Oak Ridge National Laboratory

October 7 and 8, 2025 | Point On Wave Applications Conference, The University of Tennessee at Chattanooga

# Impact assessment of geomagnetic induced current neutral blocking devices with power electronics sources on distance relay for 230 kV transmission lines[1]

[1] https://doi-org.ornl.idm.oclc.org/10.1016/j.epsr.2025.112190

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U.S. DEPARTMENT of ENERGY

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## Agenda

- Introduction
- Geomagnetic-induced current neutral blocking devices (GIC-NBDs)
- Test circuit and use case scenarios
- Phase-to-ground and phase-to-phase apparent impedance definitions
- Source impedance ratio definitions
- Results
- Conclusions

# Geomagnetic Storms, Transmission Lines and GIC-NBDs

**Geomagnetic Storms**

**Transmission Lines**

Previous work: E. C. Piesciorovsky, A. G. Tarditi. “Modeling the Impact of GIC Blocking Devices on Distance Protection Relay Operations for Transmission Lines.” Elsevier, *Electric Power Systems Research*, vol. 180, pp. 1–11, 2019. https://doi.org/10.1016/j.epsr.2019.106135.

GIC-NBDs: Geomagnetic Induced Neutral Blocking Devices

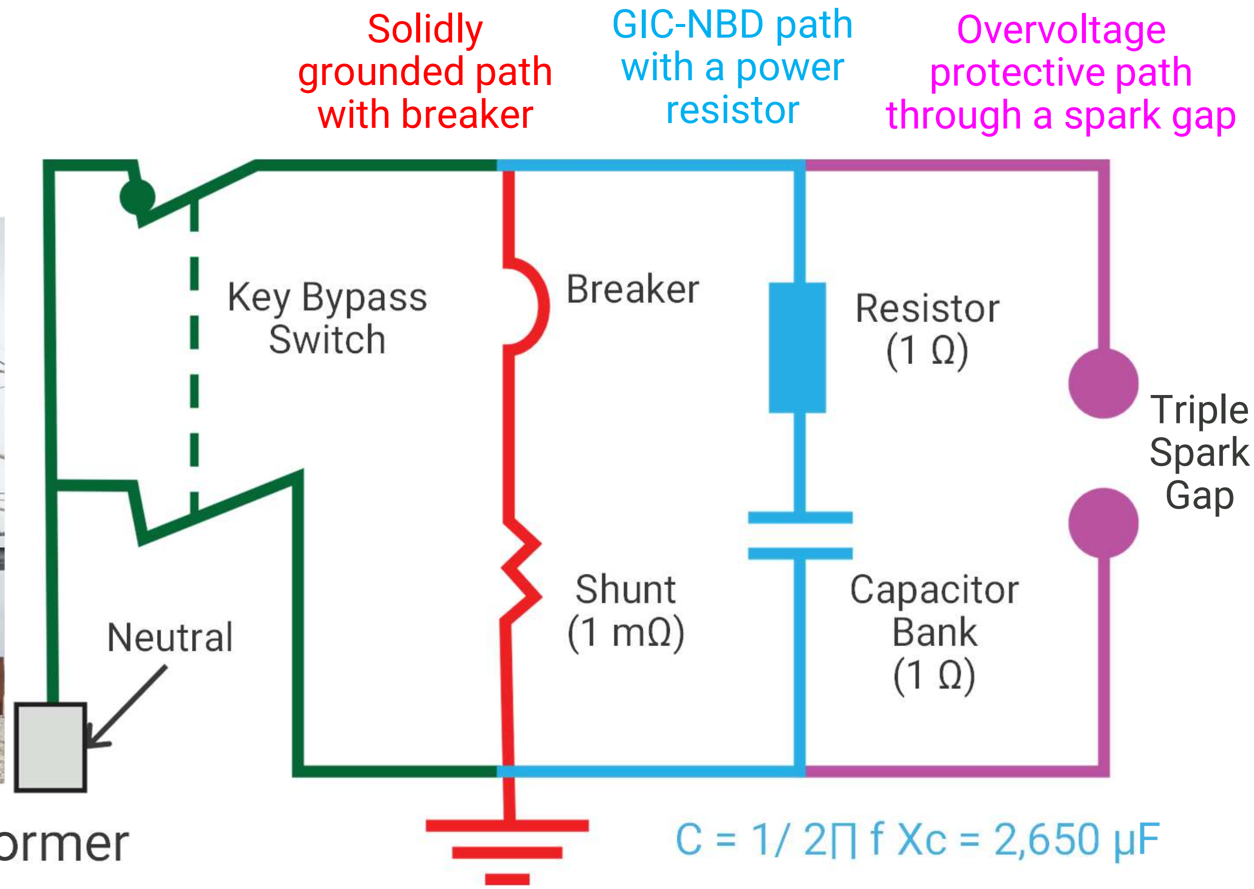
# Introduction

- **Problem:** When power electronics sources are present, can adding GIC-NBDs maintain the effectiveness of protective relaying schemes?
  - GIC-NBDs—capacitors on the neutral grounding path of wye transformer—are used to prevent geomagnetic storm damage to the power grid.

- **Approach:** Use models to study the effect of 2 MW power electronics sources with GIC-NBDs (using 2,650 µF capacitors) added on the neutral on distance protective relay operations for 230 kV transmission lines.

# One-Line Diagram of GIC-NBD

Key bypass switch allows grounding devices to be taken out for maintenance.



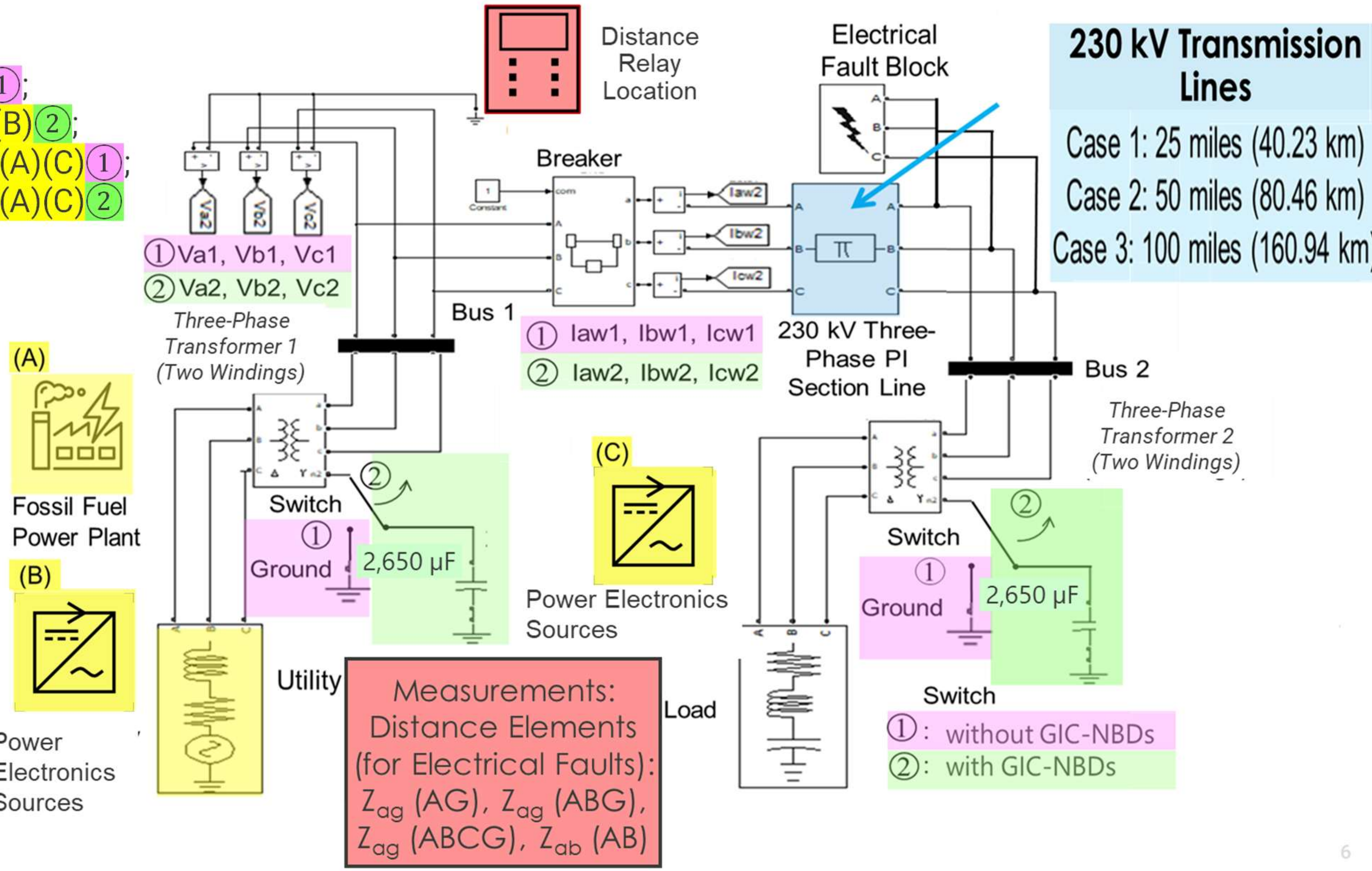

Δ/Yg—High Voltage Transformer

Source: F. R. Faxvog, et al. “High Voltage Power Transformer NBD Operating Experience in Wisconsin.” MYPSICON, Nov 2017.

# Circuit, Scenarios, Transmission Lines, and Measurements

***Scenarios:***

Radial Sys with(A)①;
Radial Sys with (A)(B)②;
Nonradial Sys with (A)(C)①;
Nonradial Sys with (A)(C)②



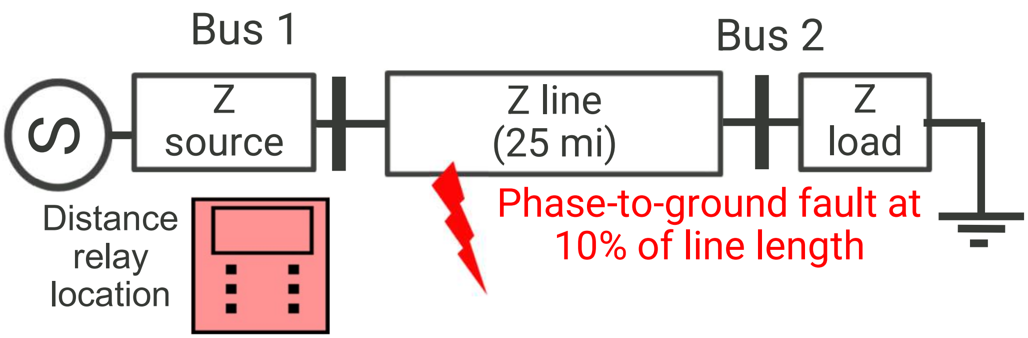
# Measurement of Distance Elements in Relays

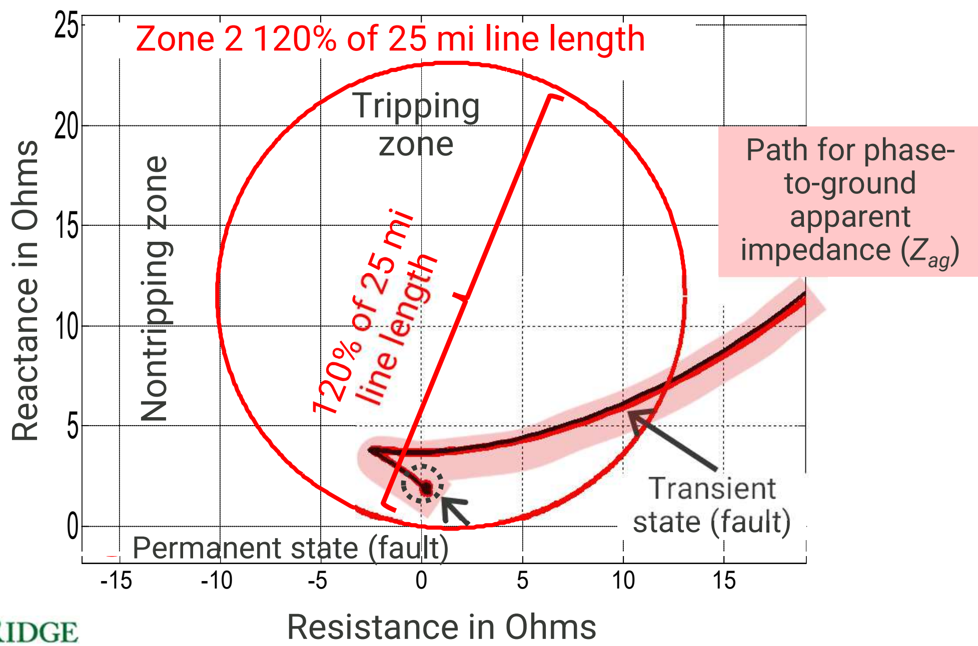
The highlighted distance elements (with electrical faults) were simulated and measured for this study.

| Distance element | | Equation | Fault type |
|---|---|---|---|
| Phase element | $Z_{ab}$ | $= V_a - V_b/(I_a - I_b)$ | ABC, AB, ABG |
| | $Z_{bc}$ | $= V_b - V_c/(I_b - I_c)$ | ABC, BC, BCG |
| | $Z_{ca}$ | $= V_c - V_a/(I_c - I_a)$ | ABC, CA, CAG |
| Ground element | $Z_{ag}$ | $= V_a/(I_a + K_0 \times 3I_0)$ | ABC, ABG, CAG, AG |
| | $Z_{bg}$ | $= V_b/(I_b + K_0 \times 3I_0)$ | ABC, ABG, BCG, BG |
| | $Z_{cg}$ | $= V_c/(I_c + K_0 \times 3I_0)$ | ABC, BCG, CAG, CG |
| *Where:* $K_0 = (Z_{L0} - Z_{L1})/(3 \times Z_{L1})$, $I_0 = (I_a + I_b + I_c)/3$ | | | |

Source: J. A. Roberts, A. Guzman, E. O. Schweitzer III. "Z = V/I Does Not Make a Distance Relay." Schweitzer Engineering Laboratories, 48th Annual Georgia Tech Protective Relaying Conference, Atlanta, GA, 1994.

# Mho Diagram and Phase-to-Ground Apparent Impedance




The relay measures $Z_{ag}$:

1

$$Z_{ag} = \frac{V_a}{I_a + K_0(3I_0)},$$

where

2

$$I_0 = \frac{I_a + I_b + I_c}{3},$$

3

$$K_0 = \frac{Z_{L0} - Z_{L1}}{3Z_{L1}}.$$

$Z_{ag}$ = phase-to-ground fault apparent impedance; $V_a$ = A-phase-to-neutral voltage; $I_a$ = A-phase current (and similarly for $I_b$ and $I_c$); $I_0$ = zero-sequence current; $K_0$ = zero-sequence current compensation factor; $Z_{L0}$ = zero-sequence impedance of the transmission line, $Z_{L1}$ = positive-sequence impedance of the transmission line

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# Phase-to-Ground (Zag) and Phase-to-Phase (Zab) Apparent Impedances

**For an AG fault, the relay measures $Z_{ag}$:**

1. $$Z_{ag} = \frac{V_a}{I_a + K_0(3I_0)},$$

where

2. $$I_0 = \frac{I_a + I_b + I_c}{3},$$

3. $$K_0 = \frac{Z_{L0} - Z_{L1}}{3Z_{L1}}.$$

$Z_{ag}$ = phase-to-ground fault apparent impedance; $V_a$ = A-phase-to-neutral voltage; $I_a$ = A-phase current (and similarly for $I_b$ and $I_c$); $I_0$ = zero-sequence current; $K_0$ = zero-sequence current compensation factor; $Z_{L0}$ = zero-sequence impedance of the transmission line; $Z_{L1}$ = positive-sequence impedance of the transmission line

**For an AB fault, the relay measures $Z_{ab}$:**

4. $$Z_{ab} = \frac{V_a - V_b}{I_a - I_b}$$

$Z_{ab}$ = phase-to-phase (AB) fault apparent impedance;
$V_a$ = A-phase-to-neutral voltage;
$I_a$ = A-phase current; $V_b$ = B-phase-to-neutral voltage;
$I_b$ = B-phase current

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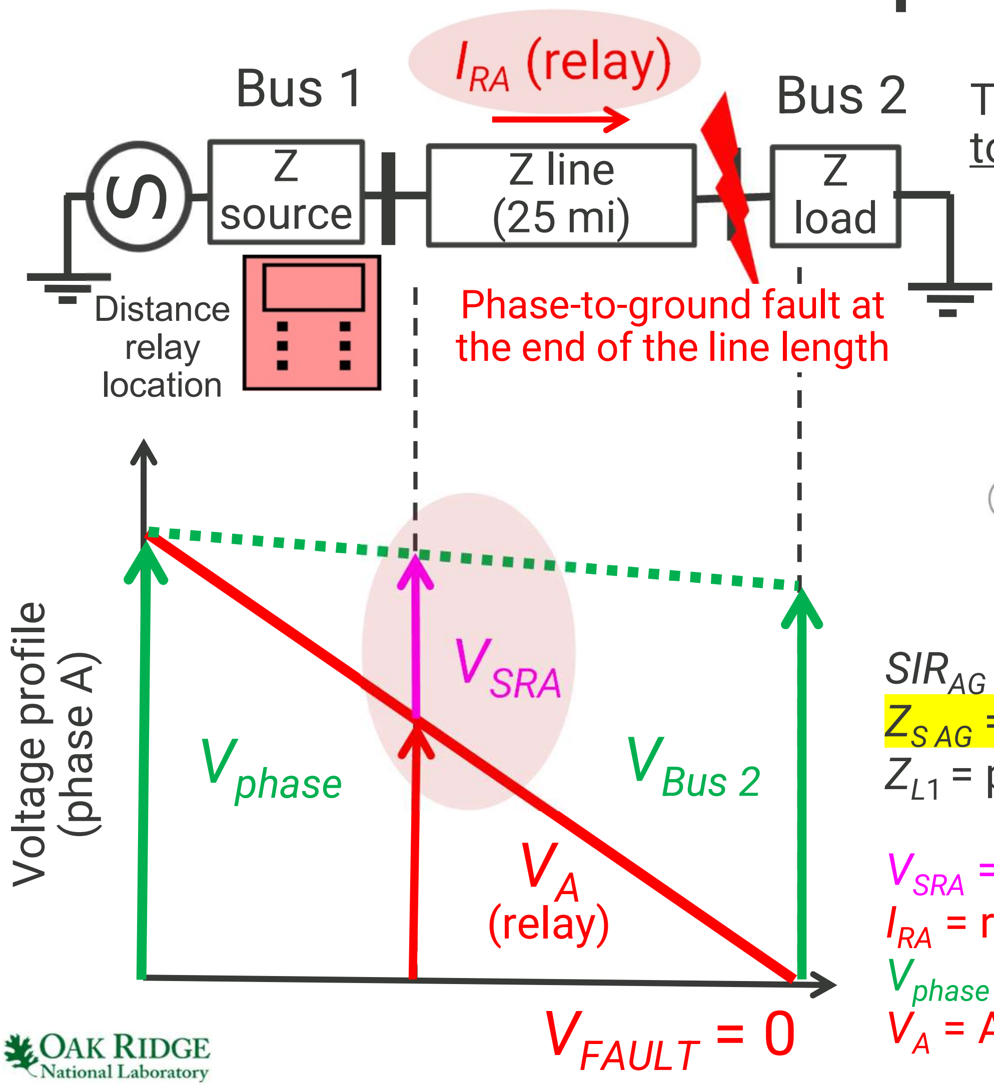
# Phase-to-Ground Source Impedance Ratio




The source impedance ratio (SIR) for the A-phase-to-ground fault is

(5) $$SIR_{AG} = \frac{|Z_{S\ AG}|}{|Z_{L1}|}.$$

**The source impedance for the A-phase-to-ground fault is**

(6) $$|Z_{S\ AG}| = \frac{V_{SRA}}{I_{RA}} = \frac{V_{phase} - V_A}{I_{RA}}.$$

$SIR_{AG}$ = SIR for the A-phase-to-ground fault;
$Z_{S\ AG}$ = source impedance for the A-phase-to-ground fault;
$Z_{L1}$ = positive impedance for the line

$V_{SRA}$ = voltage drop from the source to the relay location;
$I_{RA}$ = relay fault current for the A-phase-to-ground fault;
$V_{phase}$ = base phase-to-ground voltage;
$V_A$ = A-phase-to-neutral voltage at the relay site

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# Source Impedance Ratios for SLG and 3PH Faults

(7)

$$SIR_{SLG} = \frac{V_{phase} - V_{RELAY}}{|Z_{L1}| \times [\, I_{RELAY} + |K_0|(\, I_A + I_B + I_C\,)]}$$

**Placing**
**$V_A = V_{RELAY}$**
**$I_A = I_{RELAY}$**

**From Eq. (7), the SIR for the three-phase-to-ground (3PH) fault is (8), given by considering $I_0 = I_A + I_B + I_C = 0$.**

(8)

$$SIR_{3PH} = \frac{V_{phase} - V_{RELAY}}{|Z_{L1}| \times I_{RELAY}}$$

Source: M. J. Thompson and A. Somani. "A Tutorial on Calculating Source Impedance Ratios for Determining Line Length." 68th Annual Conference for Protective Relay Engineers, College Station, TX, USA, 2015, pp. 833–841.

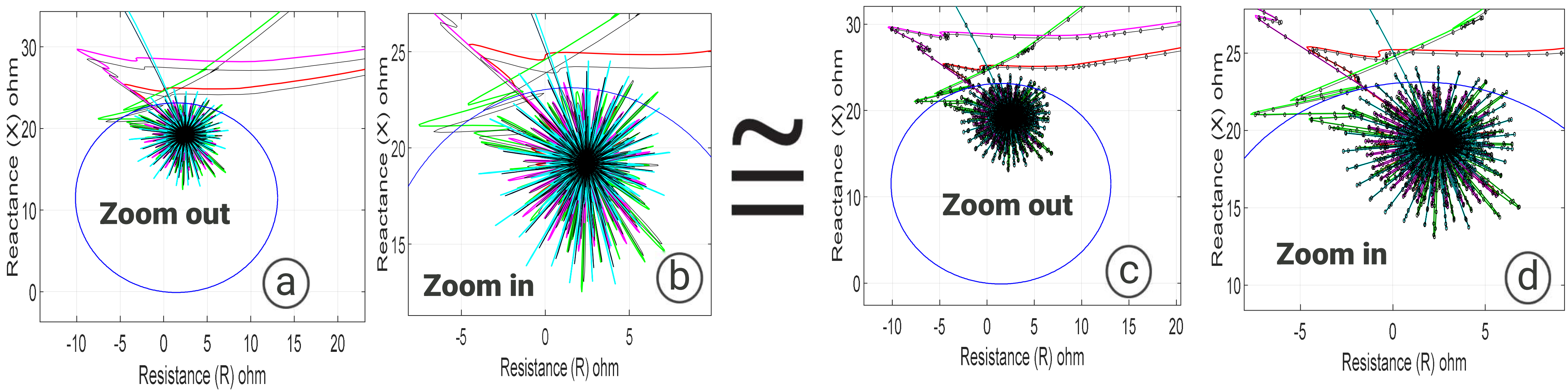
# Radial vs. Nonradial Power Systems

***Radial power system (a-b)***

$Z_{ag}$ (AG, ABG, and ABCG faults) and $Z_{ab}$ (AB fault) apparent impedances at the end of the 230 kV, 25 mi transmission line

***Nonradial power system (c-d)***

$Z_{ag}$ (AG, ABG, and ABCG faults) and $Z_{ab}$ (AB fault) apparent impedances at the end of the 230 kV, 25 mi transmission line




- 120% distance for 230 kV, 25 mi power line
- $Z_{ag}$ (AG fault) apparent impedance with GIC-NBDs and PES
- $Z_{ag}$ (ABG fault) apparent impedance with GIC-NBDs and PES
- $Z_{ag}$ (ABCG fault) apparent impedance with GIC-NBDs and PES
- $Z_{ab}$ (AB fault) apparent impedance with GIC-NBDs and PES
- $Z_{ag}$ (AG, ABG, and ABCG faults) and $Z_{ab}$ (AB fault) apparent impedances without GIC-NBDs and PES
- $Z_{ag}$ (AG, ABG, and ABCG faults) and $Z_{ab}$ (AB fault) apparent impedances without GIC-NBDs and with PES

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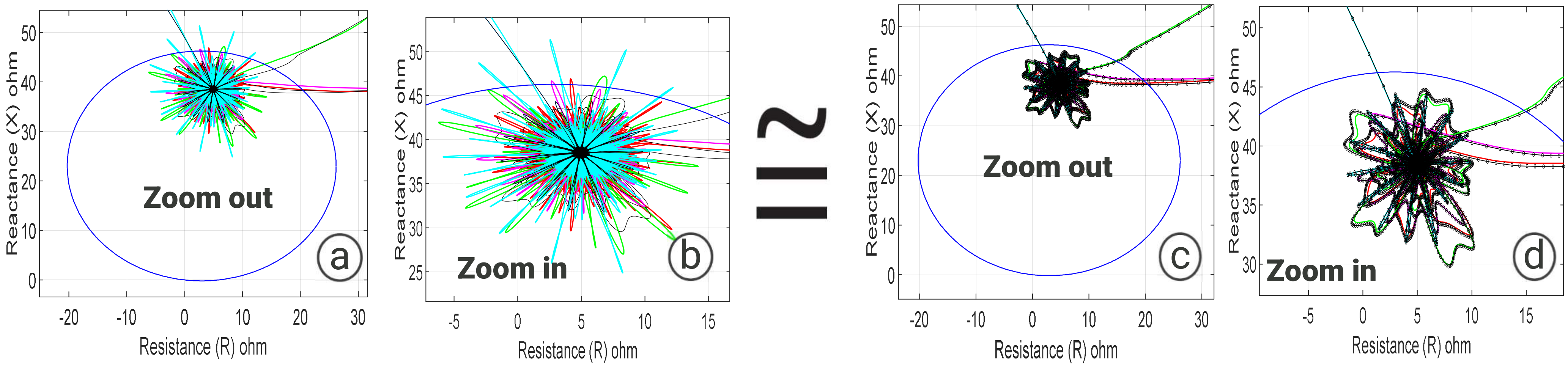
# Radial vs. Nonradial Power Systems (cont.)

***Radial power system (a-b)***

$Z_{ag}$ (AG, ABG, and ABCG faults) and $Z_{ab}$ (AB fault) apparent impedances at the end of the 230 kV, 50 mi transmission line

***Nonradial power system (c-d)***

$Z_{ag}$ (AG, ABG, and ABCG faults) and $Z_{ab}$ (AB fault) apparent impedances at the end of the 230 kV, 50 mi transmission line




- 120% distance for 230 kV, 25 mi power line
- $Z_{ag}$ (AG fault) apparent impedance with GIC-NBDs and PES
- $Z_{ag}$ (ABG fault) apparent impedance with GIC-NBDs and PES
- $Z_{ag}$ (ABCG fault) apparent impedance with GIC-NBDs and PES
- $Z_{ab}$ (AB fault) apparent impedance with GIC-NBDs and PES
- $Z_{ag}$ (AG, ABG, and ABCG faults) and $Z_{ab}$ (AB fault) apparent impedances without GIC-NBDs and PES
- $Z_{ag}$ (AG, ABG, and ABCG faults) and $Z_{ab}$ (AB fault) apparent impedances without GIC-NBDs and with PES

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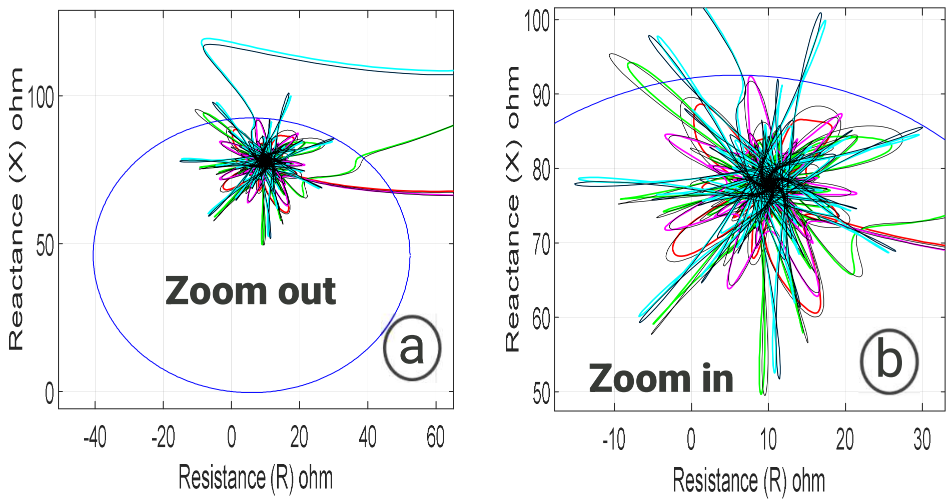
# Radial vs. Nonradial Power Systems (cont.)

***Radial power system (a-b)***

$Z_{ag}$ (AG, ABG, and ABCG faults) and $Z_{ab}$ (AB fault) apparent impedances at the end of the 230 kV, 100 mi transmission line

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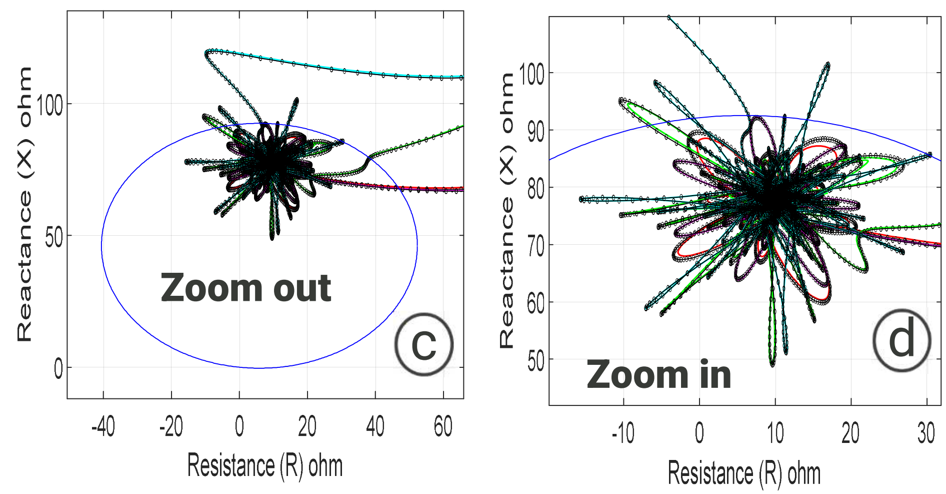
***Nonradial power system (c-d)***

$Z_{ag}$ (AG, ABG, and ABCG faults) and $Z_{ab}$ (AB fault) apparent impedances at the end of the 230 kV, 100 mi transmission line

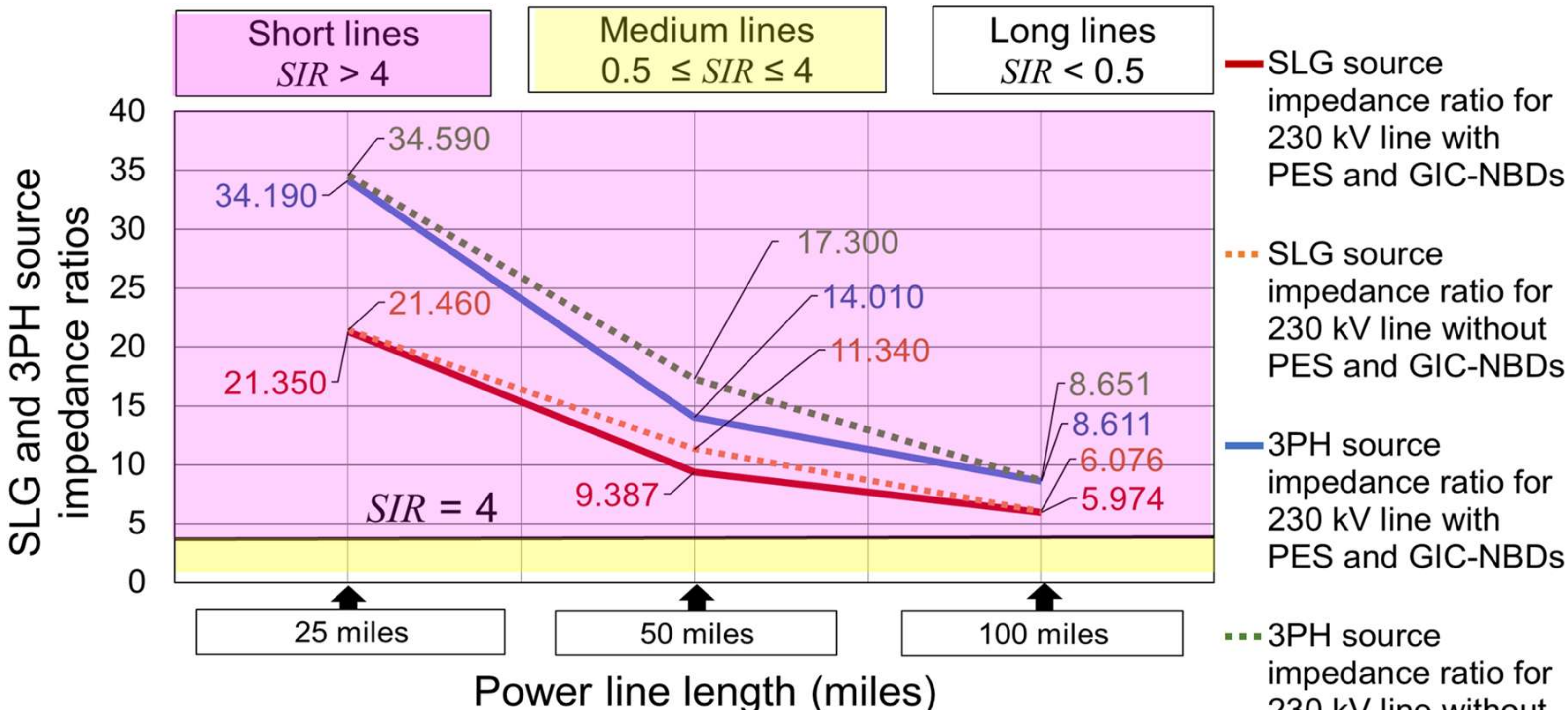



- 120% distance for 230 kV, 25 mi power line
- $Z_{ag}$ (AG fault) apparent impedance with GIC-NBDs and PES
- $Z_{ag}$ (ABG fault) apparent impedance with GIC-NBDs and PES
- $Z_{ag}$ (ABCG fault) apparent impedance with GIC-NBDs and PES
- $Z_{ab}$ (AB fault) apparent impedance with GIC-NBDs and PES
- $Z_{ag}$ (AG, ABG, and ABCG faults) and $Z_{ab}$ (AB fault) apparent impedances without GIC-NBDs and PES
- $Z_{ag}$ (AG, ABG, and ABCG faults) and $Z_{ab}$ (AB fault) apparent impedances without GIC-NBDs and with PES

# SLG/ 3PH SIRs at 230 kV Power Lines of 25, 50, and 100 Mi with and without GIC-NBDs/Power Electronics Sources as a Radial System

All power lines matched as short lines for SIRs > 4 based on IEEE C37.113-2015 Std.

For the shorter and longer transmission lines, the SIRs are larger and smaller, respectively.




*SIR: source impedance ratio; SLG: single line to ground; 3PH: three phase; GIC-NBDs: geomagnetic induced current-neutral blocking devices; PES: power electronics sources*

**Per IEEE C37.113-2015, the values of the SIRs for long, medium, and short transmission lines are less than 0.5, between 0.5 and 4, and greater than 4, respectively.**

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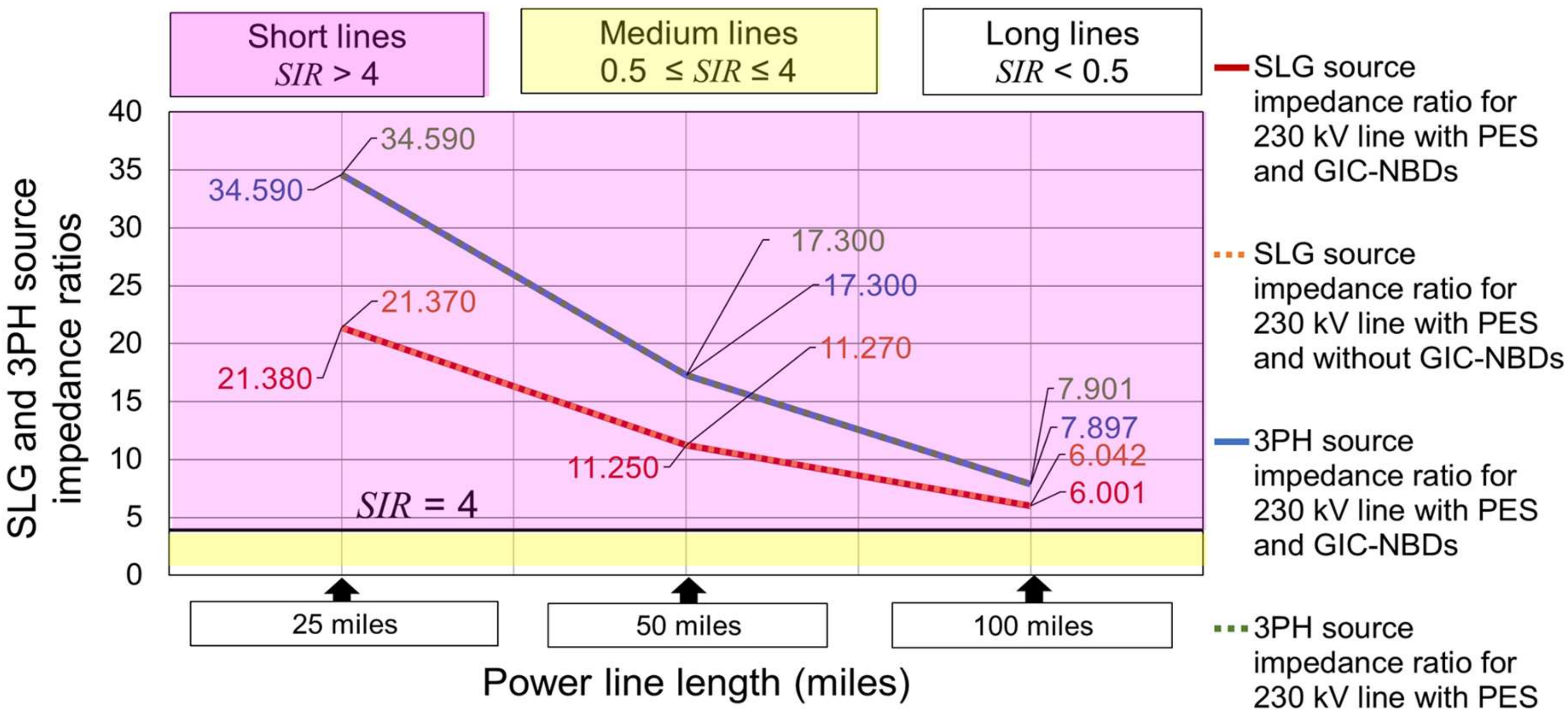
# SLG/ 3PH SIRs at 230 kV Power Lines of 25, 50, and 100 Mi Using Power Electronics Sources with and without GIC-NBDs as a Nonradial System

**All power lines matched as short lines for SIRs > 4 based on IEEE C37.113-2015 Std.**

**For the shorter and longer transmission lines, the SIRs are larger and smaller, respectively.**




SIR: source impedance ratio; SLG: single line to ground; 3PH: three phase; GIC-NBDs: geomagnetic induced current-neutral blocking devices; PES: power electronics sources

**Per IEEE C37.113-2015, the values of the SIRs for long, medium, and short transmission lines are less than 0.5, between 0.5 and 4, and greater than 4, respectively.**

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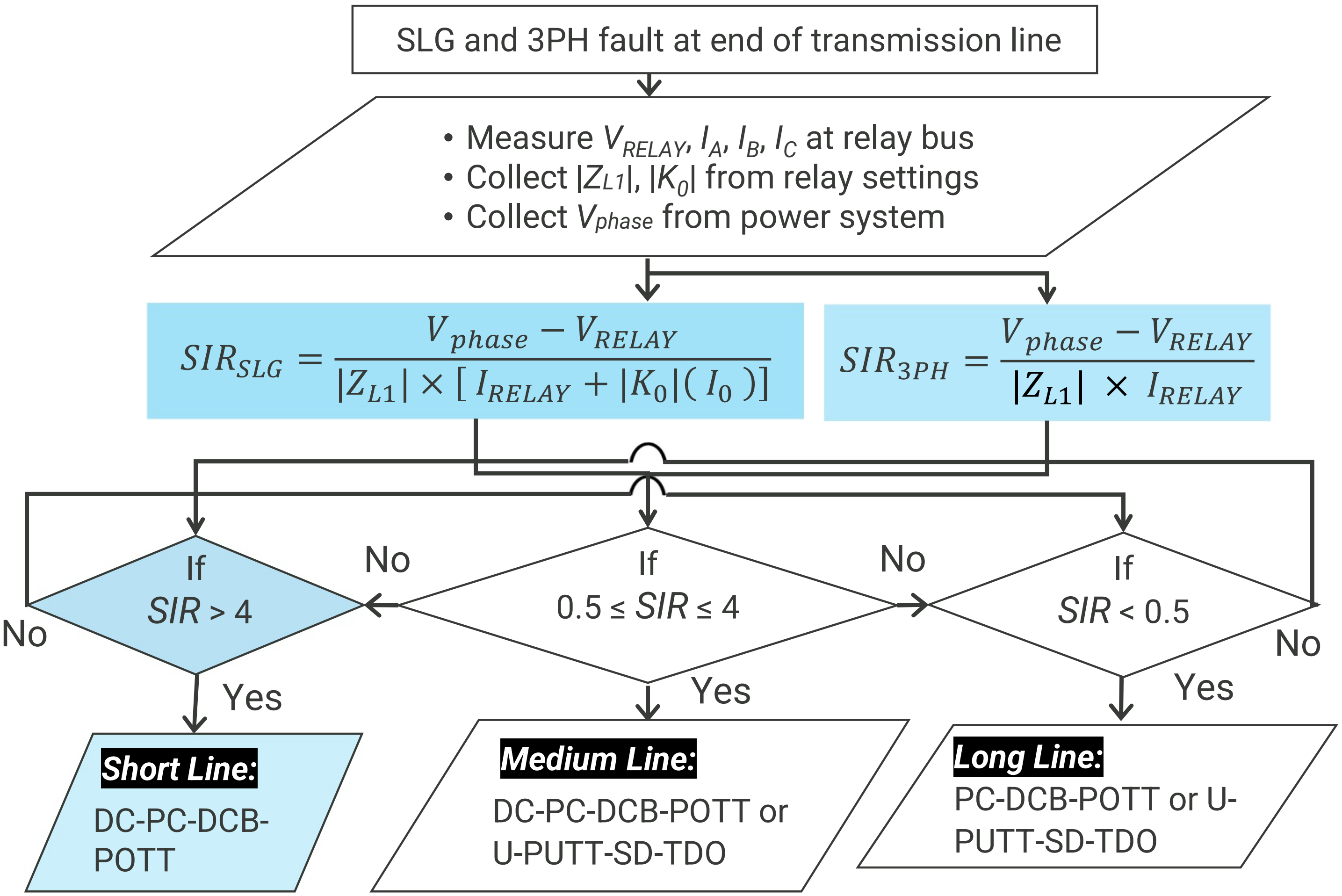
# For the 25, 50, and 100 mi power line lengths, the SIR > 4




DC: differential current
PC: phase comparison
DCB: directional comparison blocking
POTT: permissive overreaching transfer tripping

U: unblocking
PUTT: permissive underreaching transfer tripping
SD: step distance
TDO: time delay overcurrent

*IEEE Standard C37.113-2015

# Conclusions

- The traditional GIC-NBDs with a capacitor of 2,650 μF behaved well for the phase-to-ground (AG) and phase-to-phase (AB) distance elements in electrical faults at the ends of power lines.
  - *Permanent fault apparent impedances inside 120% of the power line length were shown.*
- The measured SIRs for the 25, 50, and 100 mi power line length sections were classified as short lines (SIRs > 4), based on IEEE C37.113-2015 Std.
- For the shorter and longer transmission lines, the SIRs are larger and smaller, respectively.

# Thanks

Emilio C. Piesciorovsky, PhD
Email: piesciorovec@ornl.gov

# Phase-to-Ground Source Impedance Ratio (Cont.)

**The SIR for the A-phase-to-ground fault is (from the previous slide)**

(5)
$$SIR_{AG} = \frac{|Z_{S\ AG}|}{|Z_{L1}|}.$$

**From the denominator of Eq. (4),**

(7)
$$I_{RA} = I_A + |K_0|(I_A + I_B + I_C).$$

**The source impedance for the A-phase-to-ground fault is (from the previous slide)**

(6)
$$|Z_{S\ AG}| = \frac{V_{SRA}}{I_{RA}} = \frac{V_{phase} - V_A}{I_{RA}}.$$

**Placing Eq. (7) in Eq. (6),**

(8)
$$|Z_{S\ AG}| = \frac{V_{phase} - V_A}{I_A + |K_0|(I_A + I_B + I_C)}.$$

**Placing Eq. (8) in Eq. (5),**

(9)
$$SIR_{AG} = \frac{V_{phase} - V_A}{|Z_{L1}| \times [\,I_A + |K_0|(\,I_A + \,I_B + I_C\,)]}.$$

*V* and *I* are rms values.

$SIR_{AG}$ = SIR for the A-phase-to-ground fault; $Z_{S\ AG}$ = source impedance for the A-phase-to-ground fault;
$Z_{L1}$ = positive impedance for the transmission line; $V_{SRA}$ = voltage drop from the source to the relay site for phase A;
$I_{RA}$ = relay fault current for the A-phase-to-ground fault loop; $V_{phase}$ = base phase-to-ground voltage;
$V_A$ = A-phase-to-neutral voltage at the relay site; $K_0$|= magnitude of the compensation factor; $I_A$, $I_B$, $I_C$ = A-, B-, and C-phase currents

# GIC-NBs on Distance Relays with/ without Power Electronics Sources

Electric Power Systems Research
Volume 180, March 2020, 106135

a

## Modeling the impact of GIC neutral blocking devices on distance protection relay operations for transmission lines ☆

Emilio C. Piesciorovsky, Alfonso G. Tarditi

Electric Power Systems Research
Volume 251, February 2026, 112190

b

## Impact assessment of geomagnetic induced current neutral blocking devices with power electronics sources on distance relay for 230 kV transmission lines

Emilio C. Piesciorovsky [a], Trupal Rajeshbhai Patel [b], Mathew J. Reno [b]

***Previous work (2019-20):***

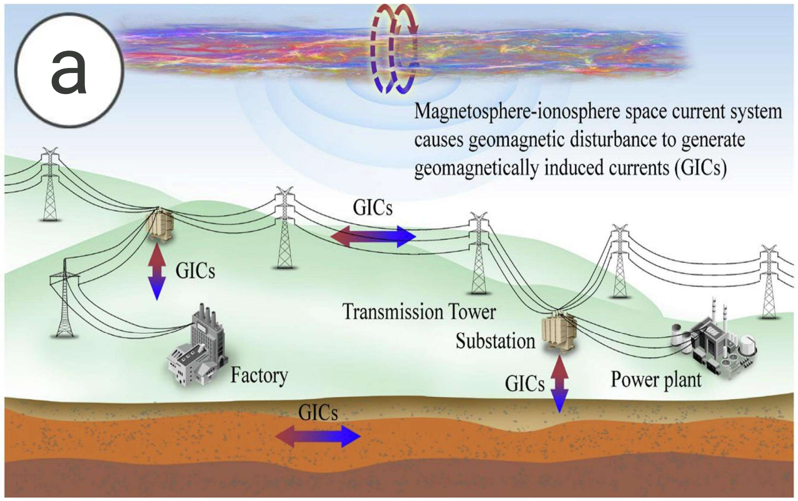
Focus on studying the impact of GIC-NBDs (2,650/ 265/ 26.5 μF) on Distance Relay Operations on 25-, 50- and 100-miles transmission power lines of 230 and 345 kV, in a radial power system with and without GIC-NBDs (measuring PGAI and SLG-SIR).

***Actual work (2025-26):***

Focus on studying the impact of GIC-NBDs (2,650 μF) on Distance Relay Operations on 25-, 50- and 100-miles transmission power lines of 230 kV, in a radial and non-radial power system using 2 MW power electronic sources with and without GIC-NBDs (measuring PGAI, PPAI, SLG-SIR and 3PH-SIR)

GIC-NBDs: Geomagnetic induced current neutral blocking devices, PGAI: phase to ground apparent impedance, PPAI: phase to phase apparent impedance, SIR: source impedance ratio

# GIC Frequency Measurements from Distance Relays



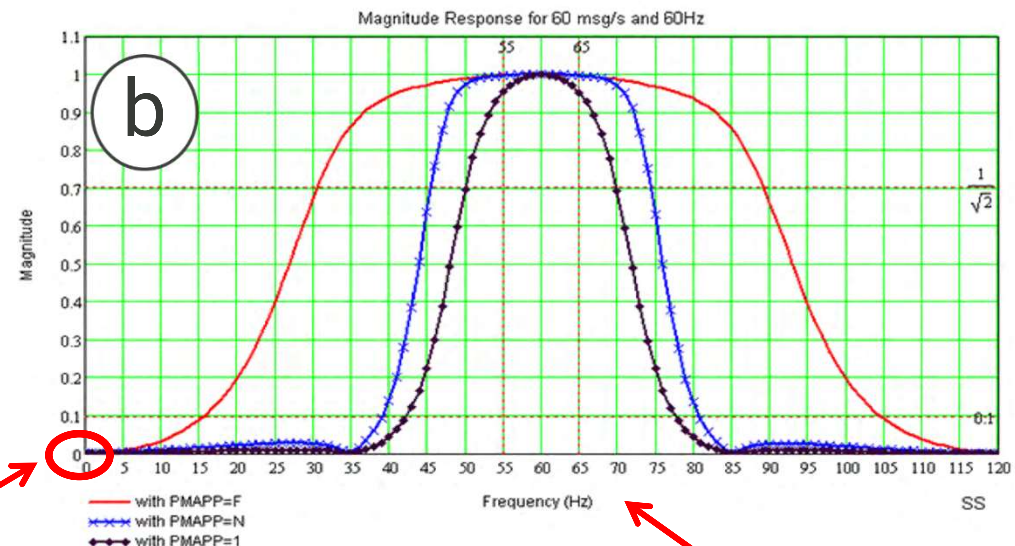




**Figure 18.2 Magnitude Frequency Response**

[1] The frequencies of GICs are in the range of 0.0001 ~ 0.01 Hz. It will lead to the half-wave saturation of the transformer, causing the power grid harmonic current to increase, voltage to drop, reactive power fluctuation, and causing the power grid to be blacked out (March 13 to 14, 1989, the 735-kV power grid collapsed in Quebec, Canada)

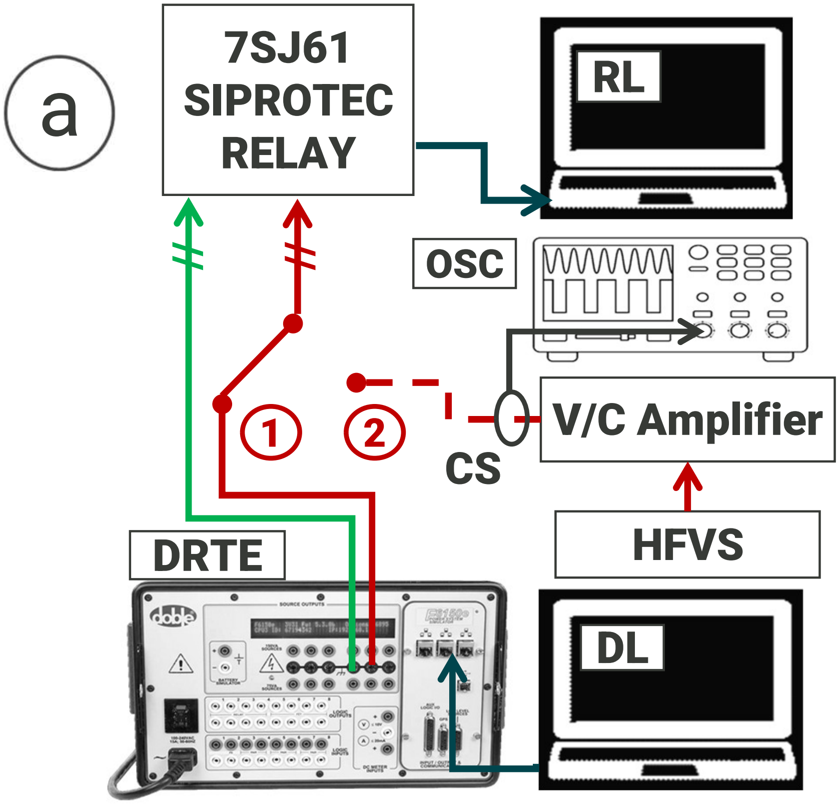
Base on Figure 18.2 [2] , distance relays cannot measure the current magnitudes of low frequency signals.

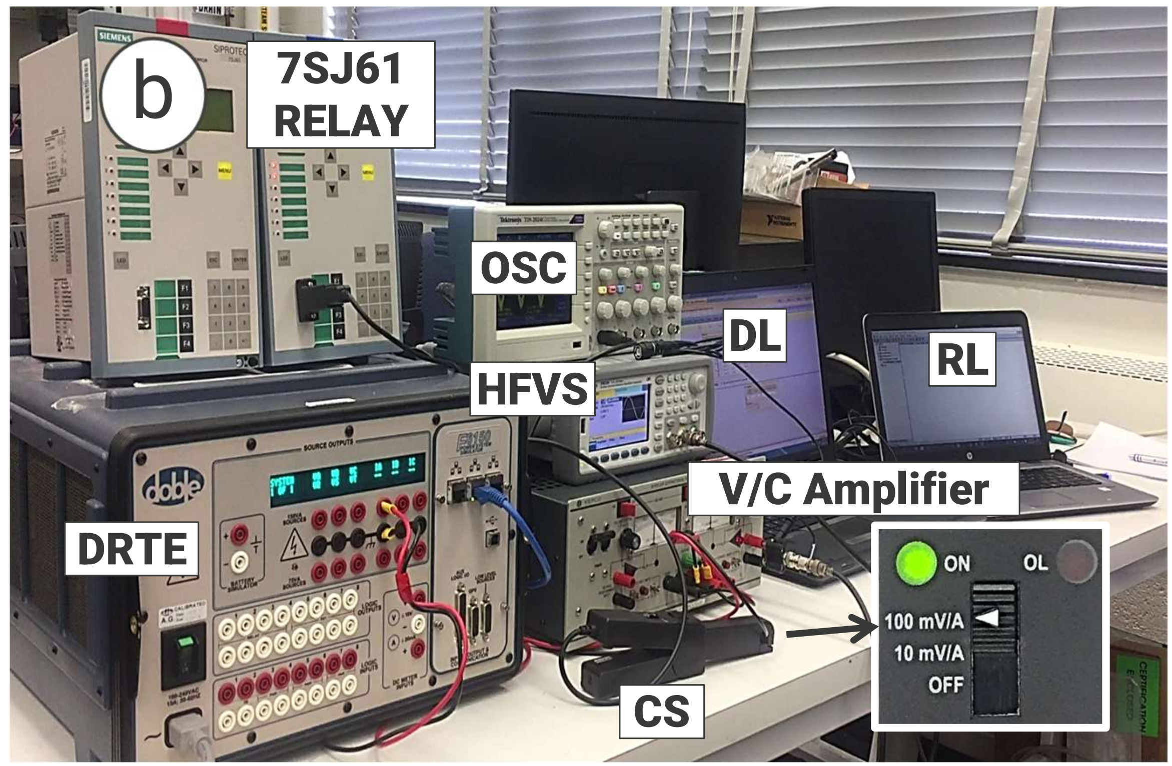
PMAPP PMU Application
(F = Fast Response, N = Narrow Bandwidth, 1 = Extra Narrow)

[1] X Zhang et al. Comparison of different geoelectric field methods to calculate geomagnetically induced currents in North China, International Journal of Electrical Power & Energy Systems, Volume 155, Part B, 2024, 109657, ISSN 0142-0615. https://doi.org/10.1016/j.ijepes.2023.109657.
[2] SEL-421-4, -5 Protection, Automation, and Control System, Instruction Manual, 20240927.

[3] EC Piesciorovsky and T Karnowski.Variable frequency response testbed to validate protective relays up to 20 kHz, Electric Power Systems Research,Volume 194, 2021, 107071, ISSN 0378-7796, https://doi.org/10.1016/j.epsr.2021.107071.

# Test bed (0.1 A/0.5 A: up to 1 kHz and up to 20 kHz)




— Phase B with 1.0 A (60 Hz)

— Exp ① : Phase A with 0.1 and 0.5 A up to 1 kHz

--- Exp ② : Phase A with 0.1 and 0.5 A up to 20 kHz

SIPROTEC relay (7SJ61), relay laptop (RL), Doble RTE (DRTE), Doble laptop (DL), oscilloscope (OSC), voltage-current amplifier (V/C Amplifier), high-frequency voltage source (HFVS) current sensor (CS)

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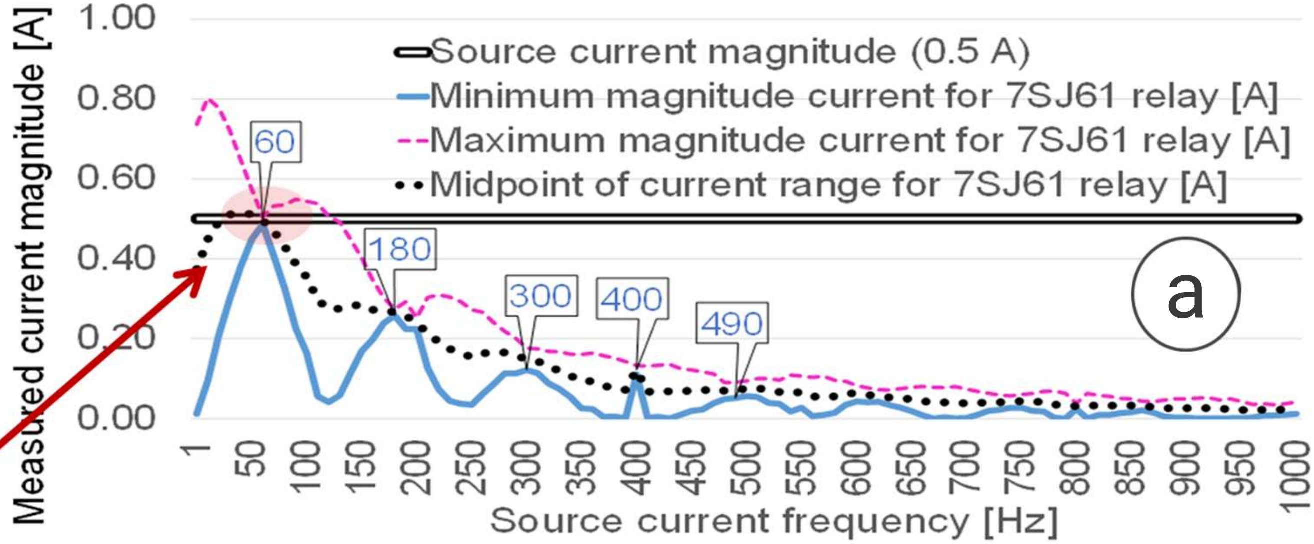
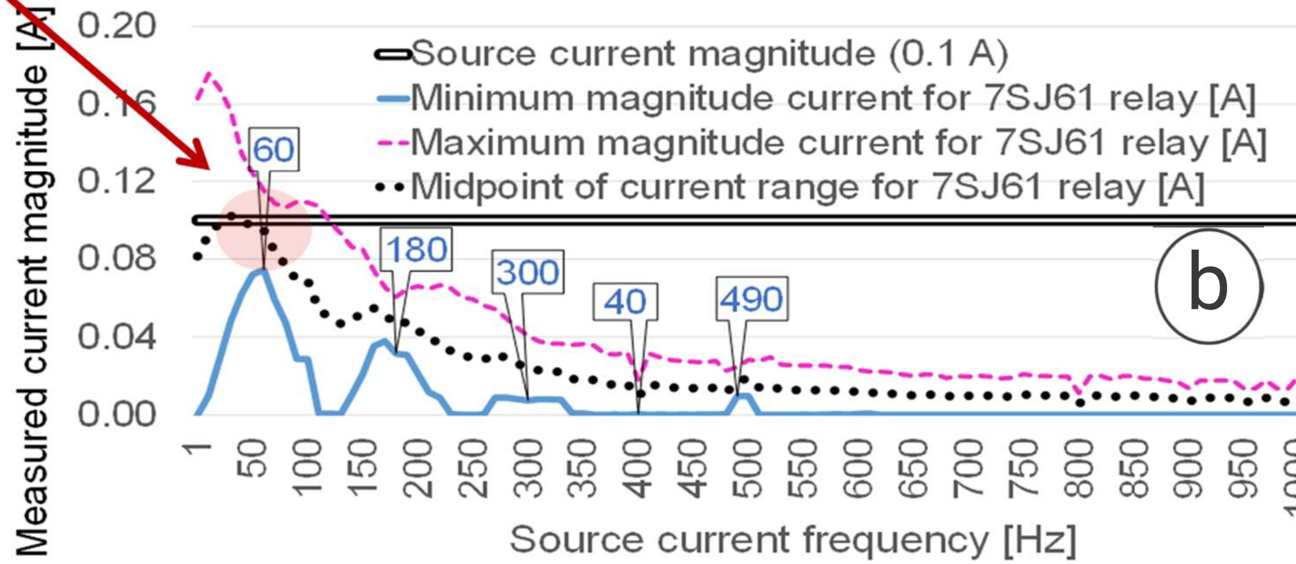
# 7SJ61 Relay

Experiment with 0.5 A current: measured vs. real current **magnitudes** from 1 to 1,000 Hz




The best current **magnitude** measurement performance was around 60 Hz

Experiment with 0.1 A current: measured vs. real current **magnitudes** from 1 to 1,000 Hz

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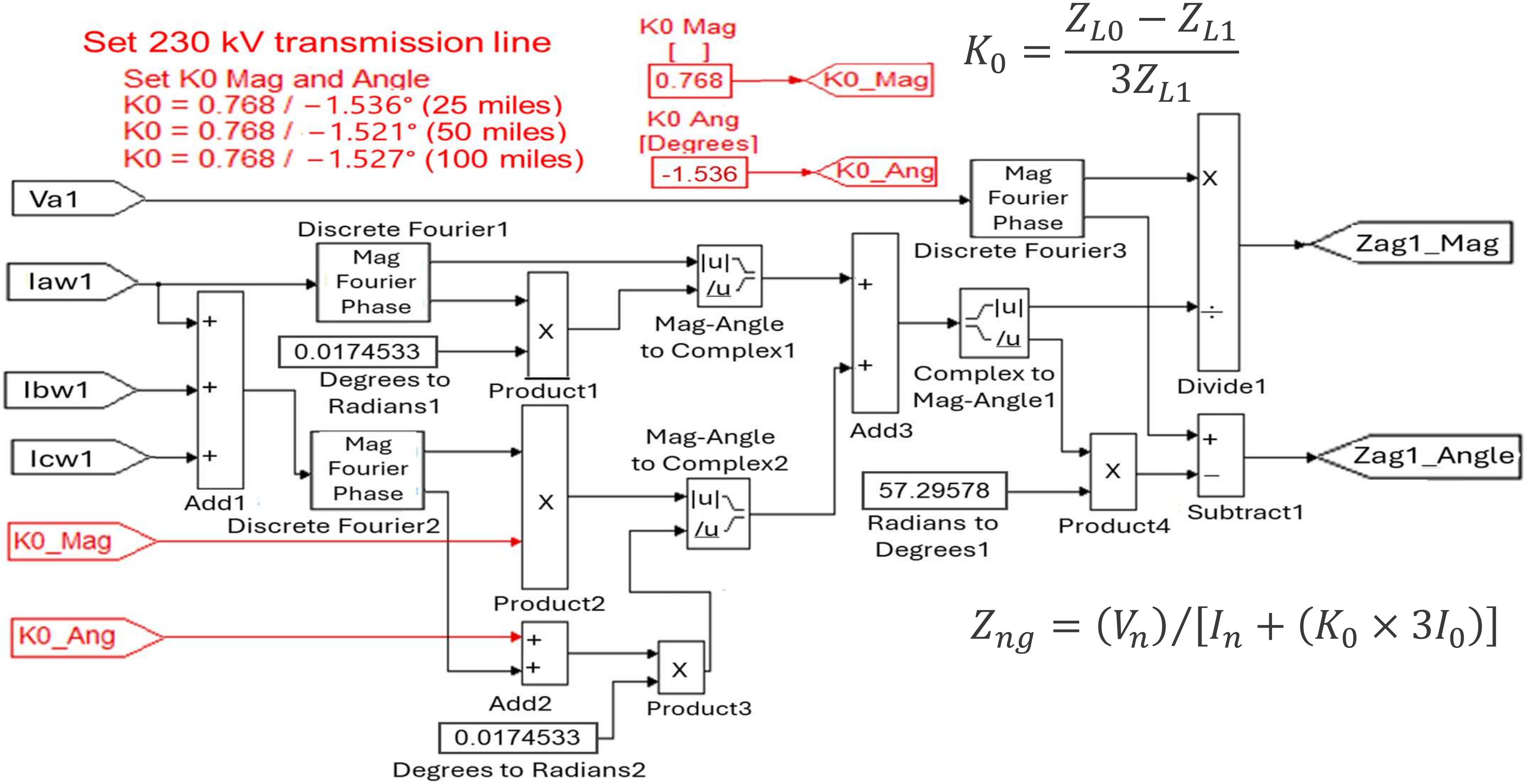
# MATLAB/Simulink model at the distance element of PGAI for phase A

$$K_0 = \frac{Z_{L0} - Z_{L1}}{3Z_{L1}}$$




$$Z_{ng} = (V_n)/[I_n + (K_0 \times 3I_0)]$$

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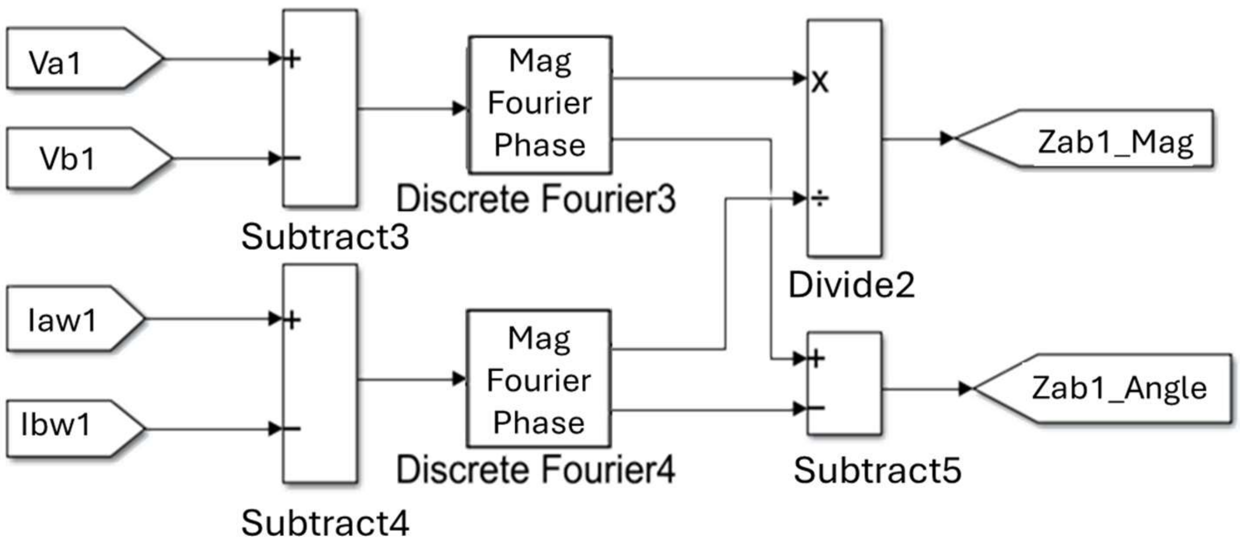
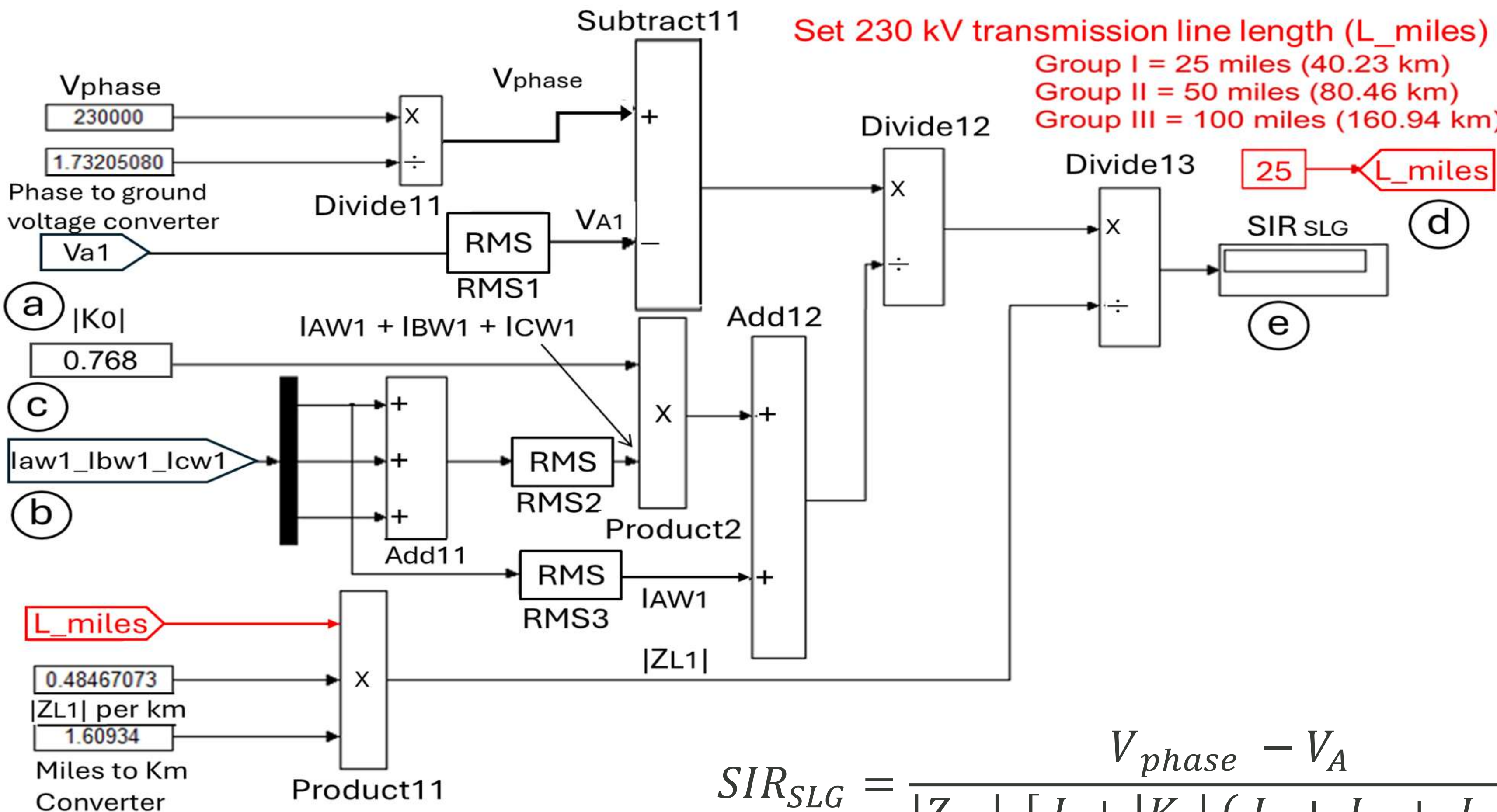
# MATLAB/Simulink model at the distance element of PPAI for phase AB



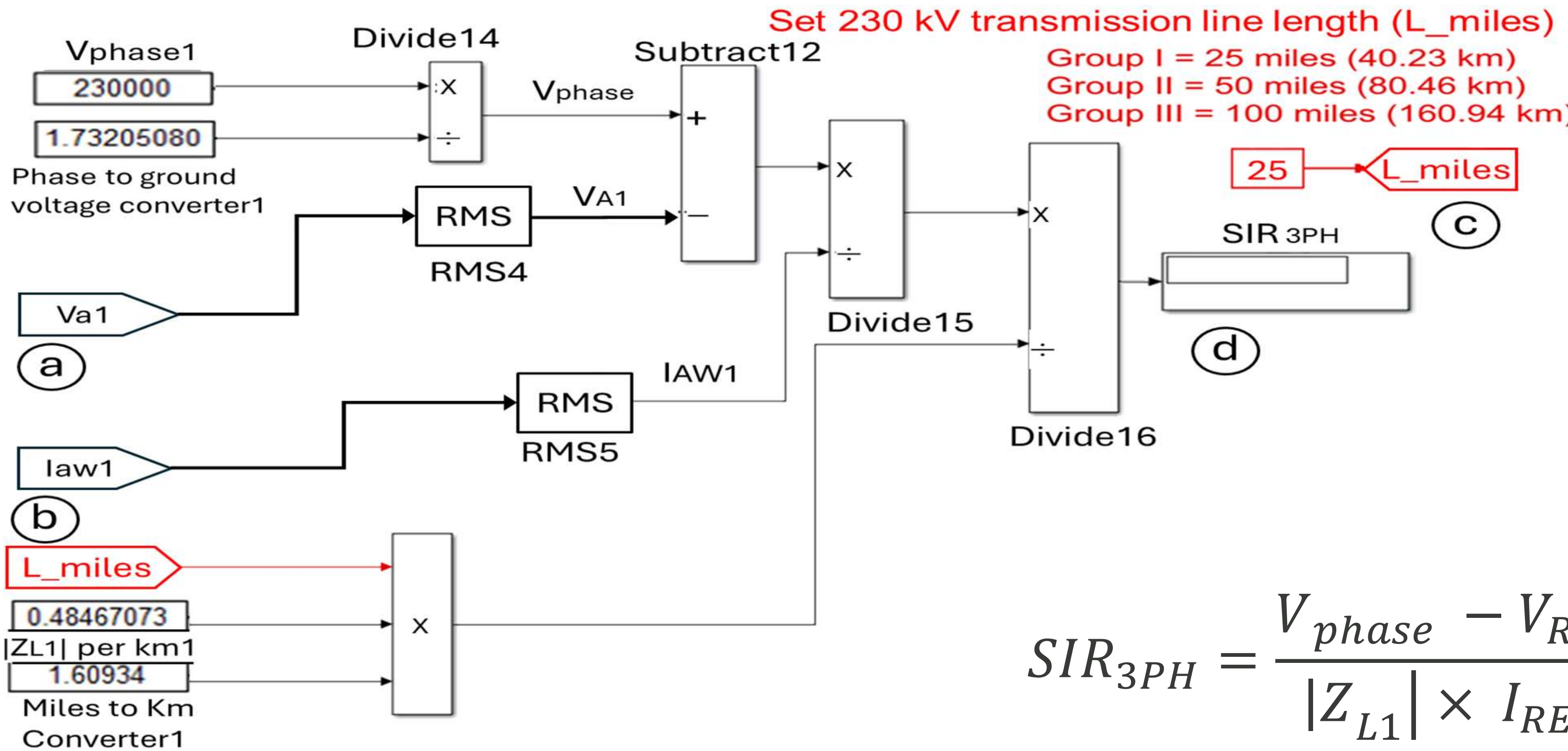

$$Z_{nm} = (V_n - V_m)/(I_n - I_m)$$

# MATLAB/Simulink model for SLG-SIR




$$SIR_{SLG} = \frac{V_{phase} - V_A}{|Z_{L1}|\ [\, I_A + |K_0|\,(\, I_A + I_B + I_C \,)\,]}$$

# MATLAB/Simulink model for 3PH-SIR




$$SIR_{3PH} = \frac{V_{phase} - V_{RELAY}}{|Z_{L1}| \times I_{RELAY}}$$