Review of SIR Calculations for Distance Protection and Considerations for Inverter-Based Resources

Ritwik Chowdhury
Schweitzer Engineering Laboratories, Inc.

Carolyn Sun
Black & Veatch

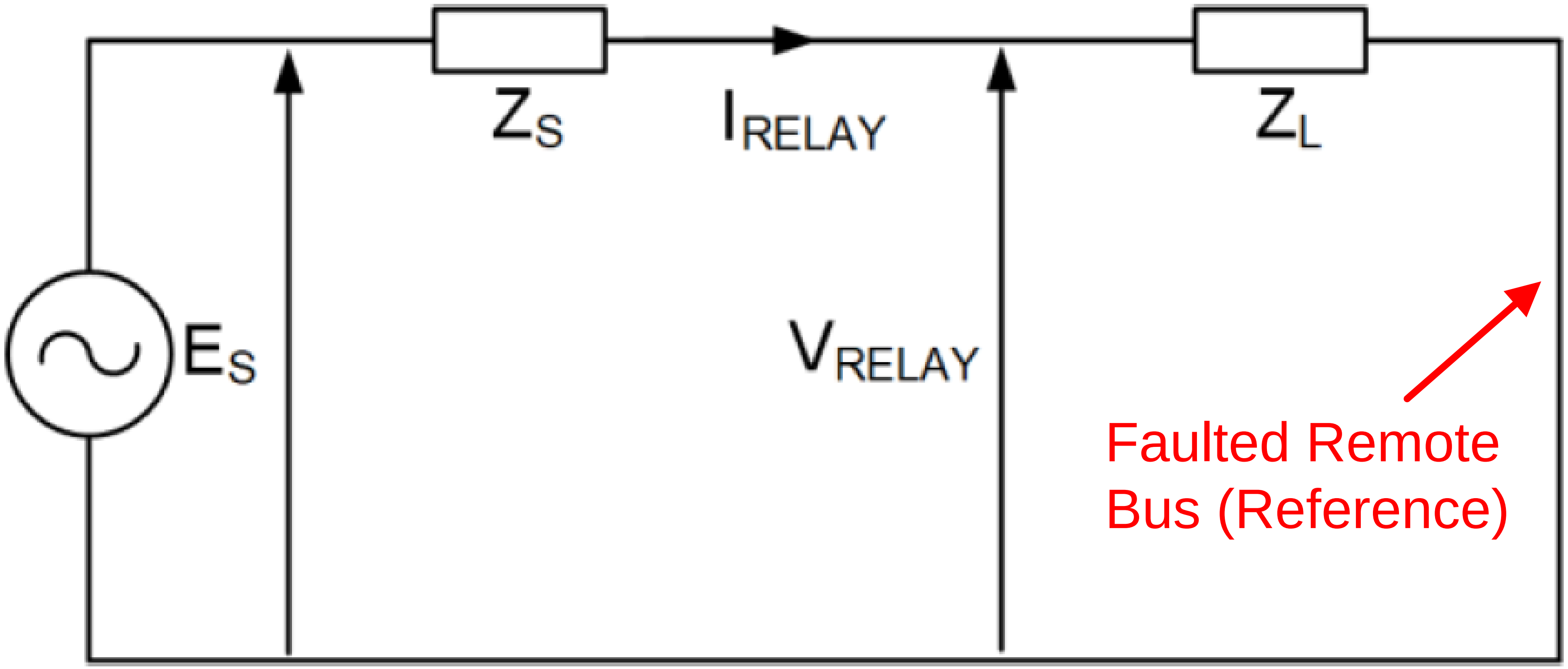
Douglas Taylor
Avista Utilities

Outline

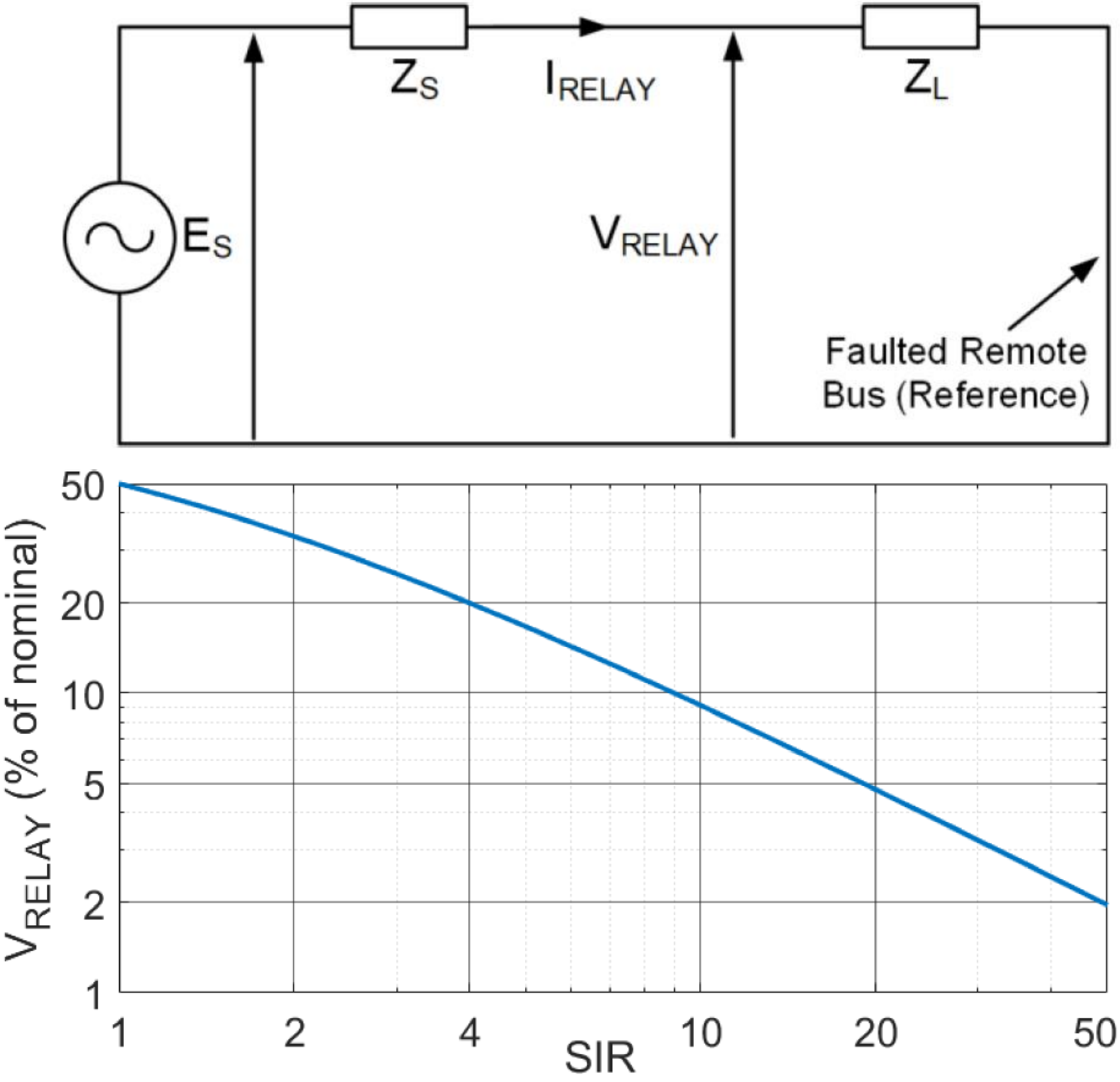
- Definition of SIR
- SIR and relay voltage
- Evolution of SIR calculation methods
- Mutual coupling
- Inverter-based resources
- Conclusion

Defining source-to-line impedance ratio (SIR)

The ratio of the source impedance behind a line terminal to the line impedance.



Relay voltage vs. SIR



Evolution of
SIR calculations

Early days (before 2000)

Literature from 1968

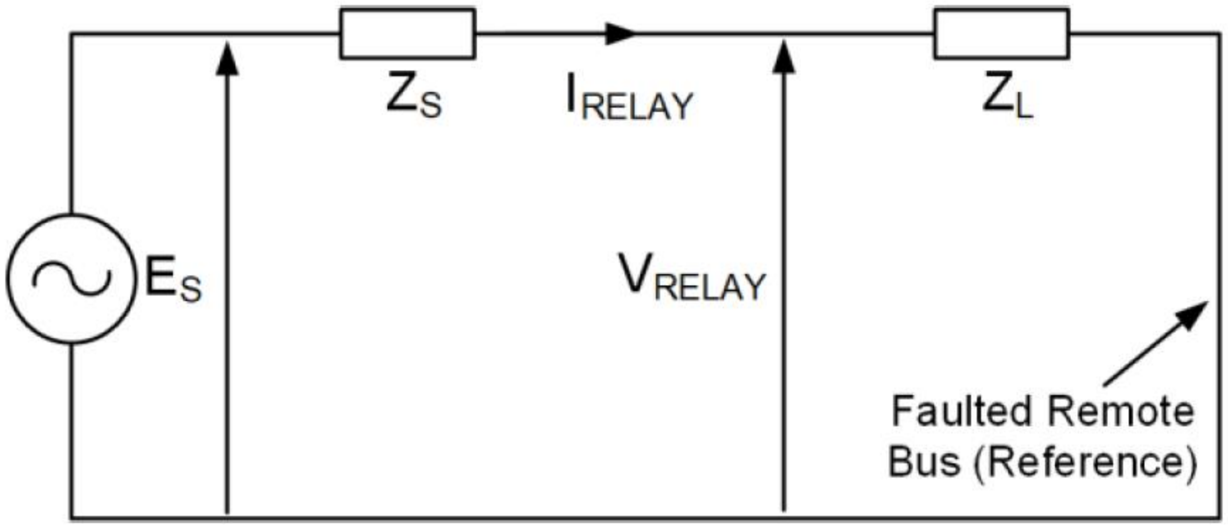
- A. R. Van C. Warrington's book—accuracy limit of distance relays as a percentage of normal voltage or a "Z_S / Z_L" ratio for electromechanical mho and reactance relays
- Static relay paper—presented accuracy and speed of their transistor distance relay versus SIR
- SIR—a tool used by manufacturer and designers to evaluate and illustrate relay performance

Early days (before 2000)

Protective relays application guide ~ 1987

$$V_{RELAY} = E_S \bullet \frac{Z_L}{Z_S + Z_L}$$

$$V_{RELAY} = E_S \bullet \frac{1}{\left(\frac{Z_S}{Z_L}\right) + 1}$$



Phase

$$V_{RELAY\_LL} = \frac{E_{S\_LL}}{\left(\frac{Z1_S}{Z1_L}\right) + 1}$$

Ground

$$V_{RELAY\_LG} = \frac{E_{S\_LN}}{\left(\frac{Z_S}{Z_L}\right) + 1}$$

Z_S is $2 \bullet Z1_S + Z0_S$

Z_L is $2 \bullet Z1_L + Z0_L$

Developments for line protection guide

IEEE Std C37.113-2015 (~2000 to 2020)

Drivers:

- Microprocessor-based relays gaining popularity
- Ground distance protection more accessible and widely applied
- Short-circuit programs starting to be used

Challenge:

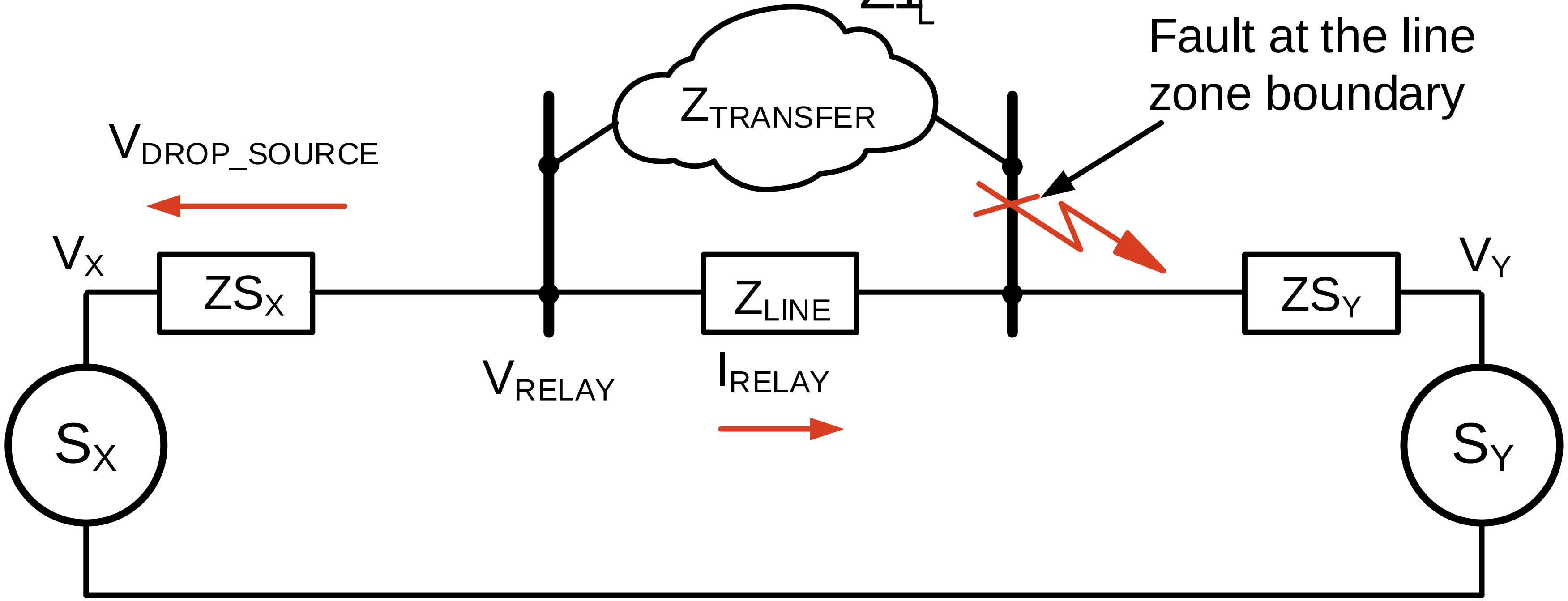
- Meshed systems with parallel paths

Developments for line protection guide

IEEE Std C37.113-2015 (~2000 to 2020)

$$ZS_{3PH} = \frac{V_{DROP\_SRC}}{I_{RELAY}} = \frac{V_{BASE\_LN} - V_{RELAY}}{I_{RELAY}}$$

$$SIR_{3PH} = \frac{ZS_{3PH}}{Z1_L}$$

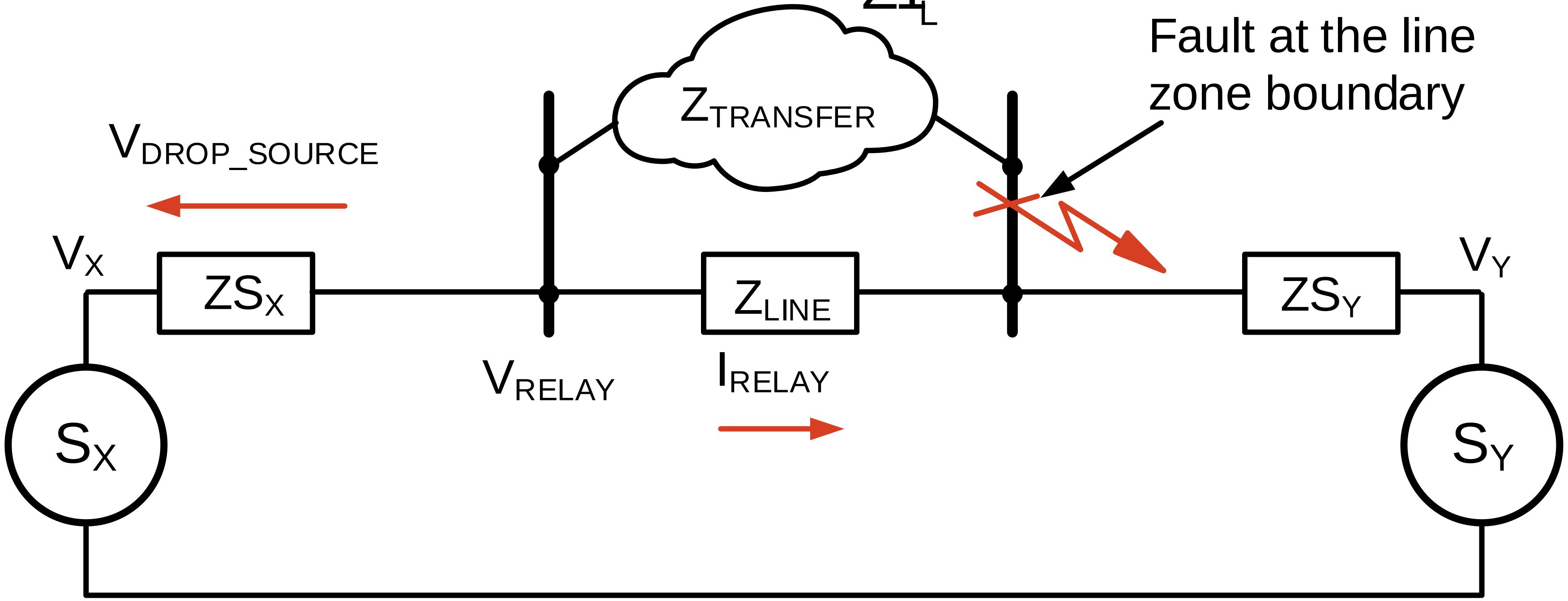


Developments for line protection guide

IEEE Std C37.113-2015 (~2000 to 2020)

$$ZS_{SLG} = \frac{V_{DROP\_SRC}}{I_{RELAY}} = \frac{V_{BASE\_LN} - V_{RELAY}}{I_{RELAY} + k_0 \bullet 3I0_{RELAY}}$$

$$SIR_{SLG} = \frac{ZS_{SLG}}{Z1_L}$$



Modern improvements (since 2020)

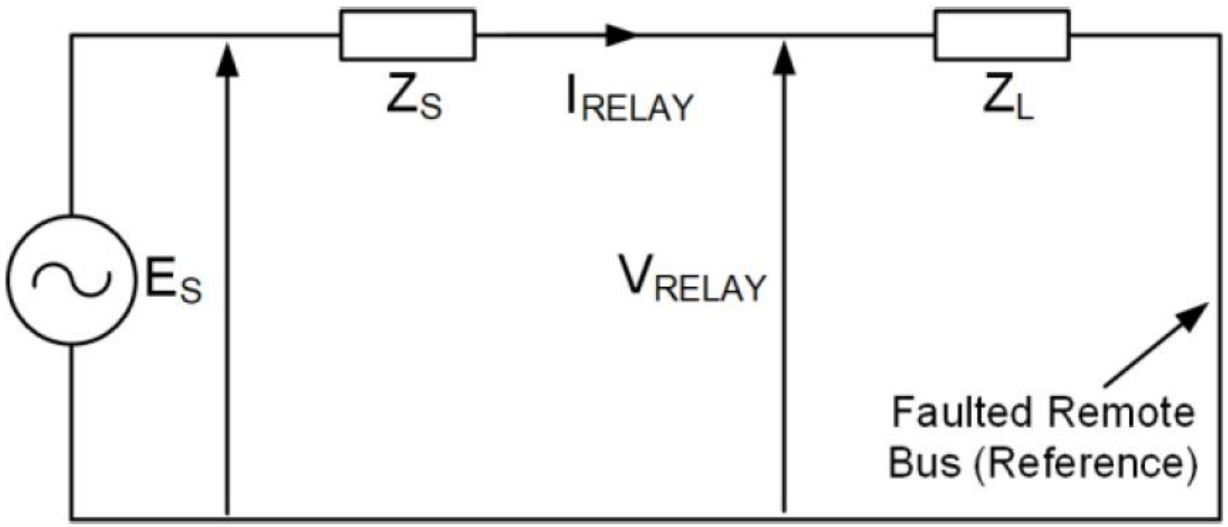
$$V_{RELAY} = E_S \bullet \frac{Z_L}{Z_S + Z_L}$$

$$V_{RELAY} = E_S \bullet \frac{1}{\left(\frac{Z_S}{Z_L}\right) + 1}$$

$$V_{RELAY} = E_S \bullet \frac{1}{SIR + 1}$$

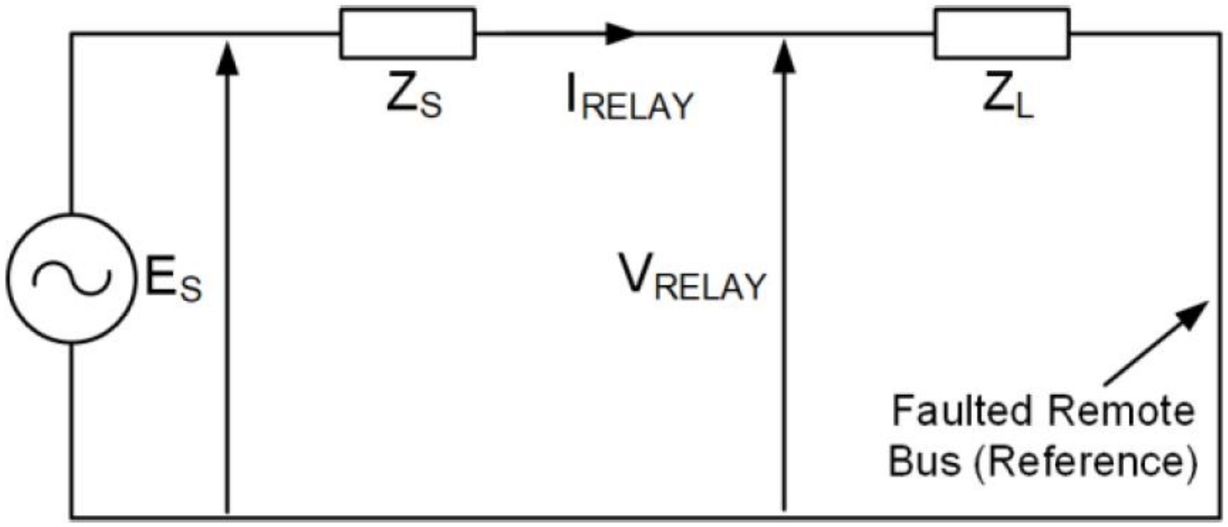
$$SIR + 1 = \frac{E_S}{V_{RELAY}}$$

$$SIR = \frac{E_S}{V_{RELAY}} - 1$$



Modern improvements (since 2020)

$$SIR = \frac{E_S}{V_{RELAY}} - 1$$



Phase

$$SIR_P = \frac{V_{BASE}}{V_{RELAY\_LL}} - 1$$

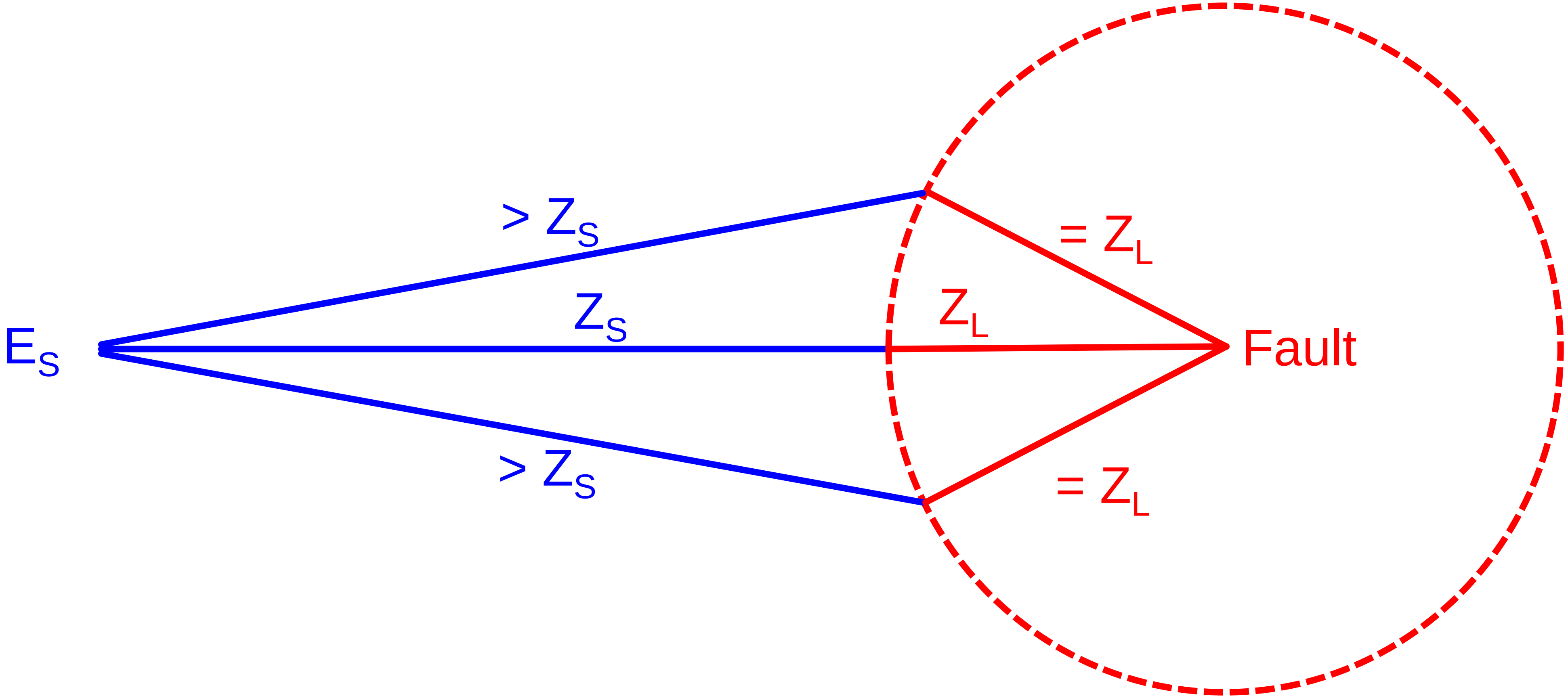
Ground

$$SIR_G = \frac{V_{BASE}}{\sqrt{3} \cdot V_{RELAY\_LG}} - 1$$

Uses loop voltage directly as used by the 21P element (V_{LL}) and 21G element (V_{LG})!

Modern improvements (since 2020)

System nonhomogeneity



Mutual coupling

Line protection guide (~2000 to 2020)

Inaccurate denominator in mutually-coupled lines

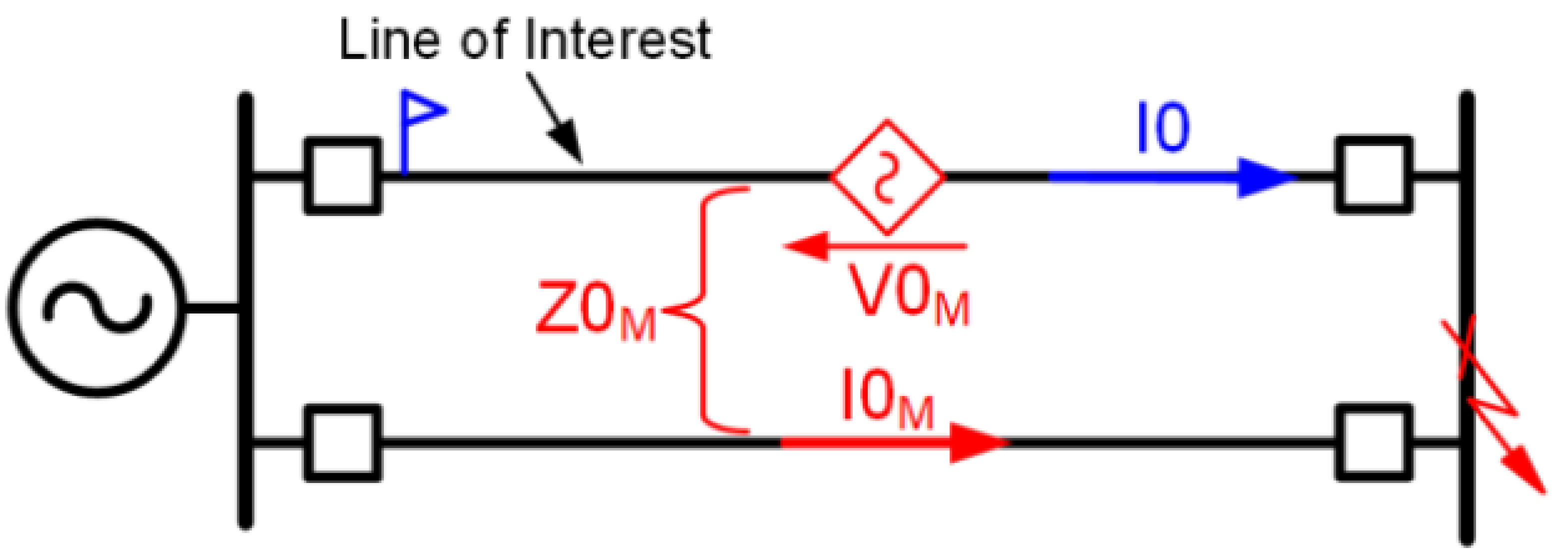
$$ZS_{SLG} = \frac{V_{DROP\_SRC}}{I_{RELAY}} = \frac{V_{BASE\_LN} - V_{RELAY}}{I_{RELAY} + k_0 \cdot 3I0_{RELAY}}$$

$$SIR_{SLG} = \frac{ZS_{SLG}}{Z1_L}$$

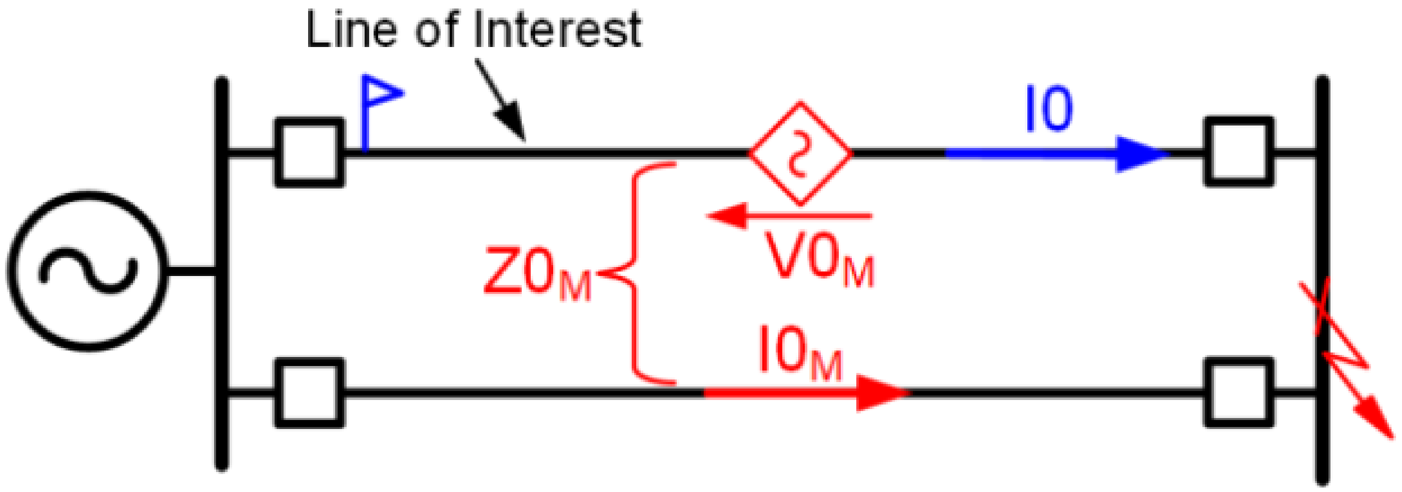
$$V_{RELAY\_LG} = Z1_L \cdot \left(I_{RELAY} + k_0 \cdot 3I0_{RELAY}\right)$$

$$V_{RELAY\_LG\_MC} = Z1_L \cdot \left(I_{RELAY} + k_0 \cdot 3I0_{RELAY}\right) + V0_M$$

$$V0_M = Z0_M I0_M$$



Line protection guide (~2000 to 2020)

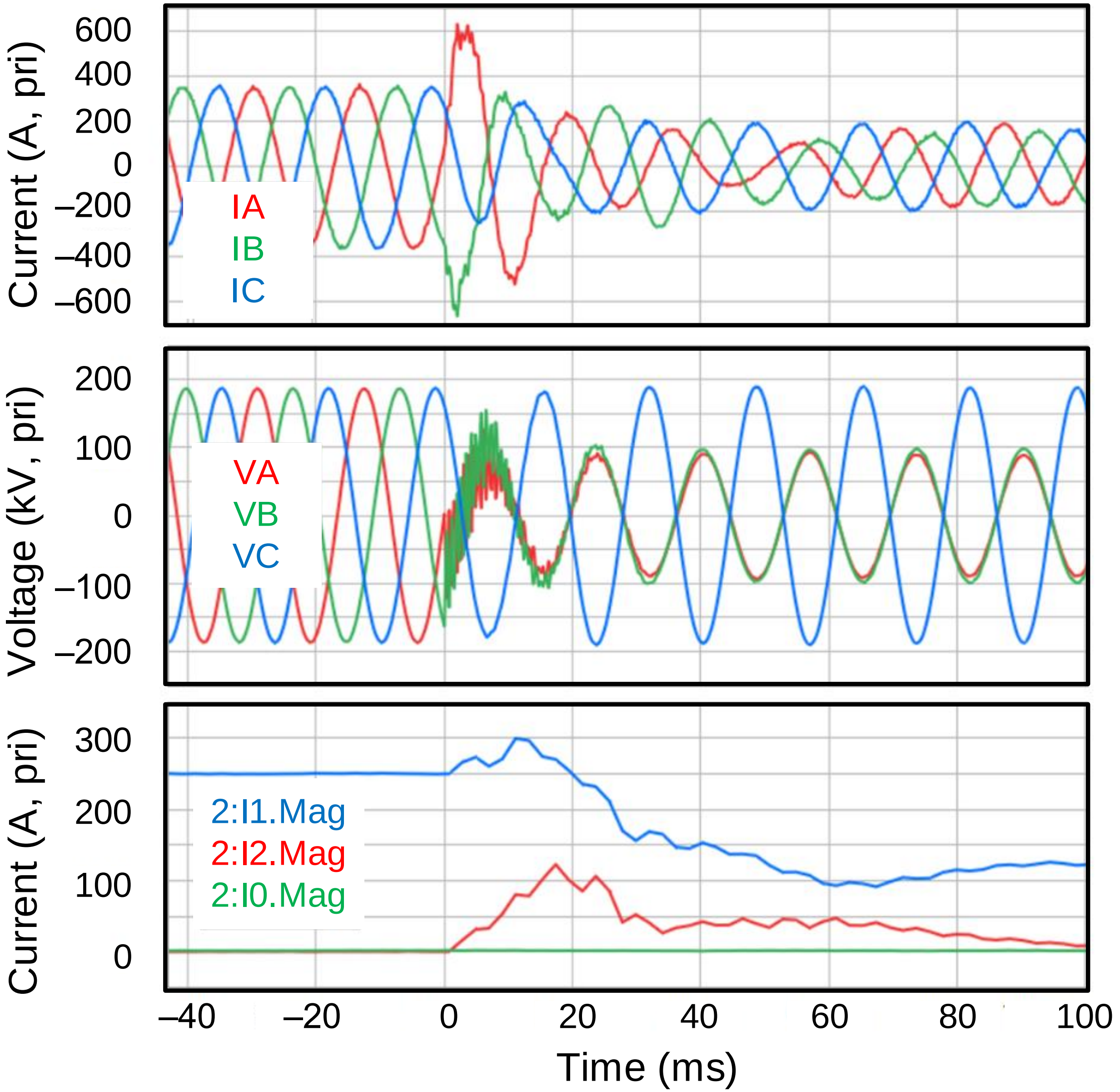


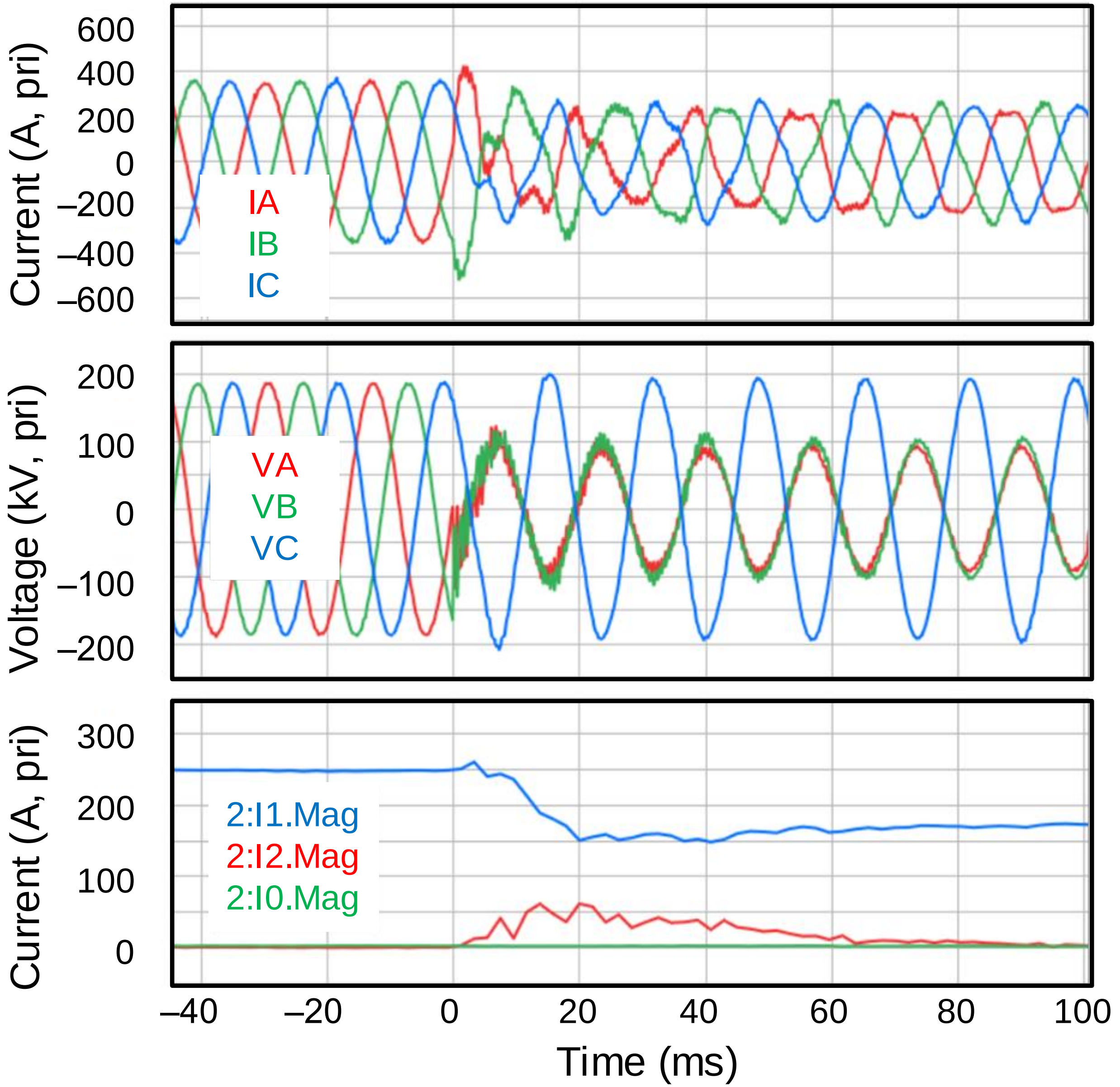
SOURCE IMPEDANCE RATIOS FOR GROUND FAULTS:					
	OUTAGE	Vdrop (V)	Irelay (A)	Vdrop/Irelay (ohm)	SIR
	None	61861.9	1290.41	47.9397	5.054

- Using relay voltage equation gives an SIR of 3.463!
- Approximately 50 percent error!

Inverter-based resources

IBR OEMs real code model response

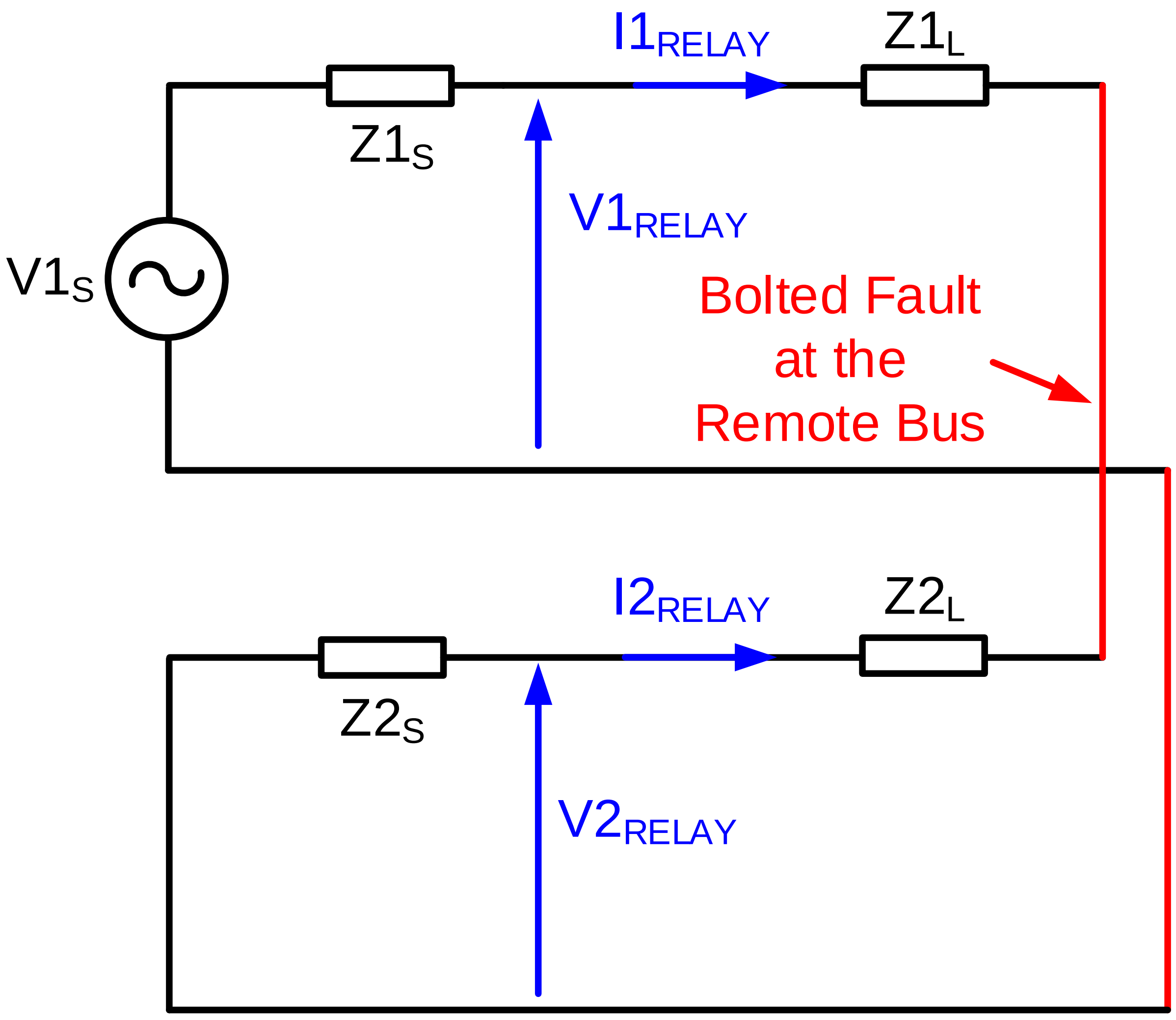




SIR_P for LL and 3P faults

$$\frac{V_{RELAY\_LL(LL\ FAULT)}}{V_{RELAY\_LL(3P\ FAULT)}} = \frac{Z1_S + Z1_L}{\left(\frac{Z1_S + Z2_S}{2}\right) + Z1_L}$$

- If $Z_{1S} = 10 \bullet Z_{1L}$ and $Z_{2S} = 10 \bullet Z_{1S}$,
  - * $SIR_{P(3P\_FAULT)} = 10$
  - * $SIR_{P(LL\_FAULT)} = 50.9!$
- Consider LL faults also to calculate SIR_P!



SIR compared to synchronous generators

- Synchronous Generators $X''_S = 0.10$ to 0.65 pu.
  With GSU (0.05 to 0.20 pu) $X''_{GEN\_PLANT} = 0.15$ to 0.85 pu
- IBRs I_{MAX} ~1.1 to 1.3 pu => $Z_S \gtrapprox 0.75$ pu.
  Including collector system impedance and GSU impedance:
  - Non-standardized IBRs limit I_2 => $Z_{IBR\_PLANT} \gtrapprox 3 \bullet X''_{GEN\_PLANT}$
  - Standardized IBRs provide I_2 => $Z_{IBR\_PLANT} \gtrapprox 2 \bullet X''_{GEN\_PLANT}$
- IBR modeling in short-circuit programs is an ongoing effort:
  - Tabular format with current-voltage pairs has been considered
  - IBR OEMs are working on DLLs for use in short-circuit programs

Estimate SIR without use of models

$$\text{Line Length} > \frac{V_{BASE}^{2}}{S_{IBR}} \bullet \frac{Z_{PLANT\_PU}}{SIR_{MAX} + Z1_{L\_PL}}$$

- 500 kV line with Z_{1L} = 0.5 Ω/mile. Interconnecting 500 MVA IBR plant has an impedance of 1.2 pu. Using this equation for an SIR_{MAX} of 4, the minimum line length is 300 miles.
- 115 kV line with Z_{1L} = 0.8 Ω/mile. Interconnecting 50 MVA IBR plant has an impedance of 2 pu. Using this equation for an SIR_{MAX} of 4, the minimum line length is 165 miles.

Improve Zone 1 security because of high SIR

Reduce reach and/or add time-delays

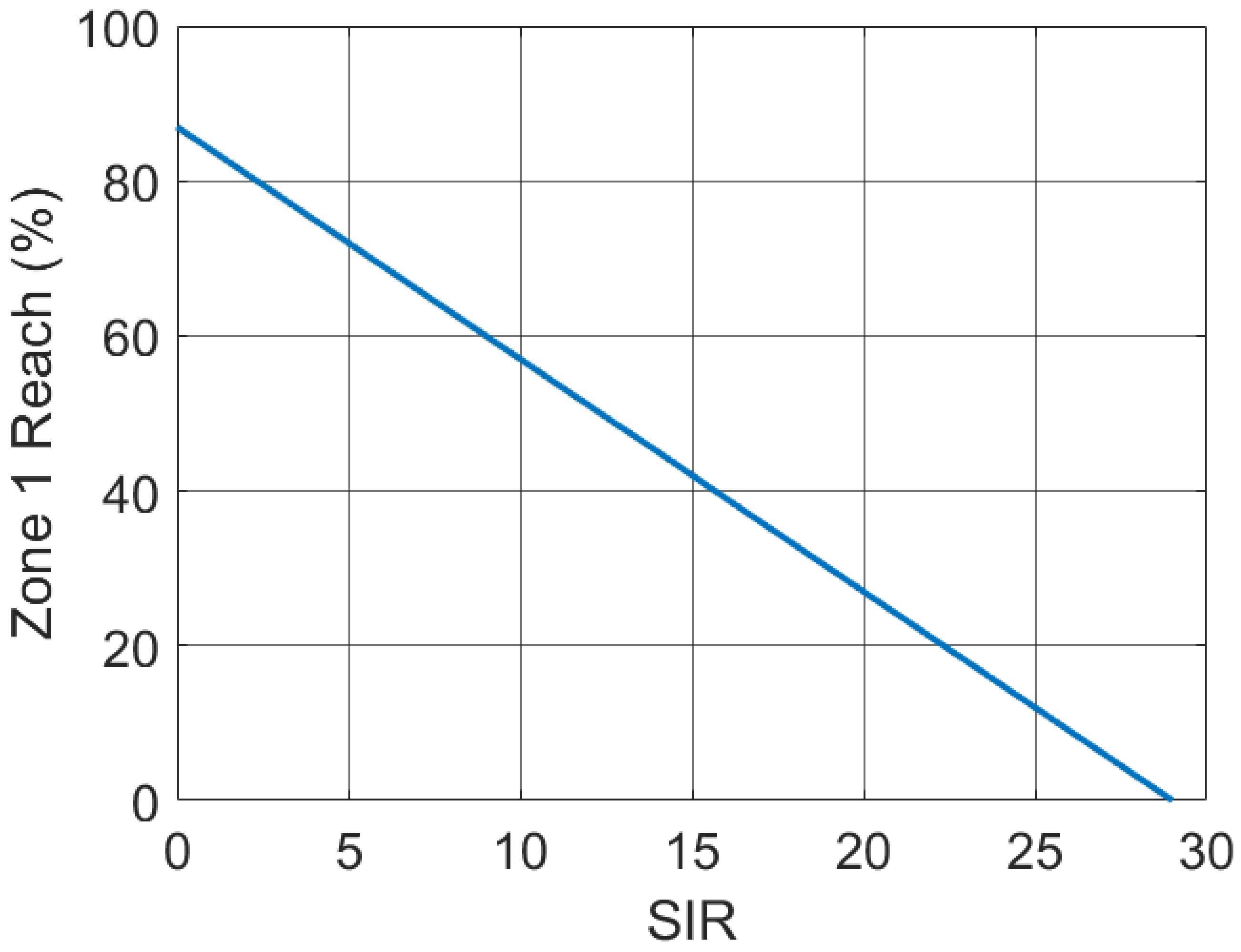
- $m_1 < m_{1RATIO} – E_{SS} \bullet (SIR + 1)$

  m_1 = Secure reach considering SIR

  m_{1RATIO} = Reach considering Ratio Errors (e.g., 0.90 pu)

  E_{SS} = Steady-state Error (e.g., 0.03 pu)

- Consider CCVT transient errors
- Use communications-assisted protection for very high SIR



Conclusion

- SIR corresponds to the relay voltage
- Newer and simpler SIR calculations use just relay voltage

$$SIR_G = \frac{V_{BASE}}{\sqrt{3} \bullet V_{RELAY\_LG}} - 1$$ (Accurate for mutually-coupled lines)

$$SIR_P = \frac{V_{BASE}}{V_{RELAY\_LL}} - 1$$ (Accurate for IBRs)

- Consider line-to-line faults in addition to three-phase faults
- Greater reliance on communications-assisted protection

Questions?