Phase Rolling and the Impacts on Protection

By: Denglin (Dennis) Tang, Burns & McDonnell

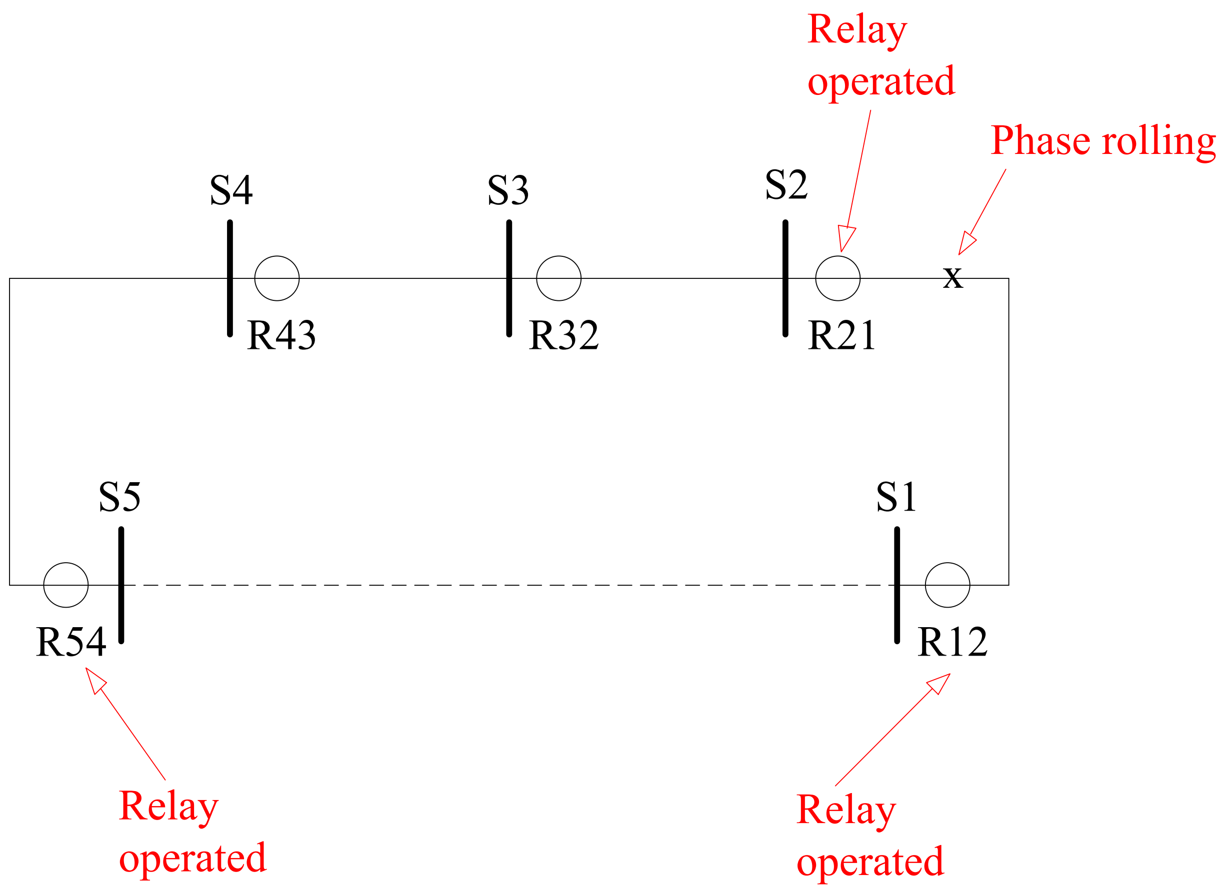
2016 Minnesota Power Systems Conference

Minnesota Power Systems Conference

Overview

- Background Introduction.
- Relays Settings and Operation.
- Phase Rolling Characteristics.
- Solving the Currents for Phase Rolling.
- Sample calculation.
- Further Discussion.

Introduction



Questions

- Why did the under-reaching zone 1 distance element which is several buses away operate?
- Is there any way to prevent such situation beforehand?

Relay Settings and the Measurements

85% reaching

Line impedance: $4.97\Omega\angle 82.96^\circ$

Zone 1 reach: $4.2\Omega\angle 82.96^\circ$

Measured voltage: $V_b = 49.5kV\angle 318.4^\circ$, $V_c = 48.4kV\angle 245.9^\circ$

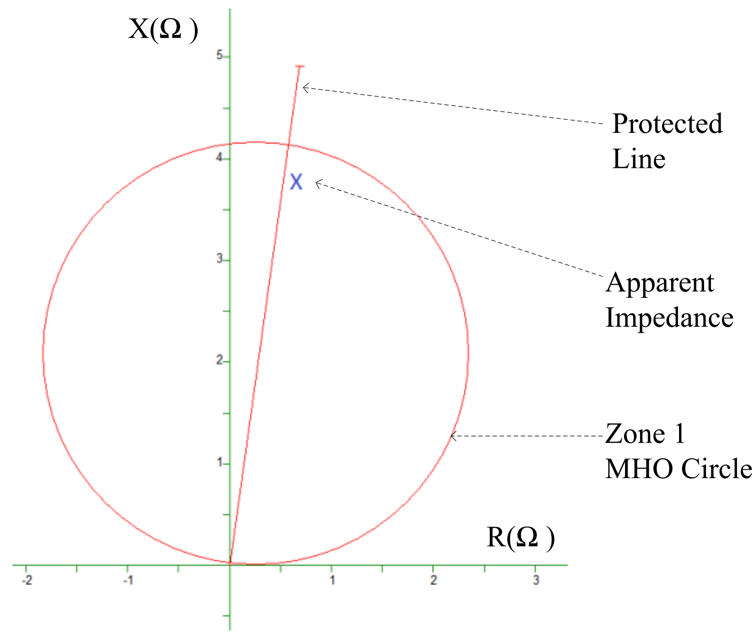
Measured current: $I_b = 7723.9A\angle 290.9^\circ$, $I_c = 7618.0\angle 111.9^\circ$

All Data in Primary Side

Relay Operation

- Phase distance element impedance measurements

$$\begin{bmatrix} Z_{AB} \\ Z_{BC} \\ Z_{CA} \end{bmatrix} = \begin{bmatrix} \dfrac{V_A - V_B}{I_A - I_B} \\ \dfrac{V_B - V_C}{I_B - I_C} \\ \dfrac{V_C - V_A}{I_C - I_A} \end{bmatrix} \quad (1)$$



$V_{bc} = 49.5kV\angle 318.4° - 48.4kV\angle 245.9° = 57.9kV\angle 11.3°$

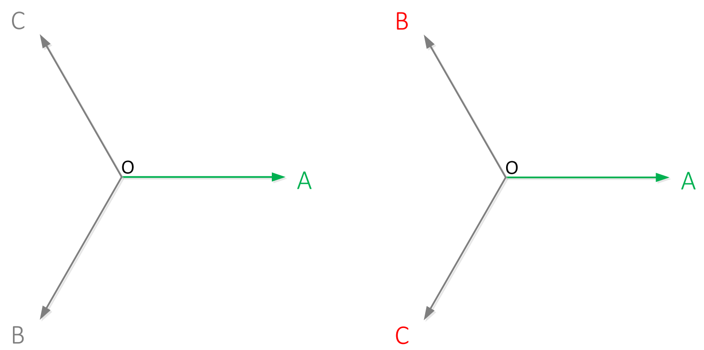
$I_{bc} = 7723.9A\angle 290.9° - 7618.0\angle 111.9° = 15341.3A\angle -68.6°$

$Z_{bc} = V_{bc} / I_{bc} = 57.9kV\angle 11.3° / 15341.3A\angle -68.6° = 3.77\Omega\angle 79.9°$

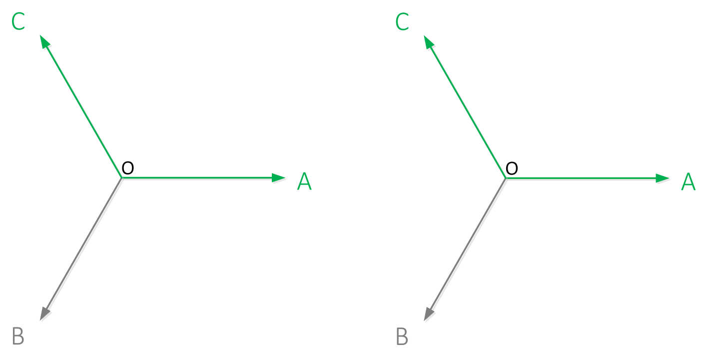
Measures to Prevent Phase Rolling

- Phasing verification during commissioning time.
  - Simple and easy
  - Has been applied so far
- Special synchronizing scheme to prevent phase rolling closing.
  - Traditional synchronizing scheme doesn't solve the issue
  - Special scheme is possible to be developed
- Treatment of distance elements is challenging.
  - Could be complicate and challenging
  - Not recommended now that there are easy and simple solutions.

Special Synchronizing Scheme

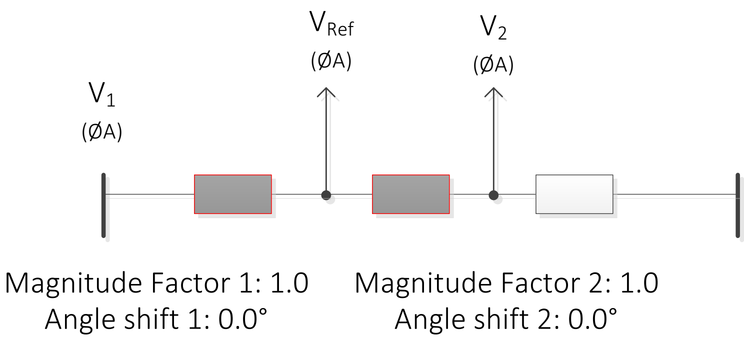


- Traditional phase synchronizing.
  - Phase A synchronized
  - Still possible to close with phase rolling

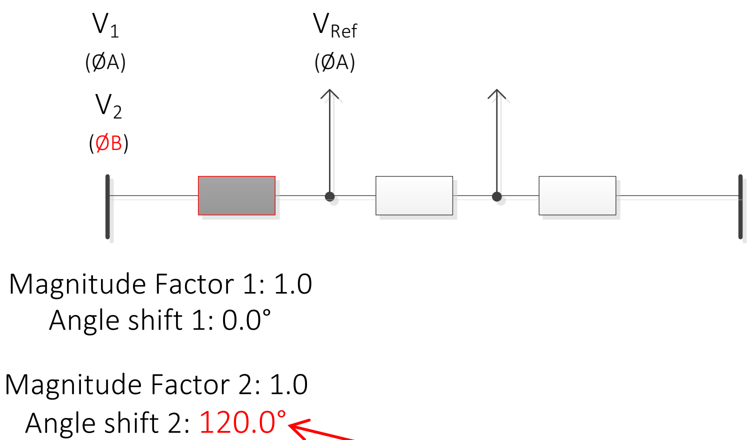


- Special synchronizing scheme.
  - Need to have 2 phases synchronized

Special Synchronizing Scheme (Cont'd)



- Typical 2 breaker synchronizing .
  - Phase A synchronized
  - Still possible to close with phase rolling



- Special synchronizing scheme.
  - Need to have 2 phases synchronized
  - Both V1 and V2 synchronized to close

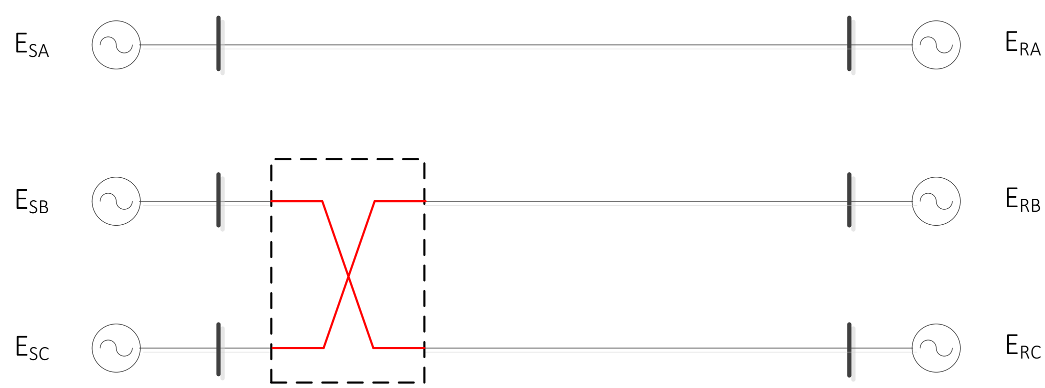
Depending on the phase rotation ABC or ACB, angle shift could be either 120° or -120°

Phase Rolling Characteristics

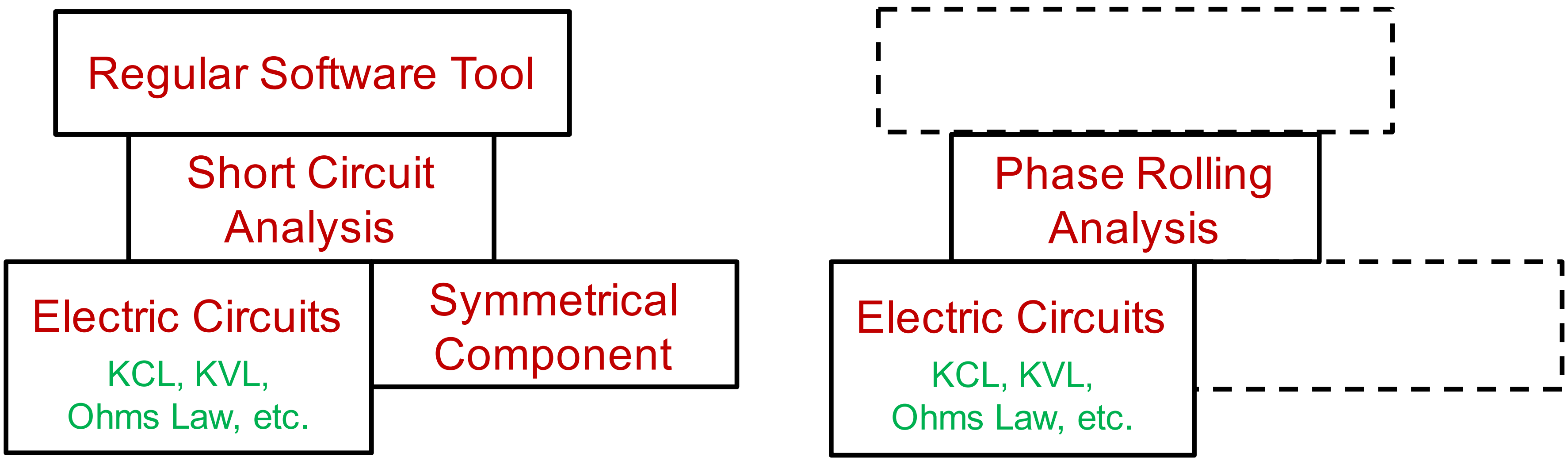
Rare Phenomenon → Regular Software Tool not Applicable

No Specific Location → Apparent Impedance

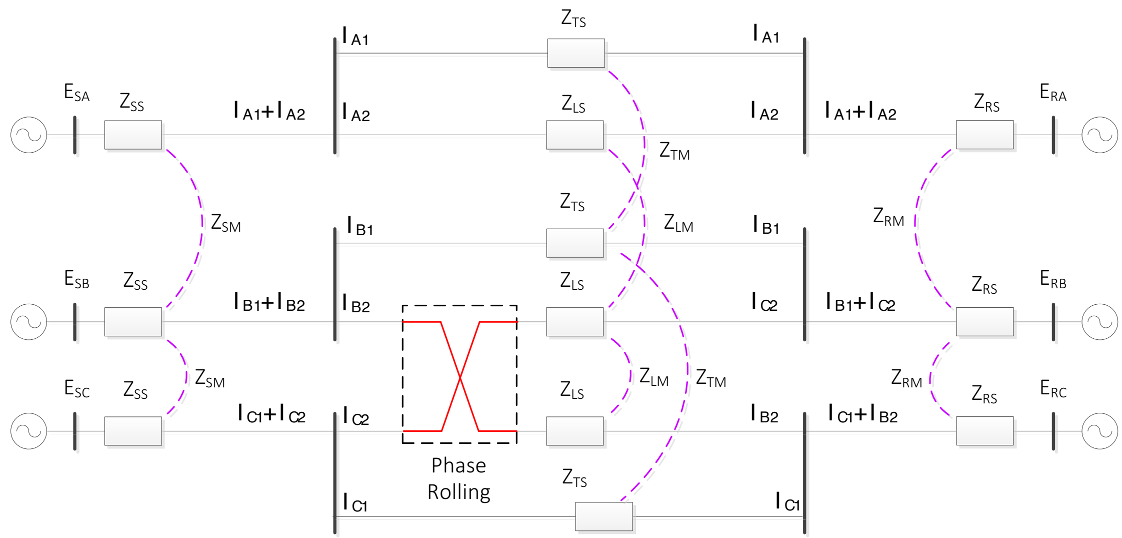
Relay – Fault Location
Relay – System Configuration



Analysis Method Compare



Solving the Phase Rolling



(Mutual are shown for phase A-B & B-C only for simplicity

E_{SA}, E_{SB}, E_{SC} – Equivalent source potential
E_{RA}, E_{RB}, E_{RC} – Remote equivalent source potential
Z_{SS}, Z_{RS} – Equivalent self-impedances behind the relay and behind the remote terminal
Z_{SM}, Z_{RM} – Equivalent mutual impedances between phases behind the relay and behind the remote terminal
Z_{LS}, Z_{TS} – Subject line and transfer self-impedances
Z_{LM}, Z_{TM} – Subject line and transfer mutual impedances between phases
I_{A1}, I_{B1}, I_{C1} – Currents through the transfer impedances
I_{A2}, I_{B2}, I_{C2} – Currents through the subject relay (phase designation swapped at remote terminal)

System Data (Impedances) Preparation

System Equivalence
(By Regular Software Tools)

↓

Sequence to Phase

$Z_S = (Z_0+2Z_1)/3$
$Z_M = (Z_0-Z_1)/3$

Where,

Z_S, Z_M – Self and mutual impedances

Z_1, Z_0 – Positive and zero sequence impedances

Polynomials

$$Z_{SS}*(I_{A1}+I_{A2}) + Z_{SM}*(I_{B1}+I_{B2}+I_{C1}+I_{C2}) + Z_{TS}*I_{A1} + Z_{TM}*(I_{B1}+I_{C1}) + Z_{RS}*(I_{A1}+I_{A2}) + Z_{RM}*(I_{B1}+I_{B2}+I_{C1}+I_{C2}) = E_{SA}-E_{RA}$$

$$Z_{SS}*(I_{A1}+I_{A2}) + Z_{SM}*(I_{B1}+I_{B2}+I_{C1}+I_{C2}) + Z_{LS}*I_{A2} + Z_{LM}*(I_{B2}+I_{C2}) + Z_{RS}*(I_{A1}+I_{A2}) + Z_{RM}*(I_{B1}+I_{B2}+I_{C1}+I_{C2}) = E_{SA}-E_{RA}$$

$$Z_{SS}*(I_{B1}+I_{B2}) + Z_{SM}*(I_{A1}+I_{A2}+I_{C1}+I_{C2}) + Z_{TS}*I_{B1} + Z_{TM}*(I_{A1}+I_{C1}) + Z_{RS}*(I_{B1}+I_{C2}) + Z_{RM}*(I_{A1}+I_{A2}+I_{C1}+I_{B2}) = E_{SB}-E_{RB}$$

$$Z_{SS}*(I_{B1}+I_{B2}) + Z_{SM}*(I_{A1}+I_{A2}+I_{C1}+I_{C2}) + Z_{LS}*I_{B2} + Z_{LM}*(I_{A2}+I_{C2}) + Z_{RS}*(I_{C1}+I_{B2}) + Z_{RM}*(I_{A1}+I_{A2}+I_{B1}+I_{C2}) = E_{SB}-E_{RC}$$

$$Z_{SS}*(I_{C1}+I_{C2}) + Z_{SM}*(I_{A1}+I_{A2}+I_{B1}+I_{B2}) + Z_{LS}*I_{C2} + Z_{LM}*(I_{A2}+I_{B2}) + Z_{RS}*(I_{B1}+I_{C2}) + Z_{RM}*(I_{A1}+I_{A2}+I_{C1}+I_{B2}) = E_{SC}-E_{RB}$$

$$Z_{SS}*(I_{C1}+I_{C2}) + Z_{SM}*(I_{A1}+I_{A2}+I_{B1}+I_{B2}) + Z_{TS}*I_{C1} + Z_{TM}*(I_{A1}+I_{B1}) + Z_{RS}*(I_{C1}+I_{B2}) + Z_{RM}*(I_{A1}+I_{A2}+I_{B1}+I_{C2}) = E_{SC}-E_{RC}$$

Re-arrange

$$(Z_{SS}+Z_{TS}+Z_{RS})*I_{A1} + (Z_{SS}+Z_{RS})*I_{A2} + (Z_{SM}+Z_{TM}+Z_{RM})*I_{B1} + (Z_{SM}+Z_{RM})*I_{B2} + (Z_{SM}+Z_{TM}+Z_{RM})*I_{C1} + (Z_{SM}+Z_{RM})*I_{C2} = E_{SA}-E_{RA}$$

$$(Z_{SS}+Z_{RS})*I_{A1} + (Z_{SS}+Z_{LS}+Z_{RS})*I_{A2} + (Z_{SM}+Z_{RM})*I_{B1} + (Z_{SM}+Z_{LM}+Z_{RM})*I_{B2} + (Z_{SM}+Z_{RM})*I_{C1} + (Z_{SM}+Z_{LM}+Z_{RM})*I_{C2} = E_{SA}-E_{RA}$$

$$(Z_{SM}+Z_{TM}+Z_{RM})*I_{A1} + (Z_{SM}+Z_{RM})*I_{A2} + (Z_{SS}+Z_{TS}+Z_{RS})*I_{B1} + (Z_{SS}+Z_{RM})*I_{B2} + (Z_{SM}+Z_{TM}+Z_{RM})*I_{C1} + (Z_{SM}+Z_{RS})*I_{C2} = E_{SB}-E_{RB}$$

$$(Z_{SM}+Z_{RM})*I_{A1} + (Z_{SM}+Z_{LM}+Z_{RM})*I_{A2} + (Z_{SS}+Z_{RM})*I_{B1} + (Z_{SS}+Z_{LS}+Z_{RS})*I_{B2} + (Z_{SM}+Z_{RS})*I_{C1} + (Z_{SM}+Z_{LM}+Z_{RM})*I_{C2} = E_{SB}-E_{RC}$$

$$(Z_{SM}+Z_{RM})*I_{A1} + (Z_{SM}+Z_{LM}+Z_{RM})*I_{A2} + (Z_{SM}+Z_{RS})*I_{B1} + (Z_{SM}+Z_{LM}+Z_{RM})*I_{B2} + (Z_{SS}+Z_{RM})*I_{C1} + (Z_{SS}+Z_{LS}+Z_{RS})*I_{C2} = E_{SC}-E_{RB}$$

$$(Z_{SM}+Z_{TM}+Z_{RM})*I_{A1} + (Z_{SM}+Z_{RM})*I_{A2} + (Z_{SM}+Z_{TM}+Z_{RM})*I_{B1} + (Z_{SM}+Z_{RS})*I_{B2} + (Z_{SS}+Z_{TS}+Z_{RS})*I_{C1} + (Z_{SS}+Z_{RM})*I_{C2} = E_{SC}-E_{RC}$$

Sample Calculation

$E_{SA} = 1.025*138kV/\sqrt{3}\angle 0^\circ$

$E_{SB} = 1.025*138kV/\sqrt{3}\angle -120^\circ$

$E_{SC} = 1.025*138kV/\sqrt{3}\angle 120^\circ$

$E_{RA} = 1.025*138kV/\sqrt{3}\angle 0^\circ$

$E_{RB} = 1.025*138kV/\sqrt{3}\angle -120^\circ$

$E_{RC} = 1.025*138kV/\sqrt{3}\angle 120^\circ$

$Z_{SS} = 25.15\Omega\angle 86.04^\circ$, $Z_{SM} = 4.62\Omega\angle -94.67^\circ$

$Z_{RS} = 1.91\Omega\angle 85.96^\circ$, $Z_{RM} = 0.12\Omega\angle -93.10^\circ$

$Z_{LS} = 3.05\Omega\angle 77.79^\circ$, $Z_{LM} = 1.37\Omega\angle 72.62^\circ$

$Z_{TS} = 25.47\Omega\angle 74.69^\circ$, $Z_{TM} = 12.57\Omega\angle 68.25^\circ$

Sample Calculation (Cont'd)

$Ia1 := 0$
$Ia2 := 0$
$Ib1 := 0$
$Ib2 := 0$
$Ic1 := 0$
$Ic2 := 0$

Given

$$\left(52.28e^{1.406i}\right)\cdot Ia1+\left(27.06e^{1.502i}\right)\cdot Ia2+\left(8.16e^{1.019i}\right)\cdot Ib1+\left(4.74e^{4.632i}\right)\cdot Ib2+\left(8.16e^{1.019i}\right)\cdot Ic1+\left(4.74e^{4.632i}\right)\cdot Ic2=0$$

$$\left(27.06e^{1.502i}\right)\cdot Ia1+\left(30.08e^{1.487i}\right)\cdot Ia2+\left(4.74e^{4.632i}\right)\cdot Ib1+\left(3.42e^{4.720i}\right)\cdot Ib2+\left(4.74e^{4.632i}\right)\cdot Ic1+\left(3.42e^{4.720i}\right)\cdot Ic2=0$$

$$\left(8.16e^{1.019i}\right)\cdot Ia1+\left(4.74e^{4.632i}\right)\cdot Ia2+\left(52.28e^{1.406i}\right)\cdot Ib1+\left(25.03e^{1.502i}\right)\cdot Ib2+\left(8.16e^{1.019i}\right)\cdot Ic1+\left(2.71e^{4.623i}\right)\cdot Ic2=0$$

$$\left(4.74e^{4.632i}\right)\cdot Ia1+\left(3.42e^{4.720i}\right)\cdot Ia2+\left(25.03e^{1.502i}\right)\cdot Ib1+\left(30.08e^{1.487i}\right)\cdot Ib2+\left(2.71e^{4.623i}\right)\cdot Ic1+\left(3.42e^{4.720i}\right)\cdot Ic2=141450e^{4.712i}$$

$$\left(4.74e^{4.632i}\right)\cdot Ia1+\left(3.42e^{4.720i}\right)\cdot Ia2+\left(2.71e^{4.623i}\right)\cdot Ib1+\left(3.42e^{4.720i}\right)\cdot Ib2+\left(25.03e^{1.502i}\right)\cdot Ic1+\left(30.08e^{1.487i}\right)\cdot Ic2=141450e^{1.571i}$$

$$\left(8.16e^{1.019i}\right)\cdot Ia1+\left(4.74e^{4.632i}\right)\cdot Ia2+\left(8.16e^{1.019i}\right)\cdot Ib1+\left(2.71e^{4.623i}\right)\cdot Ib2+\left(52.28e^{1.406i}\right)\cdot Ic1+\left(25.03e^{1.502i}\right)\cdot Ic2=0$$

Calculation in Mathcad

$$\mathrm{Find}(Ia1,Ia2,Ib1,Ib2,Ic1,Ic2)=\begin{pmatrix}-0.153+1.426i\\0.095-1.067i\\5.313\times10^{3}+693.172i\\-8.611\times10^{3}-902.537i\\-5.312\times10^{3}-695.677i\\8.61\times10^{3}+907.982i\end{pmatrix}$$

Compare: Analysis vs. Measurements

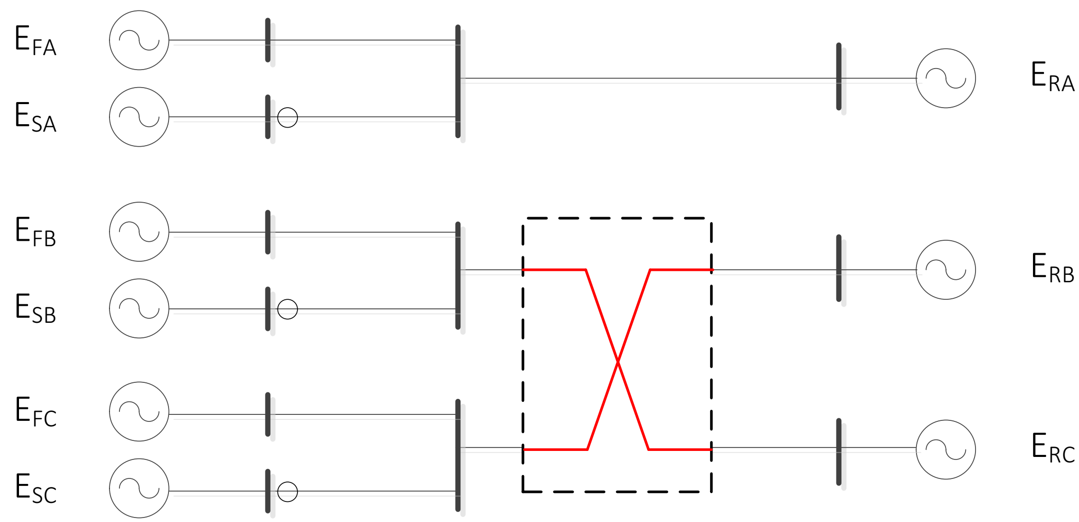
Calculation Results

	Complex-Phasor Conversion	
Phase B	-8611-903i	8658.2∠185.99
Phase C	8610+908i	8657.7∠6.02

	Measured (A)	Calculated (A)	Error	Error%
Phase B	7723.9∠290.9°	8658.2∠185.99°	934.3	**10.8**
Phase C	7618.0∠111.9°	8657.7∠6.02°	1039.7	**12**
Phasor Shift	179.0°	179.97°	0.97°	**0.97°**

Further Discussion

- In case of cross feeding, current distribution may necessary.



Further Discussion (Cont'd)

- What matters: Security Vs. Dependability
  - In case of phase rolling, the relays need to isolate the phase rolling line as soon as possible
  - The apparent impedance need to be able to operate the zone 1 or zone 2 distance element of the phase rolling line

Conclusion

- Phase rolling is a rare phenomenon.
- Phasing verification or special synchronizing scheme could be used to prevent from the phase rolling.
- Phase rolling currents/voltages could be solved electric circuits fundamental knowledges.
- Apparent impedances could be calculated to verify the possible mis-operation of the non-phase rolling lines or to confirm the relays of the phase rolling lines will operate to isolate.

Questions