Practical Considerations When Protecting Mutually Coupled Lines

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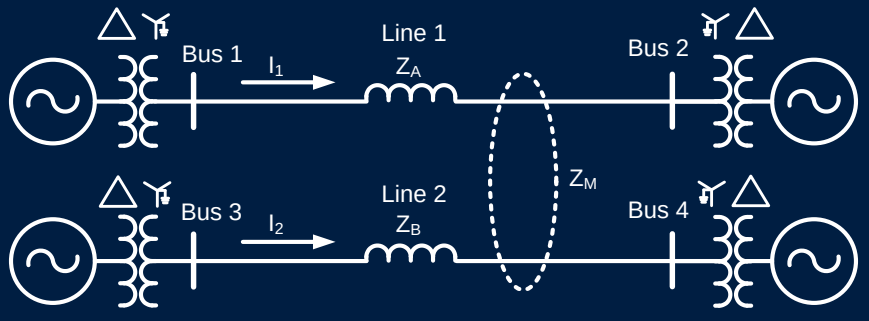
Overview

- What is mutual coupling?
- How is mutual coupling defined?
- What common configurations should be considered?
- What are the adverse affects on protection?
- What happens when settings are misapplied?

Mutual Coupling

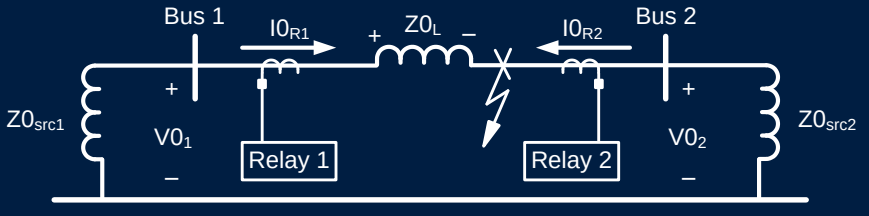
Creates complexities that require simplified network equivalents



$$V_{12} = I_1 \bullet Z_A + I_2 \bullet Z_M$$

$$V_{34} = I_2 \bullet Z_B + I_1 \bullet Z_M$$

Defining Apparent Impedance



Impedance-based directional elements measure behind relay

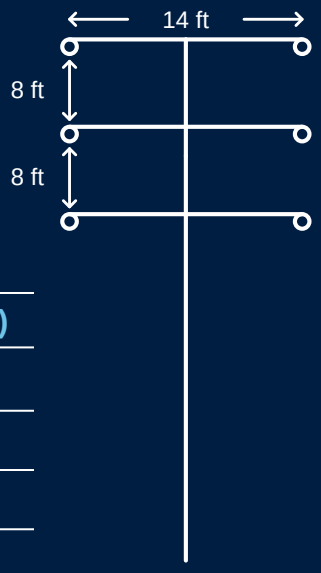
$$Z0S_{APP} = \frac{\mathrm{Re}\left[3V_0 \bullet (I_G \bullet 1\angle Z0ANG)^*\right]}{|I_G|^2}$$

Distance elements measure in front of relay

$$Z_{APP} = \frac{V_A}{I_A + k0 \bullet 3I0}$$

Defining Coupling Strength

$$\%M = \left| \frac{Z0M}{Z0L} \right| \cdot 100$$

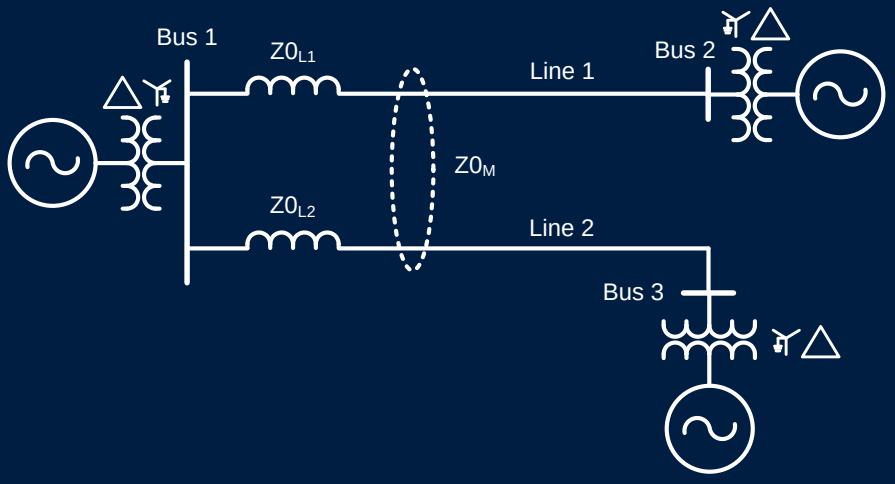


Scenario	Proximity (feet)	Z0M / Z0L (%)
1	14 (shared tower separation)	69
2	114	44
3	214	36

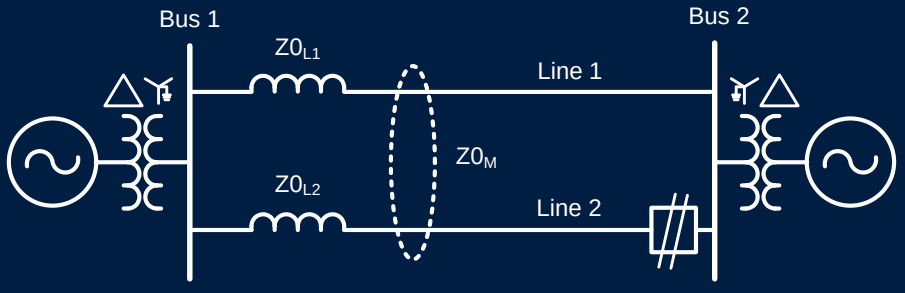
System Configurations

1. Single common bus
2. No common bus (electrically isolated systems in zero-sequence network)
3. Common buses
4. Mutually coupled line out of service and ungrounded (not analyzed)

Configuration 1
Natural

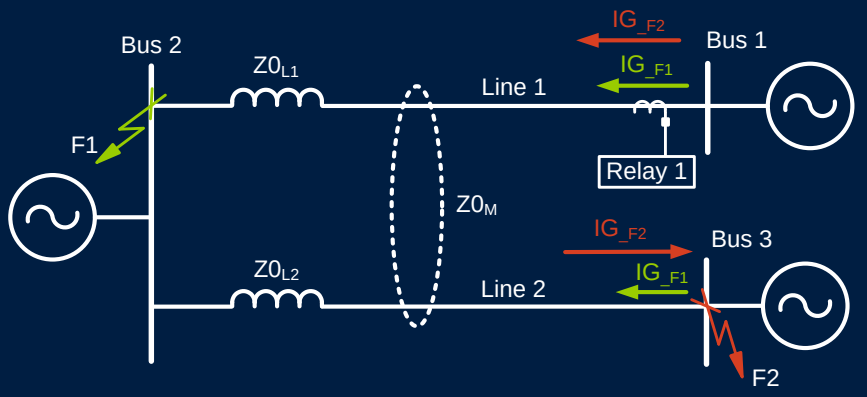


Configuration 1
By Breaker Operation

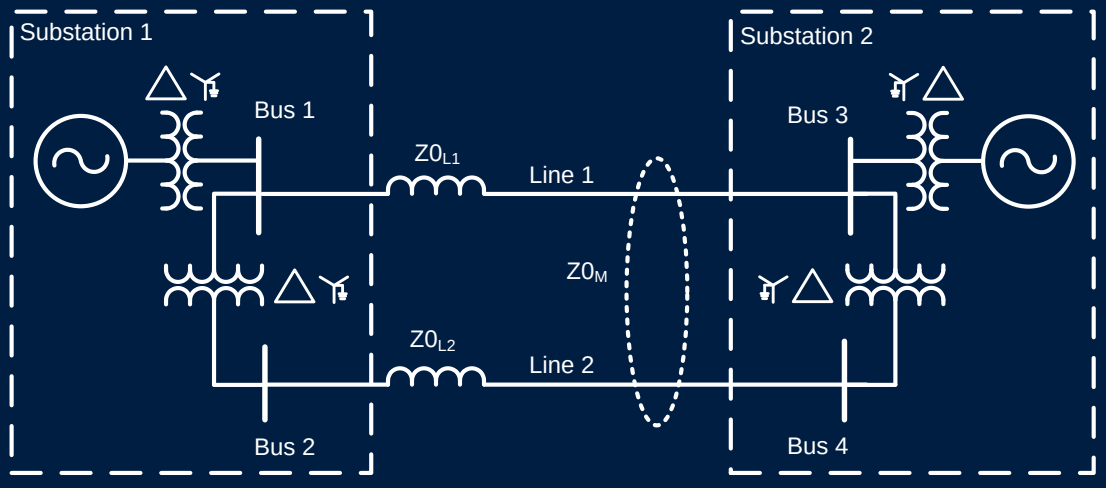


Configuration 1

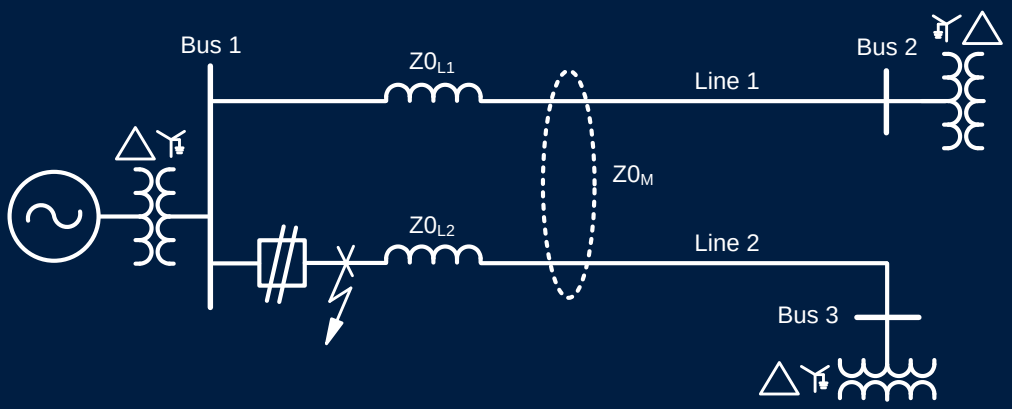
- F1, currents same direction, increased Z_{APP}
- F2, currents in opposite direction, reduced Z_{APP}



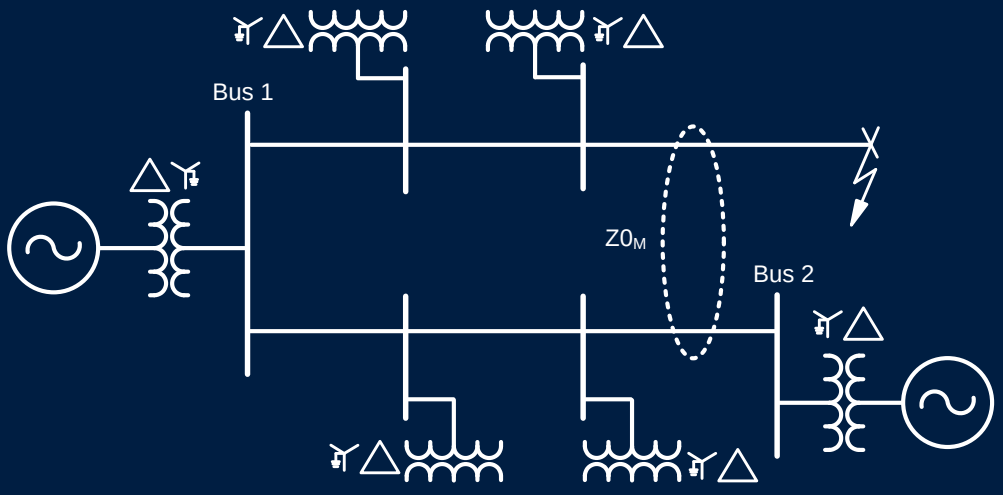
Configuration 2
Natural Isolation



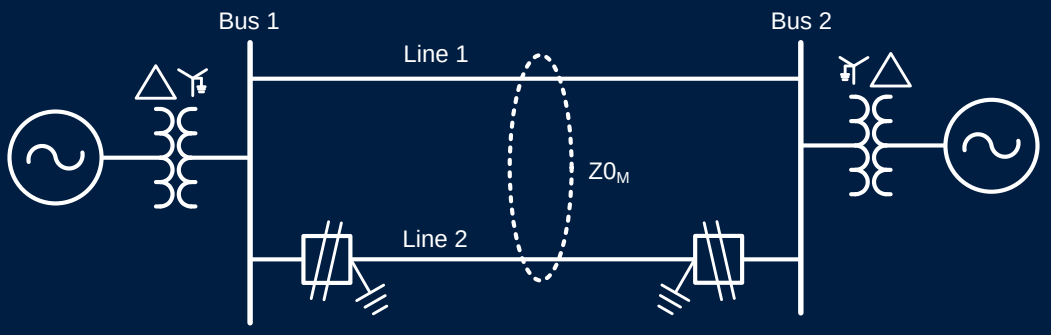
Configuration 2
By Breaker Operation



Configuration 2
Relative Isolation



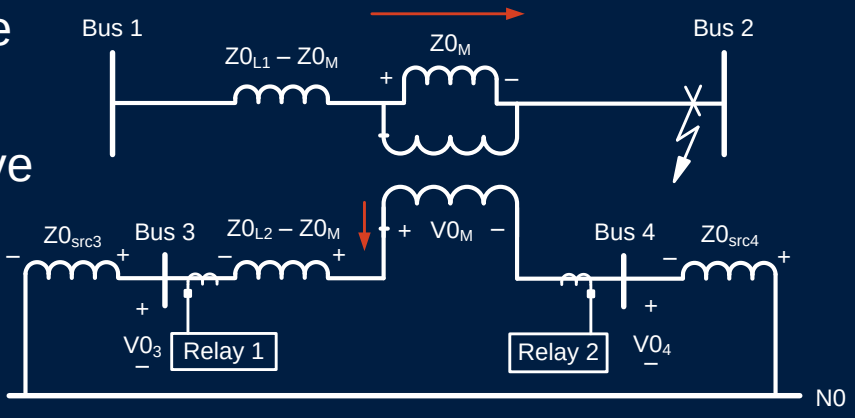
Configuration 2
Line Out of Service and Grounded



$$Z0L_{APP} = Z0_{L1} - \frac{Z0_M^2}{Z0_{L2}}$$

"Voltage Reversal"

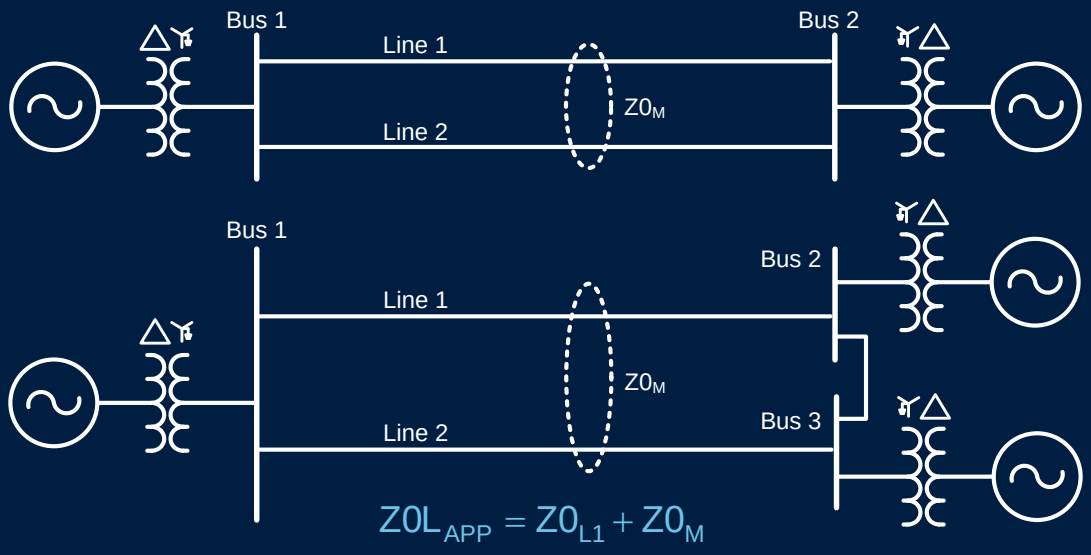
- Relay 1 positive V0 out of phase with current
- Relay 2 negative V0 in phase with current



Voltage Reversal

- Term is not useful for true Configuration 2
  - Reversal implies point of reference
  - Isolated system is not faulted
- Directional elements always declare forward
- Mutual coupling is series unbalance
- Polarizing quantities are result of induced current flow, so always forward

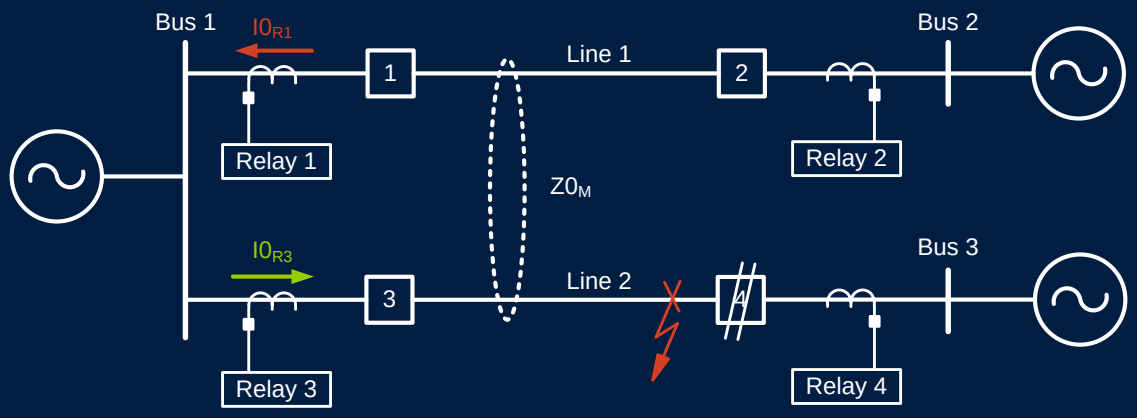
Configuration 3



$$Z0L_{APP} = Z0_{L1} + Z0_{M}$$

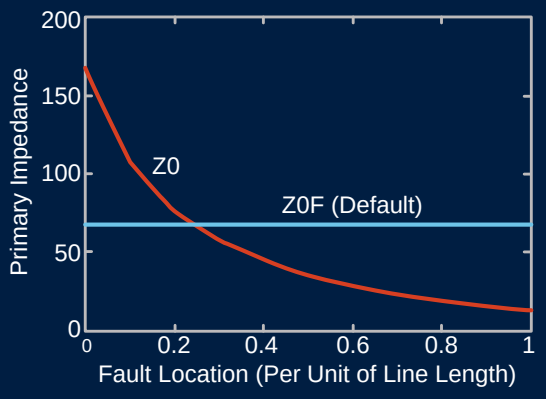
Directional Decision
Configuration 1

- Currents run in opposite directions
- $Z0S_{APP}$ is reduced

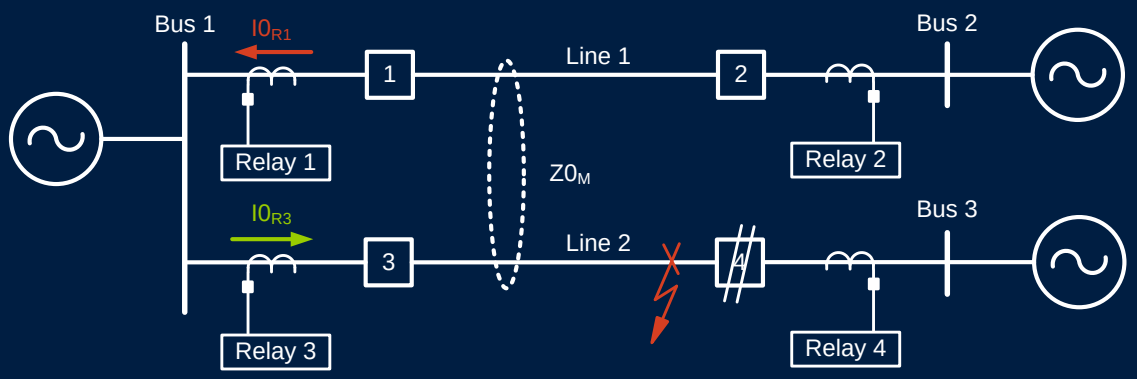


Directional Decision
Configuration 1

- $Z0S_{APP}$ apparent source impedance is significantly reduced
- Relay misoperates for fault beyond 25% of coupled line with AUTO settings



Significance Is a Function of Current



Significance Is a Function of Current

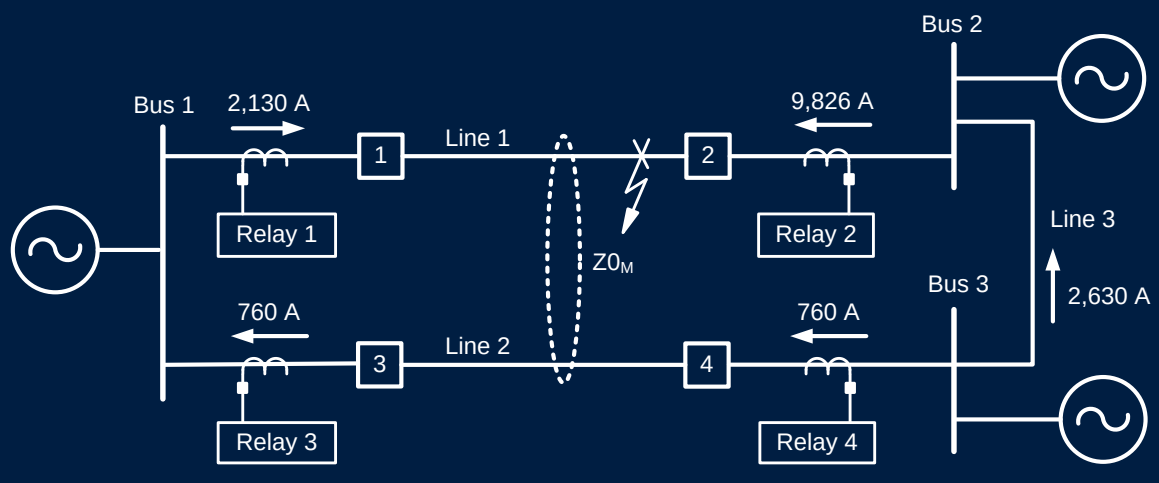
$$Z0S_{APP} = \frac{Z0_{src2} - Z0_M + Z0_{L2}}{Z0_{src1} + Z0_M} \bullet Z0_{src1}$$

Scenario	$Z0_{src1}$	$Z0_{src2}$	$Z0S_{APP}$
Both strong	0.1	0.1	0.050
Source 1 strong	0.1	1.0	0.163
Source 2 strong	1.0	0.1	0.235
Both weak	1.0	1.0	0.765

Case Study

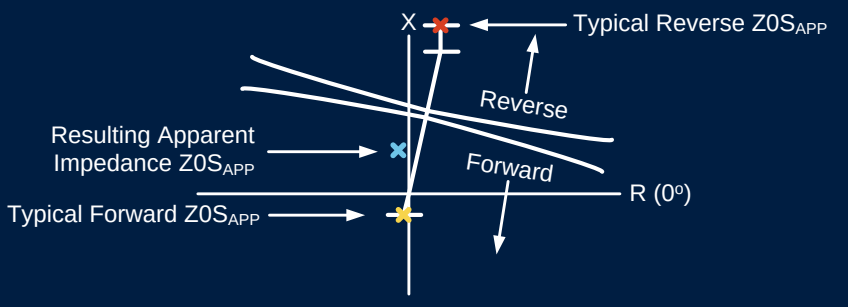
- DCB scheme misoperated
- System resembled Configuration 3 (at first glance)
- Behavior reflected Configuration 1

Case Study



Directional Decision Security Failure

- Not reverse enough
- Worst case $Z0S_{APP}$: $Z0S_{APP} = \frac{Z0_{src2} - Z0_M + Z0_{L2}}{Z0_{src1} + Z0_M} \bullet Z0_{src1}$



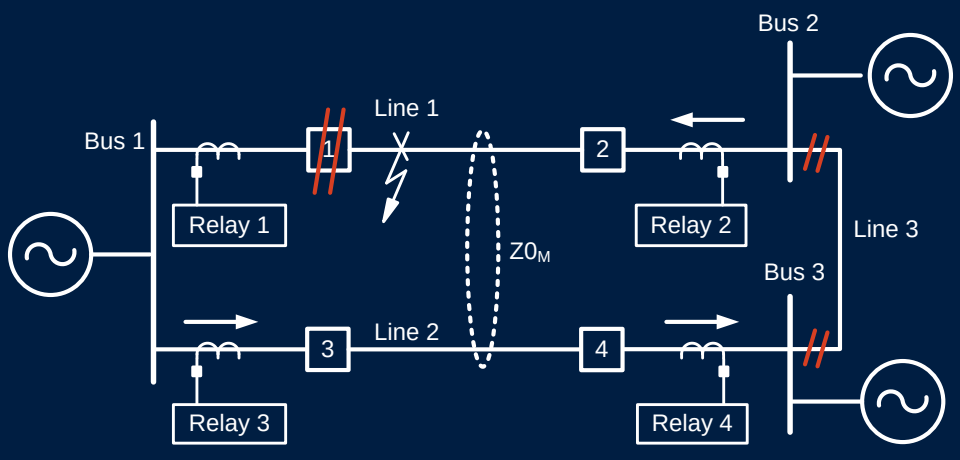
Configuration 1 Analysis

- $Z0_M$ = 36%, mutual coupling warrants consideration
- Configuration 1 was worst case for 32V element
  - AUTO = $Z0_L$ / 2 = 115 Ω
  - $Z0S_{APP}$ = 43 Ω
  - $Z0S_{APP}$ / 2 = 22 Ω
  - AUTO2 = –2.175 Ω (–0.3 Ω secondary)
- $Z0S_{APP}$ for misoperation was 71 Ω

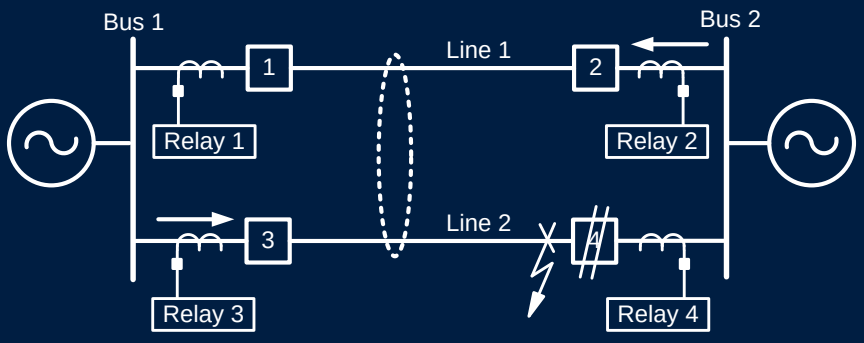
What About N-1 Conditions?

- Line 3 out of service with reclose condition can result in Configuration 2
- 32V element always declares forward regardless of Z0F setting

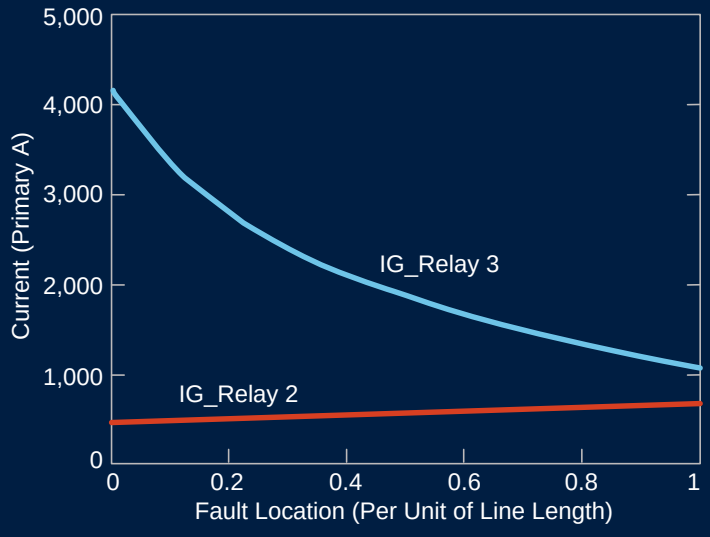
What About N-1 Conditions?



Ground Overcurrent
Configuration 1



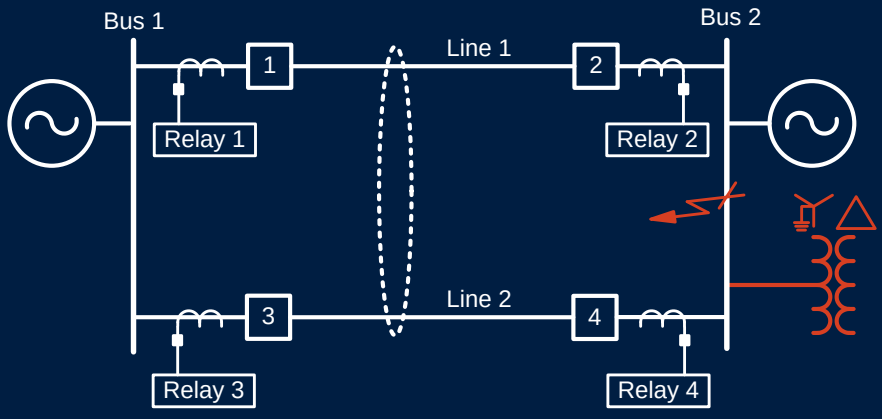
Ground Overcurrent
Configuration 1



Ground Overcurrent and Distance Scenarios

1. System normal
2. N-1, strong ground source out at remote bus
3. Line 2 out of service and grounded
4. Fault in front of Breaker 3, Breaker 3 open
5. Fault in front of Breaker 3, Breaker 3 open with new strong ground source out

Ground Overcurrent and Distance Scenarios



Ground Overcurrent and Distance
Worst Case May Not Be Same

Scenario	Relay 1 Z_{APP} (Ω)	Relay 1 3I0 (A)
1	39.4	143
2	46.2	348
3	29.2	363
4	51.1	651
5	46.0	661

Directional Comparison Pilot Schemes
Configuration 2

- Negative-sequence directional element
- Fault detectors
- Distance elements only in pilot schemes
- Negative-sequence supervision

Summary

- Configuration 1 can result in extreme $Z0S_{APP}$
- Configuration 2 results in “voltage reversal”
- Worst case for overcurrent and distance elements should not be assumed same
- Fault current in unfaulted line rises in Configuration 1 as fault moves away from shared bus on mutually coupled line

Summary

- Apply negative-sequence directional elements exclusively on lines with significant (greater than 10%) mutual coupling – reduces risk of unexpected or unidentified Configuration 1 and 2 scenarios
- Remove sensitive directional ground overcurrent pilot tripping elements from high-speed pilot schemes
- Use larger margins

Questions?