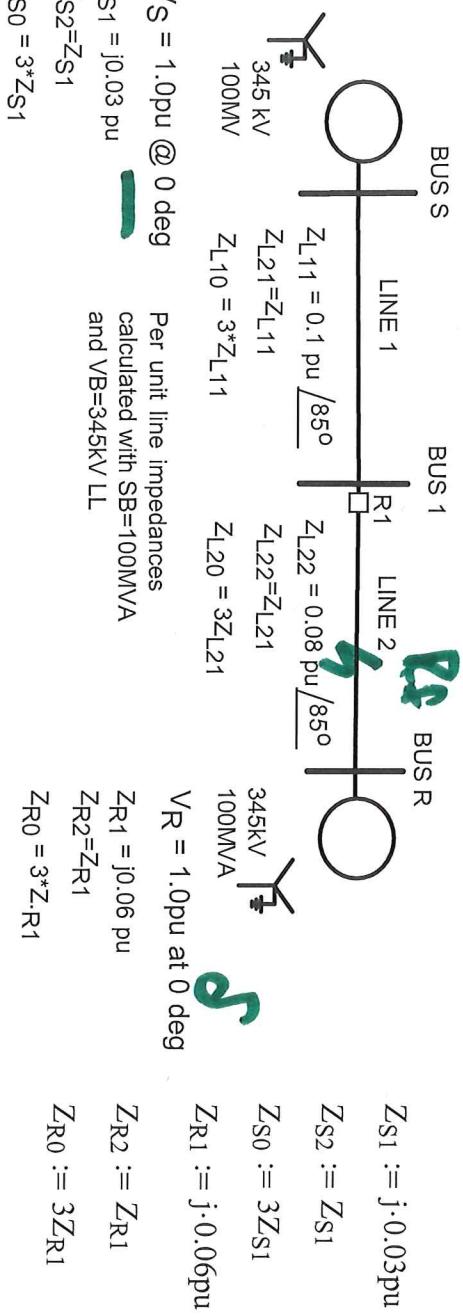
Double ended in a few minutes--

Fault Location Examples

pu := 1
MVA := 1000kW

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a := 1ej.120deg
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- *Example with two sources:*



$$\begin{aligned}
Z_{L11} &:= 0.1 \text{pu} \cdot e^{j \cdot 85\deg} & Z_{L21} &:= 0.08 \text{pu} \cdot e^{j \cdot 85\deg} \\
Z_{L11} &= 0.01 + 0.1i & Z_{L10} &:= 3 \cdot Z_{L11} \\
Z_{L12} &:= Z_{L11} & Z_{L21} &= 0.01 + 0.08i \\
Z_{L10} &= 0.03 + 0.3i & Z_{L20} &:= 3 \cdot Z_{L21} \\
Z_{L22} &:= Z_{L21} & Z_{L20} &= 0.02 + 0.24i
\end{aligned}$$



VAC

SIG fault

- Reactance Method:

$$m_{\text{relayA_reactance_phA}}(\delta, R_f) := \frac{\text{Im} \left[\frac{V_{ABC_RA}(\delta, R_f)_0}{I_{ABC_RA}(\delta, R_f)_0 + k_0 \cdot (3 \cdot I_{\text{relayA0}}(\delta, R_f))} \right]}{\text{Im}(Z_{L21})}$$

$$m_{\text{relayA_reactance_phA}}(0, 0) = 0.6$$

- What do the unfaulted phases show?

$$m_{\text{relayA_reactance_phB}}(\delta, R_f) := \frac{\text{Im} \left[\frac{V_{ABC_RA}(\delta, R_f)_1}{I_{ABC_RA}(\delta, R_f)_1 + k_0 \cdot (3 \cdot I_{\text{relayA0}}(\delta, R_f))} \right]}{\text{Im}(Z_{L21})}$$

$$m_{\text{relayA_reactance_phB}}(0, 0) = -4.81$$

$$m_{\text{relayA_reactance_phC}}(\delta, R_f) := \frac{\text{Im} \left[\frac{V_{ABC_RA}(\delta, R_f)_2}{I_{ABC_RA}(\delta, R_f)_2 + k_0 \cdot (3 \cdot I_{\text{relayA0}}(\delta, R_f))} \right]}{\text{Im}(Z_{L21})}$$

$$m_{\text{relayA_reactance_phC}}(0, 0) = -4.14$$

Both unfaulted phases show a negative value. Faulted phase selection logic is definitely needed.

- What do the remote end show?

$$m_{\text{relayB_reactance_phA}}(\delta, R_f) := \frac{\text{Im} \left[\frac{V_{ABC_RB}(\delta, R_f)_0}{I_{ABC_RB}(\delta, R_f)_0 + k_0 \cdot (3 \cdot I_{\text{relayB0}}(\delta, R_f))} \right]}{\text{Im}(Z_{L21})}$$

$$m_{\text{relayB_reactance_phA}}(0, 0) = 0.4$$

- Modified Takagi Method Using Negative Sequence

$$m_{\text{relayA_Takagi_phA}}(\delta, R_f) := \frac{\text{Im} \left[V_{ABC_RA}(\delta, R_f)_0 \cdot \overline{(I_{\text{relayA2}}(\delta, R_f))} \right]}{\text{Im} \left[Z_{L21} \cdot [I_{ABC_RA}(\delta, R_f)_0 + k_0 \cdot (3 \cdot I_{\text{relayA0}}(\delta, R_f))] \cdot \overline{(I_{\text{relayA2}}(\delta, R_f))} \right]}$$

2 **GA + NO 3 IN** **I_{2S}** **I_{2S}***

$$m_{\text{relayA_Takagi_phA}}(0, 0) = 0.6$$

- Remote end calculation

$$m_{\text{relayB_Takagi_phA}}(\delta, R_f) := \frac{\text{Im} \left[V_{ABC_RB}(\delta, R_f)_0 \cdot \overline{(I_{\text{relayB2}}(\delta, R_f))} \right]}{\text{Im} \left[Z_{L21} \cdot [I_{ABC_RB}(\delta, R_f)_0 + k_0 \cdot (3 \cdot I_{\text{relayB0}}(\delta, R_f))] \cdot \overline{(I_{\text{relayB2}}(\delta, R_f))} \right]}$$

$$m_{\text{relayB_Takagi_phA}}(0, 0) = 0.4$$

- Add fault resistance $R_f := 0, 0.05..0.2$

$$\delta_r := -20, -10..20$$

$$m_{\text{relayA_reactance_phA}}(\delta_r, 0) =$$

| |
|-----|
| 0.6 |
| 0.6 |
| 0.6 |
| 0.6 |
| 0.6 |

$$m_{\text{relayA_reactance_phA}}(0, R_f) =$$

| |
|------|
| 0.6 |
| 0.56 |
| 0.49 |
| 0.41 |
| 0.3 |

$$m_{\text{relayA_reactance_phA}}(\delta_r, 0.1) =$$

| |
|------|
| 0.6 |
| 0.04 |
| 0.2 |
| 0.49 |
| 1.03 |
| 1.97 |

$$m_{\text{relayA}}(\delta_r, 0) =$$

| |
|-----|
| 0.6 |
| 0.6 |
| 0.6 |
| 0.6 |
| 0.6 |

$$m_{\text{relayA}}(0, R_f) =$$

| |
|------|
| 0.6 |
| 0.57 |
| 0.55 |
| 0.55 |
| 0.54 |
| 0.51 |
| 0.52 |
| 0.47 |

$$m_{\text{relayA}}(\delta_r, 0.1) =$$

| |
|------|
| 0.55 |
| 0.55 |
| 0.55 |
| 0.54 |
| 0.52 |
| 0.49 |

$$m_{\text{relayB}}(\delta_r, 0) =$$

| |
|-----|
| 0.4 |
| 0.4 |
| 0.4 |
| 0.4 |
| 0.4 |

$$m_{\text{relayB}}(0, R_f) =$$

| |
|------|
| 0.4 |
| 0.41 |
| 0.43 |
| 0.45 |
| 0.48 |

$$m_{\text{relayB}}(\delta_r, 1) =$$

| |
|------|
| 0.17 |
| 0.17 |
| 1.56 |
| 0.56 |
| 0.49 |
| 0.46 |

$$m_{\text{relayB}}(\delta_r, 0) =$$

| |
|-----|
| 0.4 |
| 0.4 |
| 0.4 |
| 0.4 |
| 0.4 |

$$m_{\text{relayB}}(0, R_f) =$$

| |
|------|
| 0.4 |
| 0.41 |
| 0.42 |
| 0.42 |
| 0.43 |

$$m_{\text{relayB}}(\delta_r, 1) =$$

| |
|------|
| 0.17 |
| 0.17 |
| 1.56 |
| 0.56 |
| 0.49 |
| 0.46 |

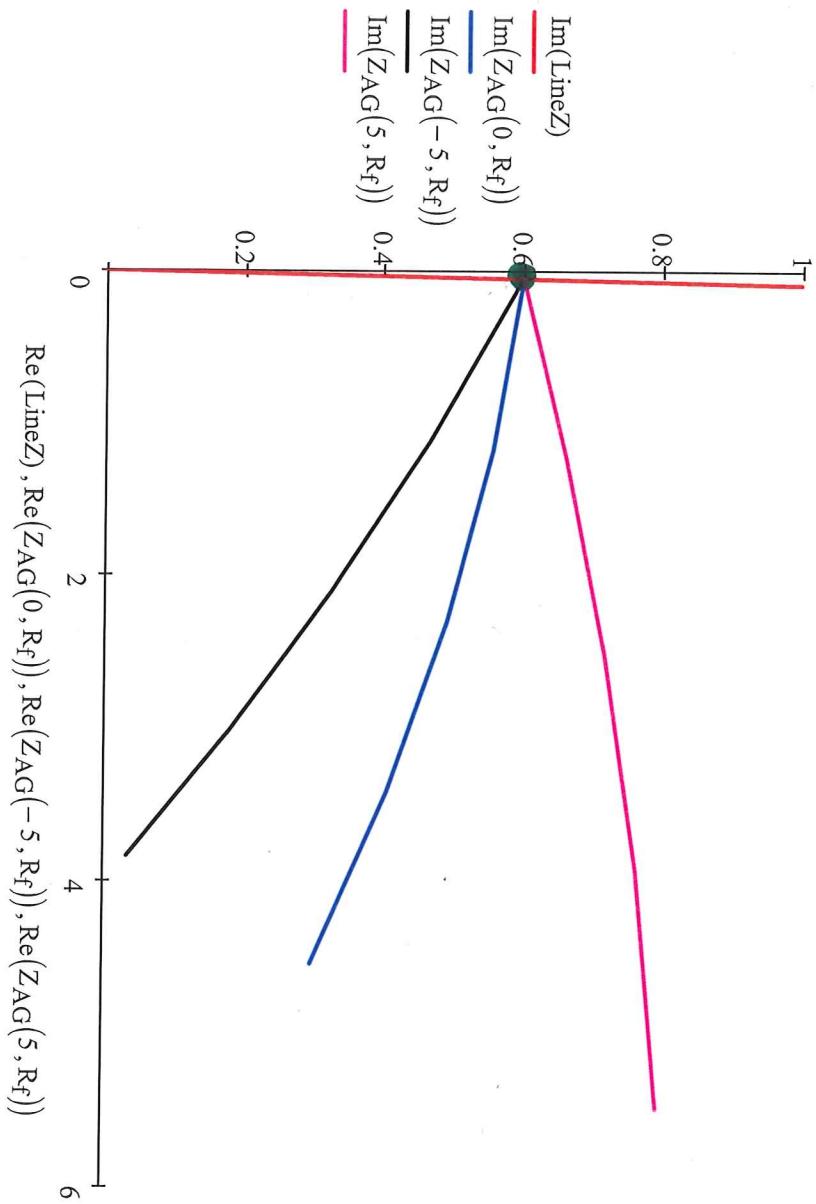
- Plot performance of impedance calculation with load flow (without taking imaginary part)

$$Z_{1\text{MAG}} := |Z_{L21}| \quad Z_{1\text{ANG}} := \arg(Z_{L21}) \quad k := 0, 1..719$$

- Line impedance vector for impedance plane diagram:

$$\text{LineZ} := \begin{pmatrix} 0 \\ Z_{1\text{MAG}} \end{pmatrix}$$

$$Z_{\text{AG}}(\delta, R_f) := \frac{\left[\begin{array}{c} V_{ABC_RA}(\delta, R_f)_0 \\ I_{ABC_RA}(\delta, R_f)_0 + k_0 \cdot (3 \cdot I_{\text{relayA}}(\delta, R_f)) \end{array} \right]}{|Z_{L21}|}$$



at both ends

Double-ended with I2 (requires time aligned data)

$$m_{\text{relay1_twoendedI2}} = \frac{\text{Im}[\overline{V_{ARI_1} \cdot (I_{2\text{right}} + I_{2\text{left}})}]}{\text{Im}[Z_{L1} \cdot [I_{AR1} + k_0 \cdot [3 \cdot (I_{0\text{left}})]] \cdot (I_{2\text{right}} + I_{2\text{left}})]}$$

does not necessarily require time aligned data

Double-ended with V2 and I2 (requires time aligned data)

$$m_{\text{relay1_twoended}} = \frac{V_{2_R1} - V_{2_R2} + I_{2\text{right}} \cdot Z_{L2}}{(I_{2\text{left}} + I_{2\text{right}}) \cdot Z_{L2}}$$

remote end

V2 and I2

- Two ended method with ~~both ends~~
- Option 1. If have exactly time aligned measurements from both ends (we have that here, but in the field we would need phasor measurement). This is sufficient for this assignment.*

$$m_{\text{relayA_twoended_p2}}(\delta, R_f) := \frac{V_{\text{relayA2}}(\delta, R_f) - V_{\text{relayB2}}(\delta, R_f) + I_{\text{relayB2}}(\delta, R_f) \cdot Z_{L22}}{(I_{\text{relayA2}}(\delta, R_f) + I_{\text{relayB2}}(\delta, R_f)) \cdot Z_{L22}}$$

$$\text{mrelayA_twoended_p2}(0, 0) = 0.6$$

$$\text{mrelayB_twoended_p2}(\delta, R_f) := \frac{V_{\text{relayB2}}(\delta, R_f) - V_{\text{relayA2}}(\delta, R_f) + I_{\text{relayA2}}(\delta, R_f) \cdot Z_{L22}}{(I_{\text{relayB2}}(\delta, R_f) + I_{\text{relayA2}}(\delta, R_f)) \cdot Z_{L22}}$$

$$\text{mrelayB_twoended_p2}(0, 0) = 0.4$$

Again, accurate results

- Note that since this is entirely a negative sequence calculation, the phase indication is not needed

Option 2: If you don't have time synchronized data. Note that this requires knowledge of source impedances.

We need to rearrange the equation below, and solve it.

$$|I_{2R}| = \frac{|(I_{2S}Z_{2S}) + m \cdot (I_{2S} \cdot Z_{2L})|}{|(Z_{2R} + Z_{2L}) - m \cdot Z_{2L}|}$$

Sources
impedances

See the paper, "Impedance-Based Fault Location Experience, shows the equation after it has been rearranged into a quadratic form to solve for m.

$$0 = A \cdot m^2 + B \cdot m + C$$

$$a_1(\delta, R_f) := \operatorname{Re} [I_{\text{relayA2}}(\delta, R_f) \cdot (Z_{S2} + Z_{L12})]$$

$$c_1(\delta, R_f) := \operatorname{Re} (I_{\text{relayA2}}(\delta, R_f) \cdot Z_{L22})$$

$$\begin{aligned} b_1(\delta, R_f) &:= \operatorname{Im} [I_{\text{relayA2}}(\delta, R_f) \cdot (Z_{S2} + Z_{L12})] \\ d_1(\delta, R_f) &:= \operatorname{Im} (I_{\text{relayA2}}(\delta, R_f) \cdot Z_{L22}) \end{aligned}$$

$$\begin{aligned} e_1 &:= \operatorname{Re} (Z_{R2} + Z_{L22}) \\ g_1 &:= \operatorname{Re} (Z_{L22}) \end{aligned}$$

$$A_{\text{dbl}}(\delta, R_f) := (|I_{\text{relayB2}}(\delta, R_f)|)^2 \cdot (g_1^2 + h_1^2) - (c_1(\delta, R_f))^2 + d_1(\delta, R_f)^2$$

$$B_{\text{dbl}}(\delta, R_f) := -2 \cdot (|I_{\text{relayB2}}(\delta, R_f)|)^2 \cdot (e_1 \cdot g_1 + f_1 \cdot h_1) - 2 \cdot (a_1(\delta, R_f) \cdot c_1(\delta, R_f) + b_1(\delta, R_f) \cdot d_1(\delta, R_f))$$

$$C_{\text{dbl}}(\delta, R_f) := (|I_{\text{relayB2}}(\delta, R_f)|)^2 \cdot (e_1^2 + f_1^2) - (a_1(\delta, R_f))^2 + b_1(\delta, R_f)^2$$

Now we can use the standard quadratic equation solver (we'll look at both solutions):

$$m_{1,2}(\delta, R_f) := \frac{-B_{\text{dbl}}(\delta, R_f) + \sqrt{B_{\text{dbl}}(\delta, R_f)^2 - 4 \cdot A_{\text{dbl}}(\delta, R_f) \cdot C_{\text{dbl}}(\delta, R_f)}}{2 \cdot A_{\text{dbl}}(\delta, R_f)}$$

Solution

$$\text{Solve for } m_2 \text{ p2}(\delta, R_f) := \frac{-B_{\text{dbl}}(\delta, R_f) - \sqrt{B_{\text{dbl}}(\delta, R_f)^2 - 4 \cdot A_{\text{dbl}}(\delta, R_f) \cdot C_{\text{dbl}}(\delta, R_f)}}{2 \cdot A_{\text{dbl}}(\delta, R_f)}$$

$m_1 \text{ p2}(0, 0) = 5.35$ Number much greater than 1, not proper solution.

$$m_2 \text{ p2}(0, 0) = 0.6$$

- Time aligned method:

$$m_{\text{relayA_twoended_p2}}(\delta_r, 0) = \begin{pmatrix} 0.6 \\ 0.6 \\ 0.6 \\ 0.6 \\ 0.6 \end{pmatrix}$$

$$m_2 \text{ p2}(\delta_r, 0) =$$

$$\begin{pmatrix} 0.6 \\ 0.6 \\ 0.6 \\ 0.6 \\ 0.6 \end{pmatrix}$$

$$m_2 \text{ p2}(0, R_f) =$$

$$\begin{pmatrix} 0.6 \\ 0.6 \\ 0.6 \\ 0.6 \\ 0.6 \end{pmatrix}$$

$$m_{\text{relayA_twoended_p2}}(0, R_f) = \begin{pmatrix} 0.6 \\ 0.6 \\ 0.6 \\ 0.6 \\ 0.6 \end{pmatrix}$$

$$\begin{pmatrix} 0.6 \\ 0.6 \\ 0.6 \\ 0.6 \\ 0.6 \end{pmatrix}$$

$$m_2 \text{ p2}(0, R_f) =$$

$$m_{\text{relayA_twoended_p2}}(-40, R_f) = \begin{pmatrix} 0.6 \\ 0.6 \\ 0.6 \\ 0.6 \\ 0.6 \end{pmatrix}$$

Another fault location approach

- System approach
- assume don't have data from even line end.
- collecting event reports at an operating center or response/dispatch center
- synchronized phasor measurements (synchrophasors)



(synchrophasors)