Protecting Mutually Coupled Transmission Lines: Challenges and Solutions

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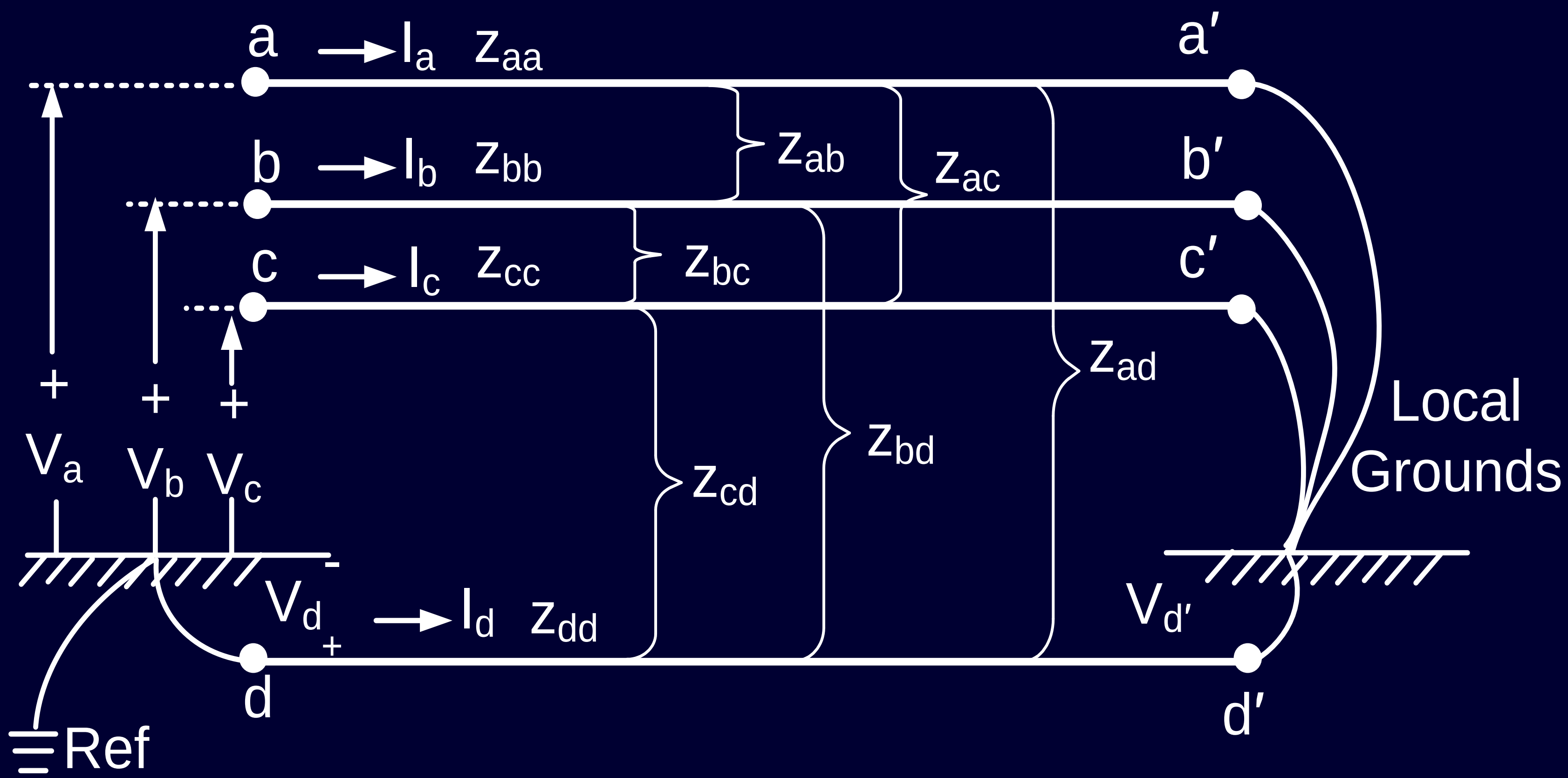
Introduction

- Transmission line protection principles
- Mutually coupled transmission lines
- Directional element polarization problems
- Distance element reach errors
- Current differential scheme behavior
- Double-circuit lines operated as single circuit

Transmission Line Protection Principles

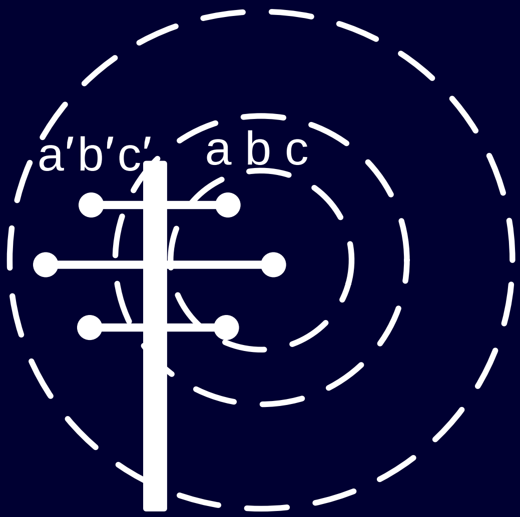
- Directional overcurrent
- Distance
- Directional comparison
- Current differential

Transmission Line Impedances



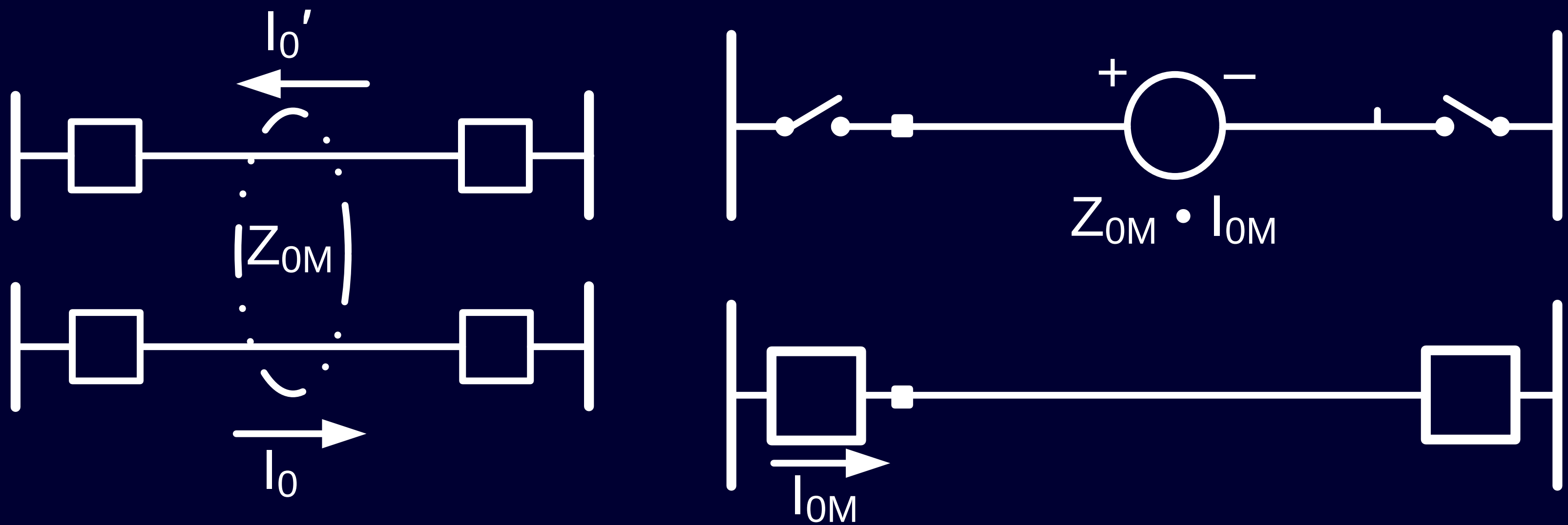
$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

Two Mutually Coupled Lines



- Positive- and negative-sequence currents add to zero
- Zero-sequence magnetic flux links the coupled line

Zero-Sequence Mutual Impedance Modeling



Zero-sequence current on one line induces zero-sequence voltage along coupled line

Mutually Coupled Transmission Lines

$$\left[Z_{SEQ}\right] = \begin{bmatrix} Z_{00} & 0 & 0 & Z_{0M} & 0 & 0 \\ 0 & Z_{11} & 0 & 0 & 0 & 0 \\ 0 & 0 & Z_{22} & 0 & 0 & 0 \\ Z_{0M} & 0 & 0 & Z_{00}^{'} & 0 & 0 \\ 0 & 0 & 0 & 0 & Z_{11}^{'} & 0 \\ 0 & 0 & 0 & 0 & 0 & Z_{22}^{'} \end{bmatrix}$$

Regardless of transpositions,
Z_{0M} is always present

Ground Directional Elements (67N)

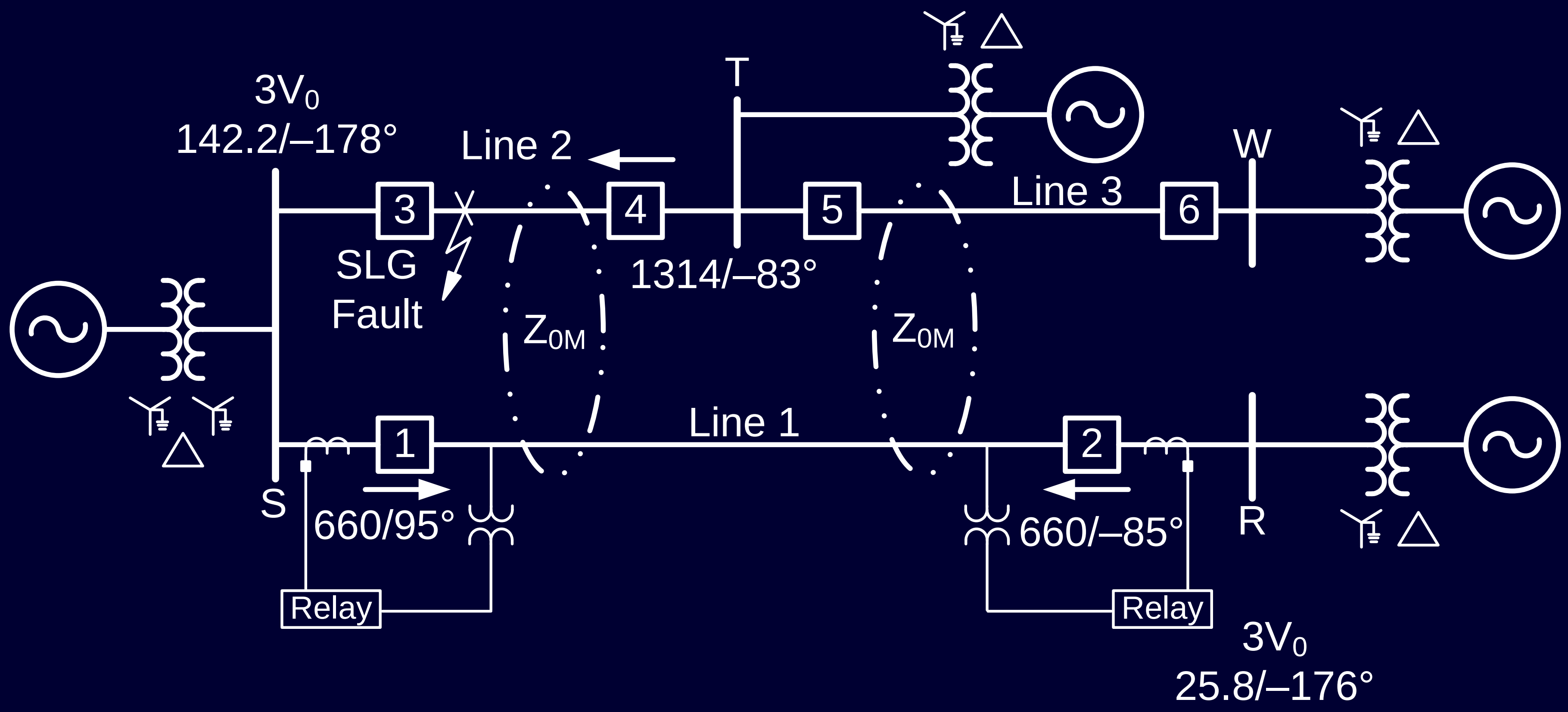
Performing phase comparison

$$T = \mathrm{Re}\left[\left(S_{POL}\right)\left(I_{OP} \bullet 1\angle\phi_{MS}\right)^{*}\right]$$

Measuring sequence impedances

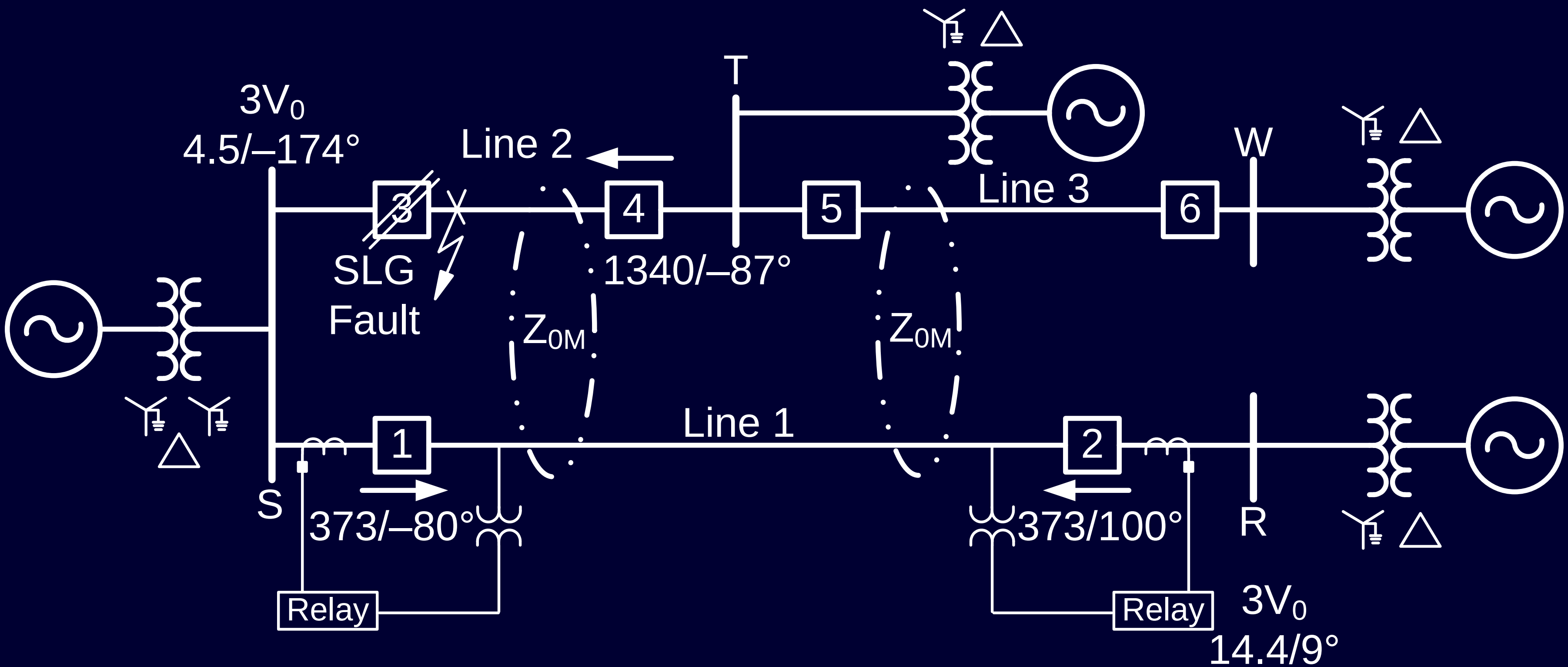
$$z_2 = \frac{\mathrm{Re}\left[V_2\left(I_2 \bullet 1\angle\phi_{MS2}\right)^{*}\right]}{\left|I_2\right|^2}$$

Polarization Problems



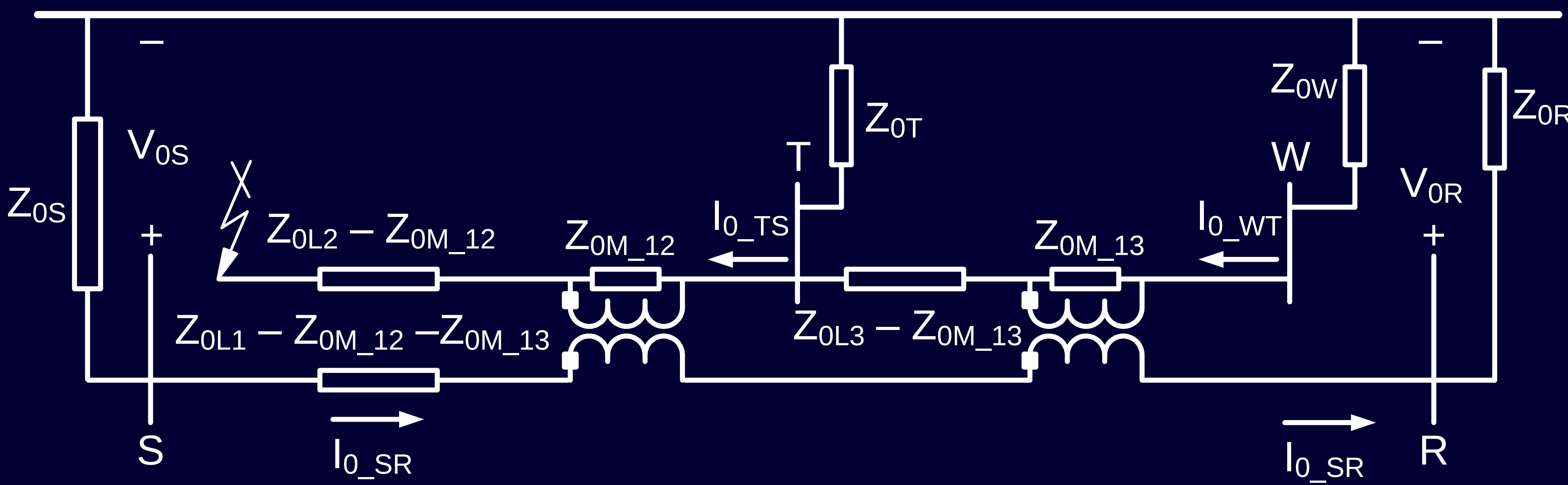
67N elements perform properly when electrical connection is strong

Polarization Problems



- Breaker 3 opens and isolates zero-sequence networks
- Line 1 could trip for external fault

Polarization Problems

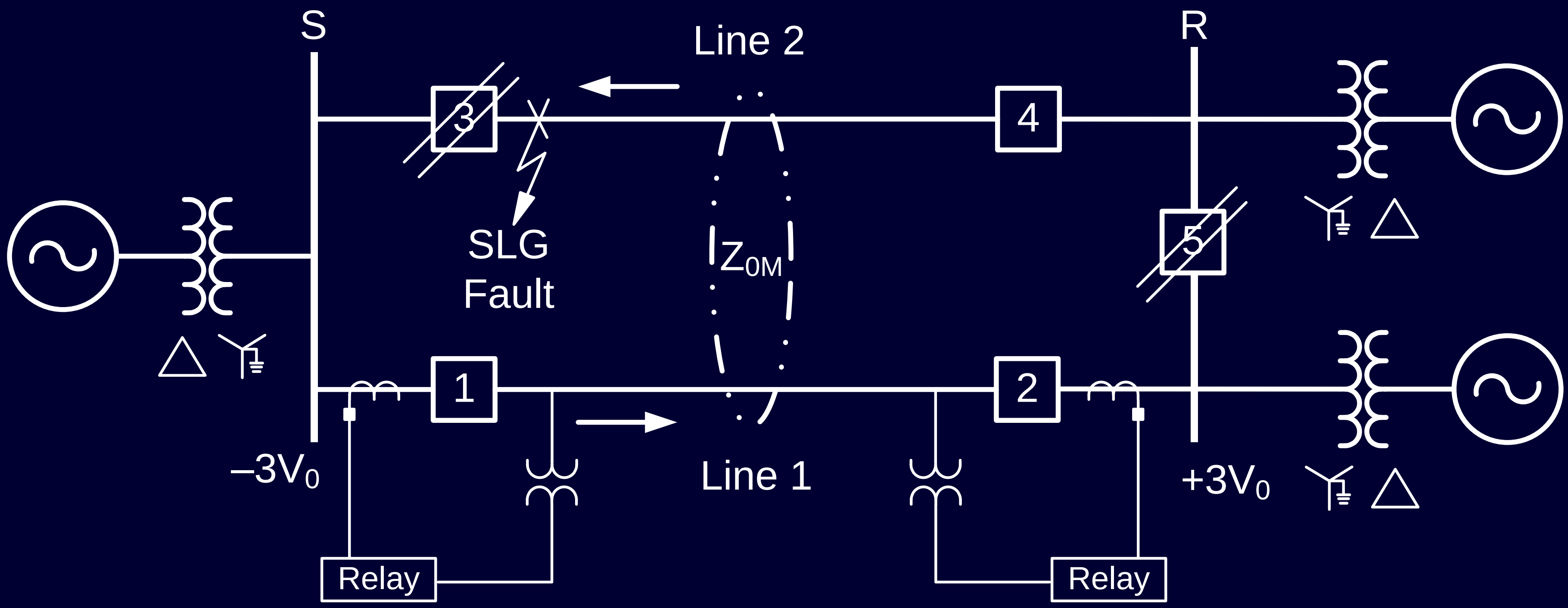


$V_{0S} = -I_{0\_SR}\, Z_{0S}$

$V_{0R} = I_{0\_SR}\, Z_{0R}$

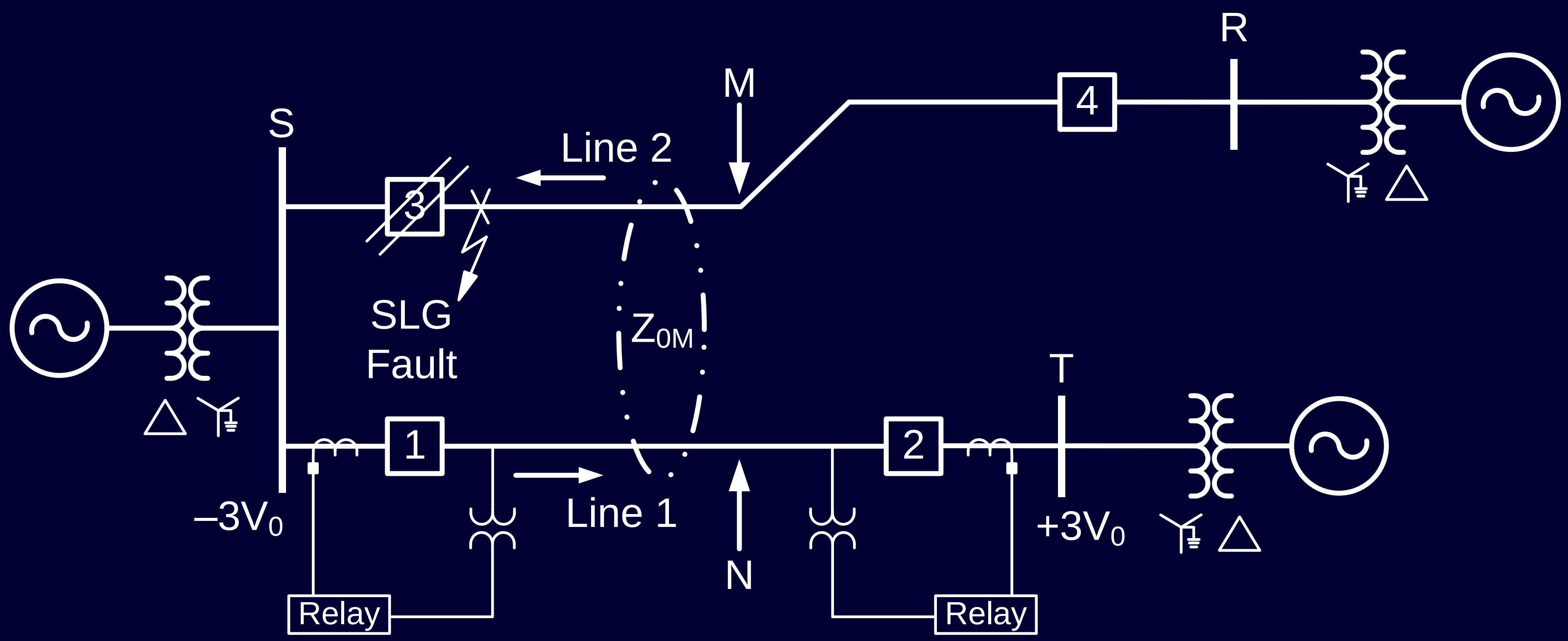
- Mutual coupling causes zero-sequence quantity reversal
- Wrong directional decision at R

Polarization Problems



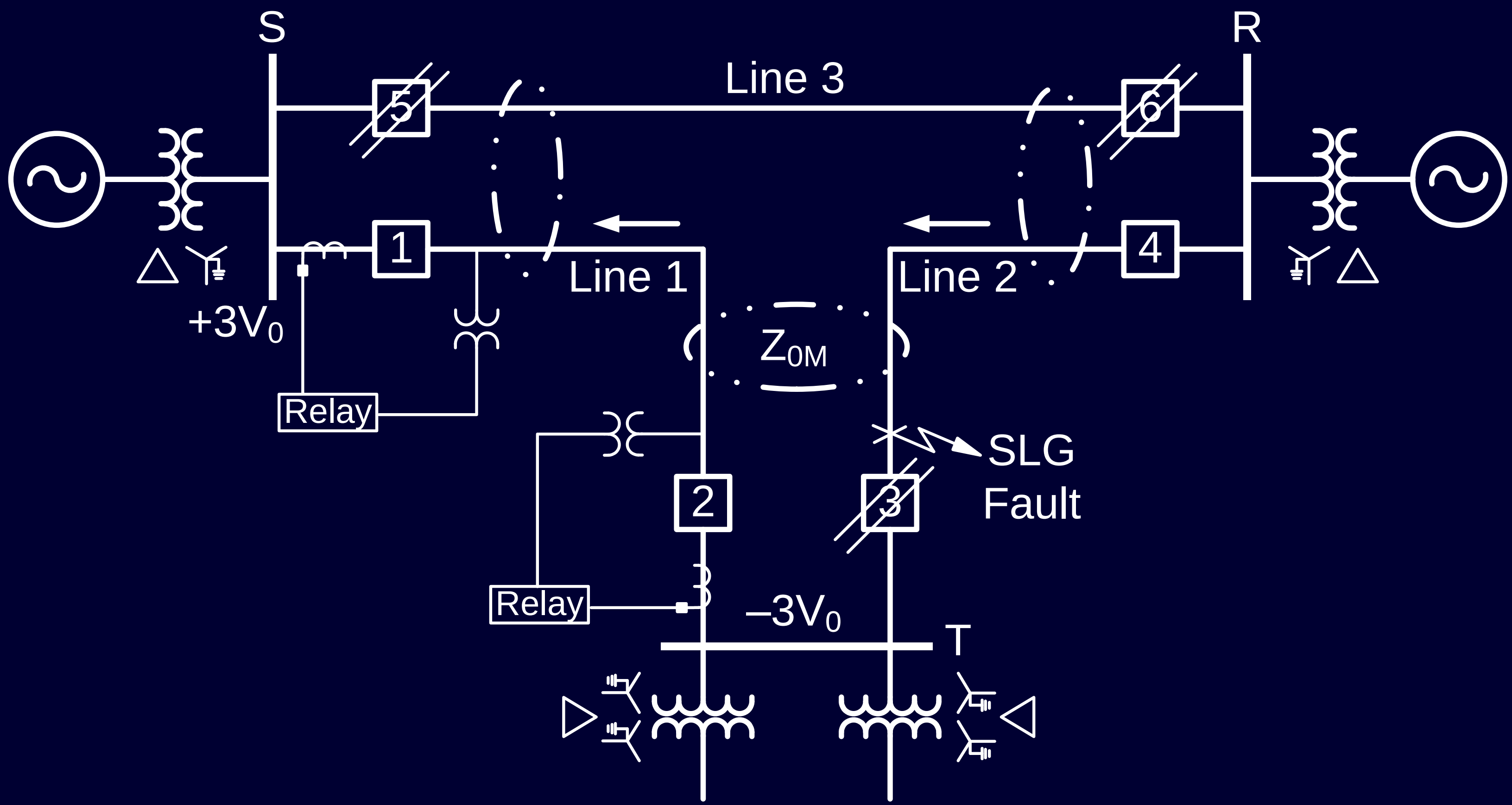
- Coupler breaker open – Breaker 3 opens and isolates the zero-sequence networks
- Wrong directional decision at R

Polarization Problems



- Breaker 3 opens and isolates the zero-sequence networks
- Wrong directional decision at T

Polarization Problems



- Line 3 out of service – Breaker 3 opens and isolates the zero-sequence networks
- Wrong directional decision at S

Polarization Solutions

- Using negative-sequence directional elements
- Supervising ground directional comparison schemes with negative-sequence overcurrent elements
- Applying current differential schemes

Ground Instantaneous Overcurrent Element Settings

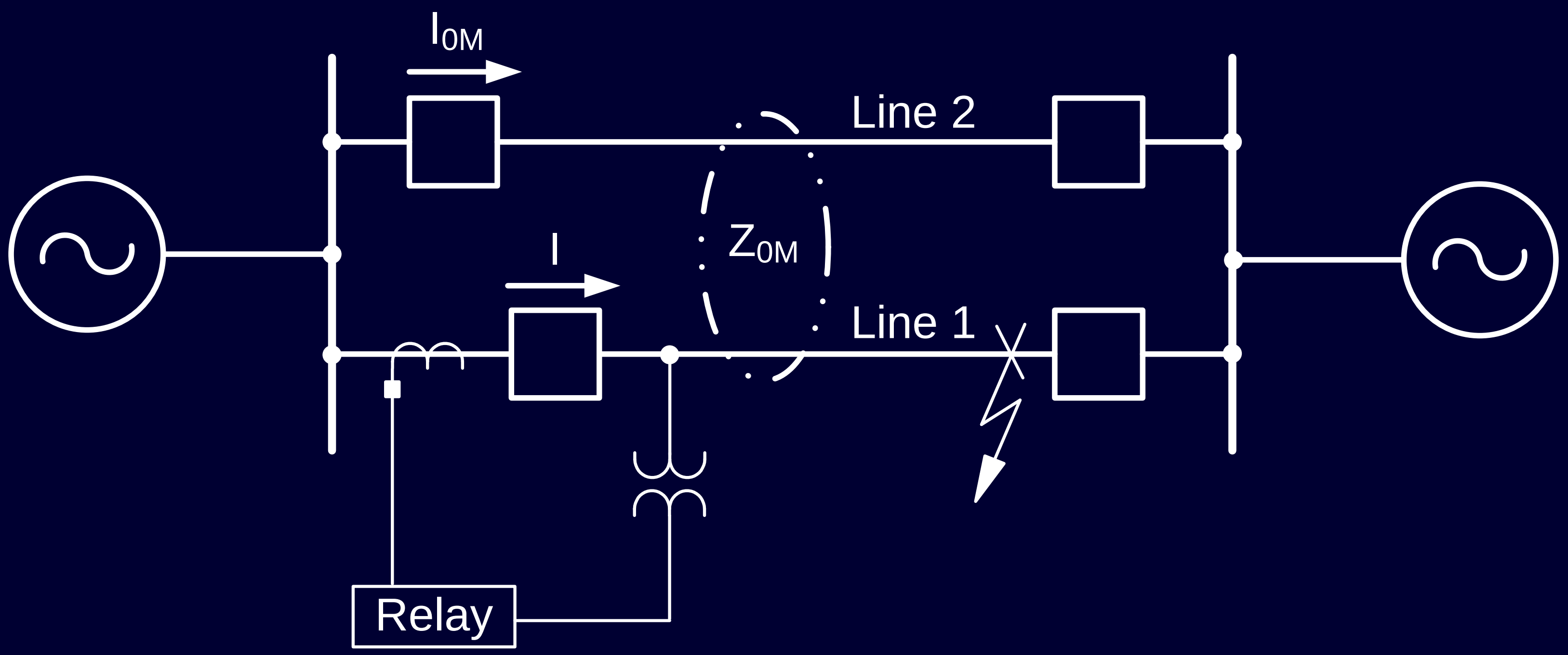
- Extensive short-circuit studies
  - Strongest system behind relay
  - SLG fault at remote bus removing ground sources
  - SLG fault at remote bus removing parallel line
  - SLG fault at open end of parallel line
- Maximum fault current of different scenarios: $I_{SET} = 1.25\ I_{FLT\ MAX}$

Input Signals to Traditional Ground Distance Elements

Element	Voltage	Current
AG	V_a	$I_a + k_0 \, I_r$
BG	V_b	$I_b + k_0 \, I_r$
CG	V_c	$I_c + k_0 \, I_r$

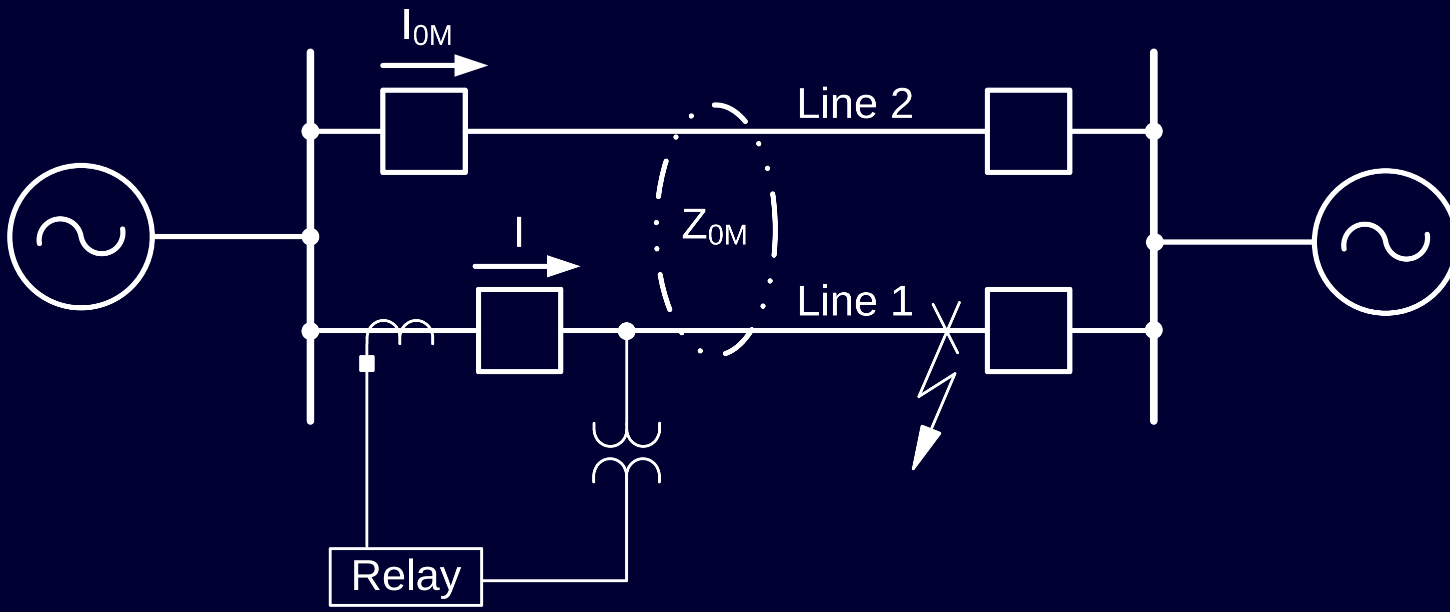
$$k_0 = \frac{Z_{0L} - Z_{1L}}{3Z_{IL}} \qquad I_r = I_a + I_b + I_c$$

Impact of Mutual Coupling



$$V_a = mZ_{1L}\left(I_a + k_0\ I_r\right) + mZ_{0M}\ I_{0M}$$

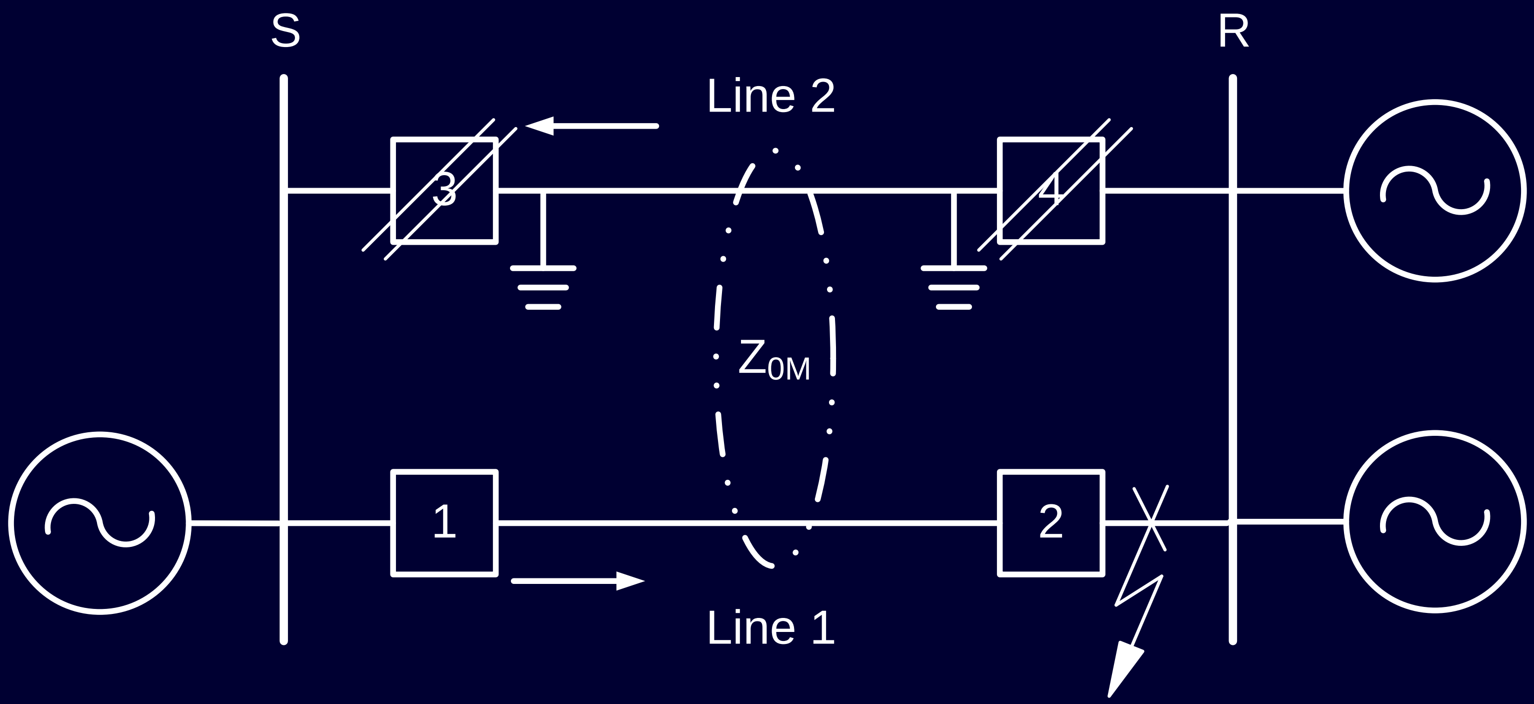
Mutual Coupling Affects Reach



$$Z_{APP} = \frac{V_a}{I_a + k_0 \; I_r} = mZ_{1L} + mZ_{0M} \frac{I_{0M}}{I_a + k_0 \; I_r}$$

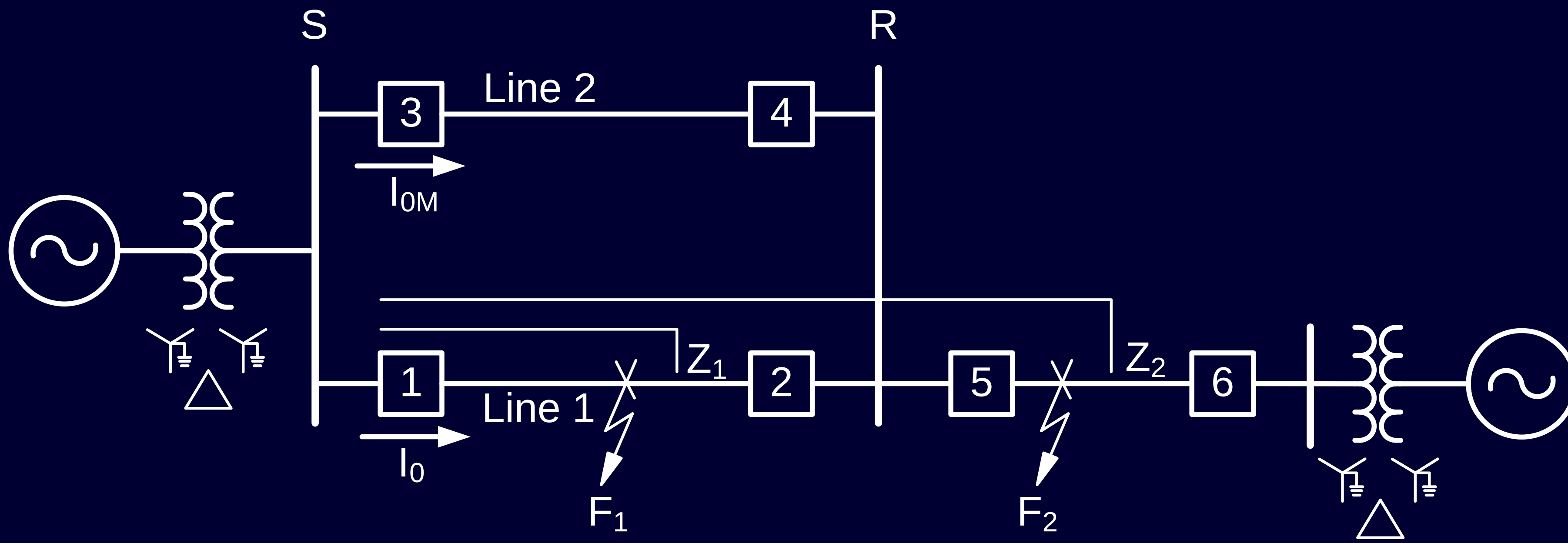
- Underreach if I_{0M} and I_0 in same direction
- Overreach if I_{0M} and I_0 in opposite directions

Another Cause of Reach Errors



- Parallel line grounded at both ends
- Zone 1 may overreach

Solutions: Applying Reach Settings



- Zone 1 should never overreach
- Zone 2 and other overreaching zones should never underreach

Solutions: Applying Reach Settings

Measured Impedances for Different Switching States of the Coupled Line

State of Coupled Line	Measured Impedance
In service	$Z_{APP} = Z_{1L} + \frac{Z_{0M}}{3(1+k_0)}$
Out of service and grounded at one point or not grounded	$Z_{APP} = Z_{1L}$
Out of service and grounded at both line ends	$Z_{APP} = Z_{1L} - \frac{Z_{0M}^2}{3Z_{0L}(1+k_0)}$

Solutions: Using I_{0M}

$$V_a = mZ_{1L}\left(I_a + k_0\, I_r + \frac{Z_{0M}}{Z_{IL}} I_{0M}\right)$$

- Compromises relay security during external faults in coupled line
- I_{0M} is not always available
- Increases wiring complexity
- Is not widely accepted

Solutions: Applying k_0 Settings

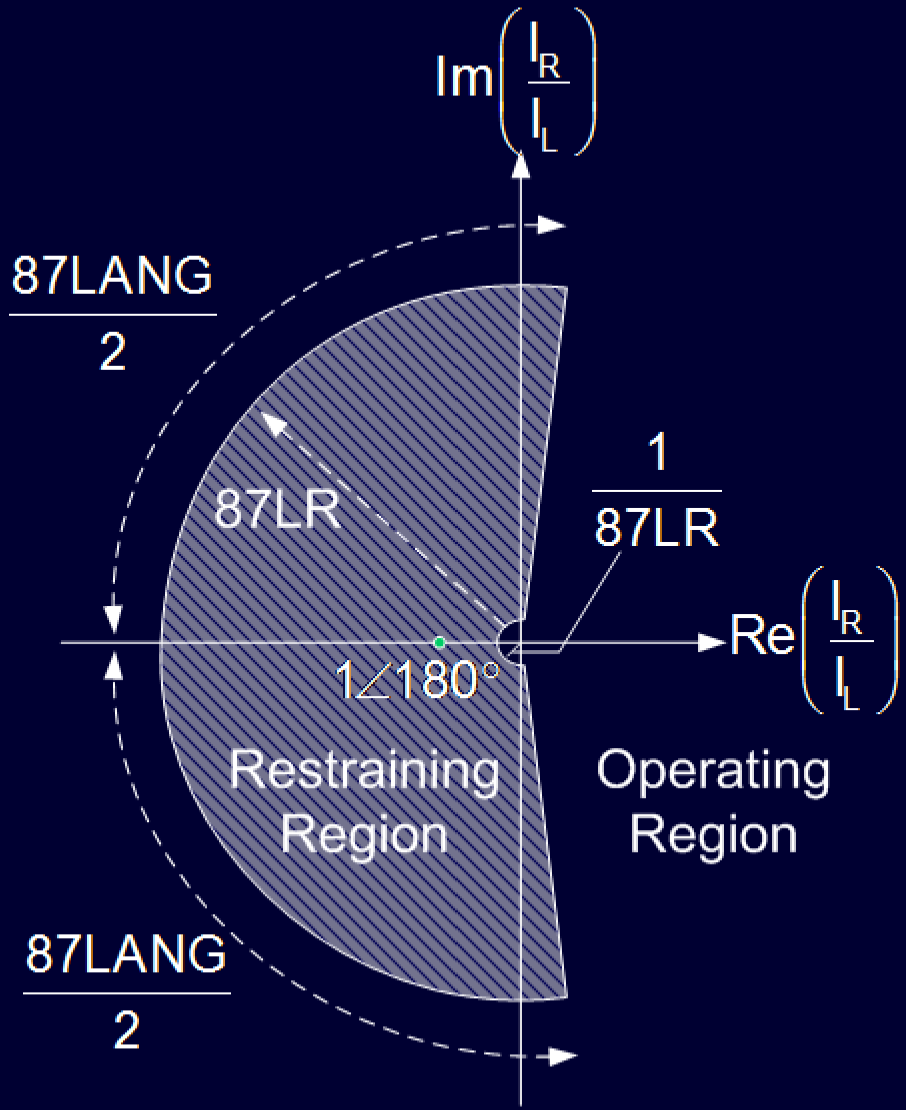
State of Coupled Line	Measured Impedance
In service	$k_0' = \dfrac{Z_{0L} - Z_{1L} + Z_{0M}}{3Z_{IL}}$
Out of service and grounded at one point or not grounded	$k_0 = \dfrac{Z_{0L} - Z_{1L}}{3Z_{IL}}$
Out of service and grounded at both line ends	$k_0'' = \dfrac{Z_{0L} - Z_{1L} - \dfrac{Z_{0M}^{\ 2}}{Z_{0L}}}{3Z_{IL}}$

- Prevents Z_1 overreach and Z_2 underreach
- Is applicable for lines connected in parallel

Fault Locating Algorithms

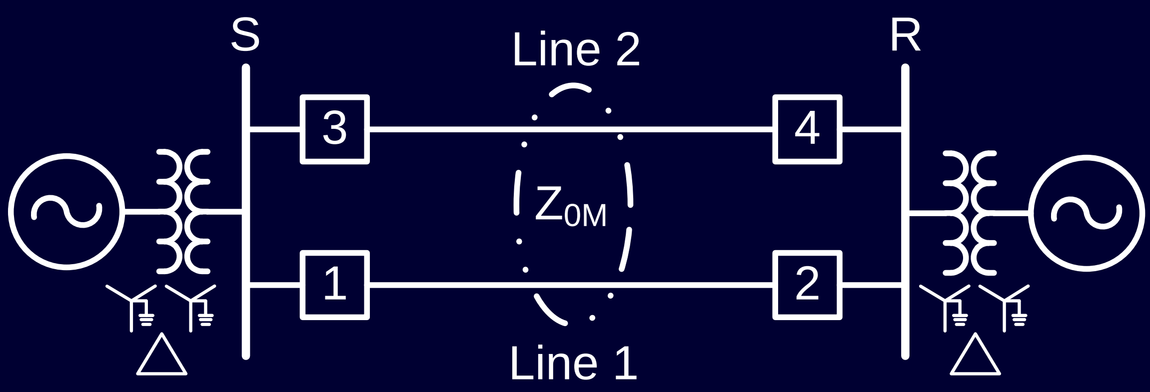
- Zero-sequence single-ended algorithms not using I_{0M} have errors
- Solutions
  - Obtain I_{0M} via relay-to-relay communications
  - Use negative-sequence multi-ended algorithms
  - Use traveling wave algorithms

Line Current Differential Schemes

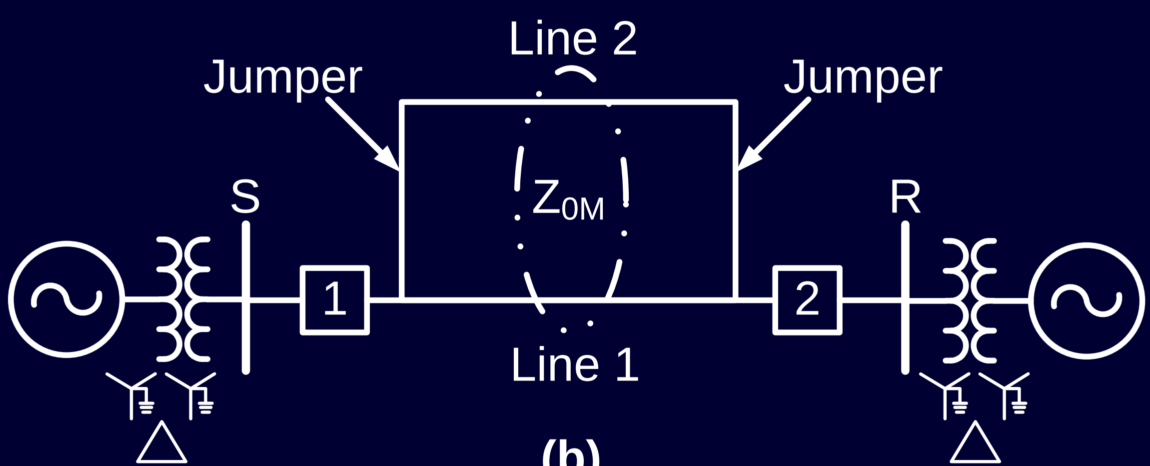


- Not affected by mutual coupling
- Best solution if communications channel available

Double-Circuit Transmission Lines Operated as a Single Circuit



(a)



(b)

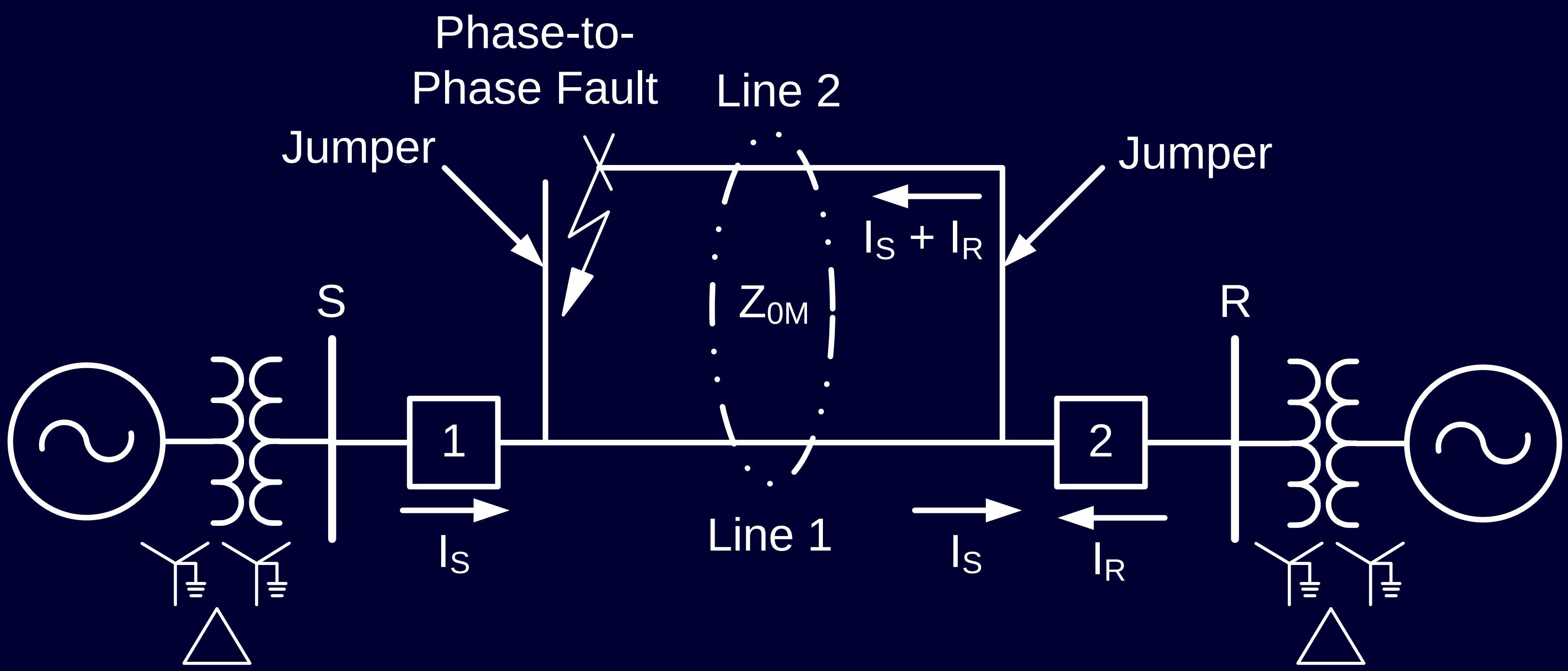
Measured Impedances at Bus S and R

Three-Phase Faults on Line 2

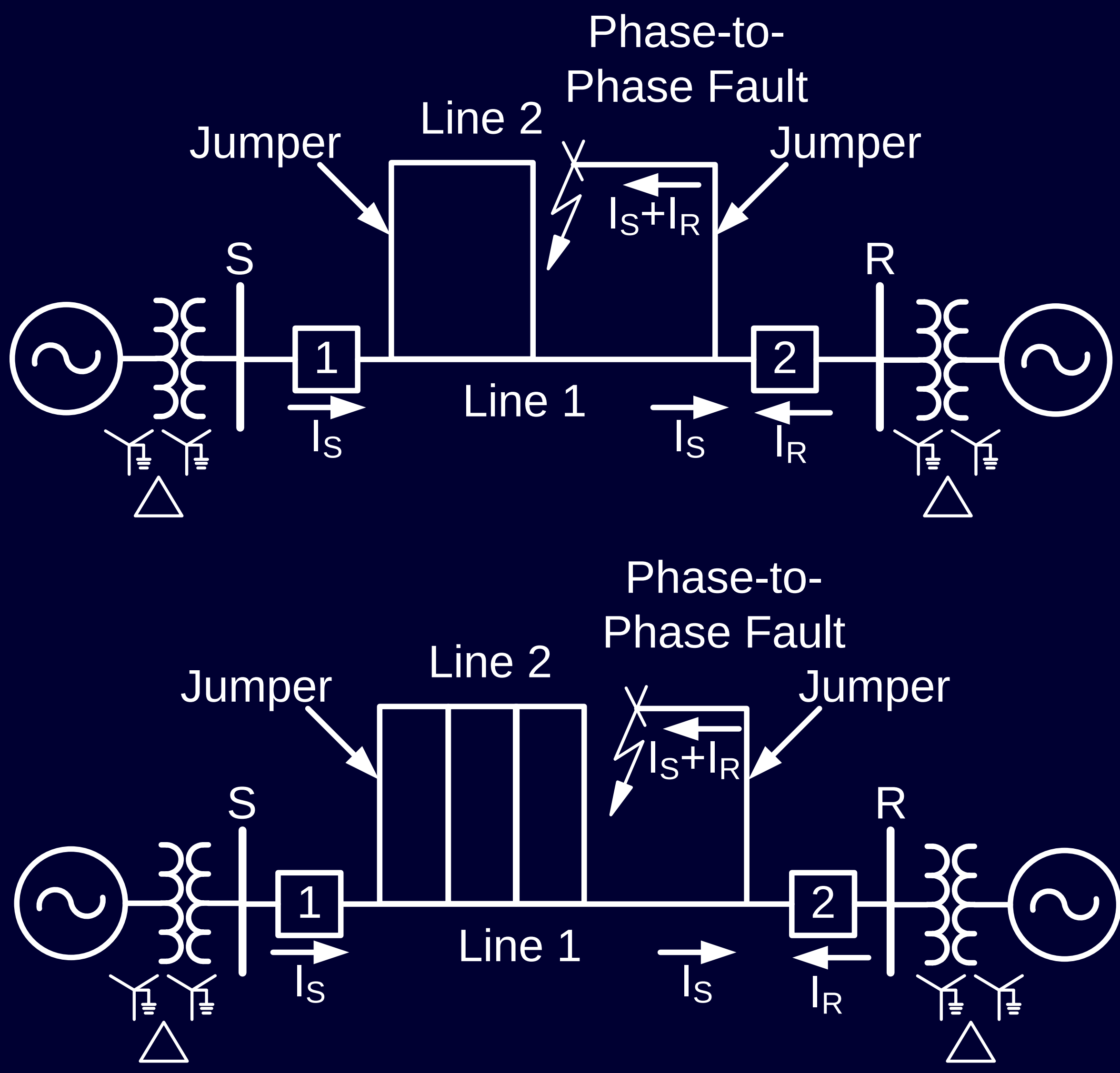
Distance From Bus R (% of Line Length)	Impedance at Bus S (Ohms)	Impedance at Bus R (Ohms)
100	0.0	19.55
90	4.24	25.22
85	6.31	33.22
80	8.35	26.22

$Z_{1L}/2 = 19.5$ ohms

A Challenging Fault for Analyzing Underreach



Additional Jumpers Reduce Underreach



Measured Impedances at Bus S

n Jumpers Placed at Equidistant Points Along the Lines

$$Z_{APP} = Z_{1L}\left(\frac{(n+4)}{2(n+1)} + \frac{2}{2(n+1)}\frac{I_R}{I_S}\right)$$

$$Z_{APP} = \frac{Z_{1L}}{2}\frac{(n+4)}{(n+1)}$$

Conclusions

- Mutual coupling affects zero-sequence polarized ground directional elements
- Negative-sequence polarization is the solution
- Mutual coupling can cause ground distance element under- or overreach
- Distance element compensation methods are difficult to apply

Conclusions

- Zero-sequence single-ended fault locating without I_{0M} information is not accurate
- Operating a double-circuit line as a single circuit with jumpers causes distance element underreach
- Current differential protection is the best solution for mutually coupled lines

Questions?