Voltage and Current Inversion Challenges When Protecting Series-Compensated Lines
A Case Study

Eric Bakie and Curtis Westhoff
Idaho Power Company

Normann Fischer and Jordan Bell
Schweitzer Engineering Laboratories, Inc.

Agenda

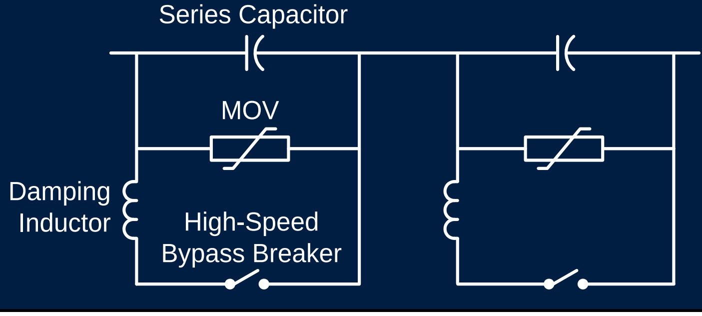
- Project overview
- Theory overview
- System model
- Utility analysis / results
- Relay manufacturer analysis / results
- Conclusion

Project Overview

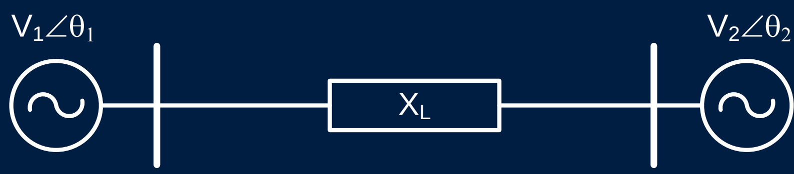
- Goals
  - Replace 230 kV series capacitor banks (≈ 50 years of service)
  - Increase nominal and emergency ampacity by 25%
  - Increase path transfer capability ≈ 300 MW
- Series compensation requirements
  - Increase series compensation to 70%

Series Capacitor Bank
Equipment Characteristics

- Two segments with independent bypass breakers
- MOV
  - High current and energy bypass protection logic
  - Energy capacity – worst case external faults



Basic Theory Overview

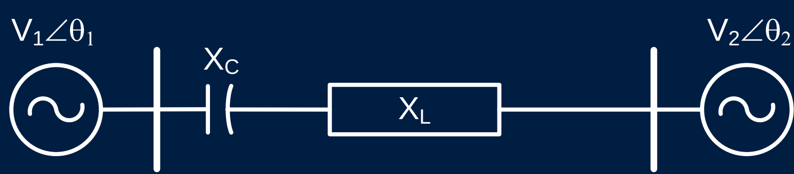


Uncompensated

$$P = \frac{V_1 V_2 \sin(\theta_{12})}{X_L}$$

Basic Theory Overview

Decreased line reactance results in increased power transfer

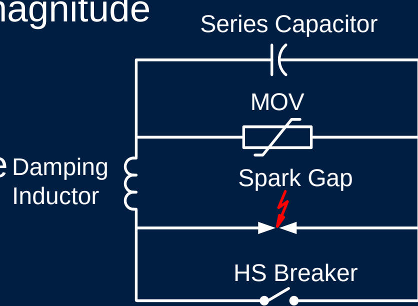


Compensated

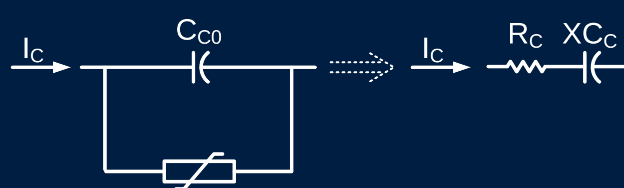
$$P = \frac{V_1 V_2 \sin(\theta_{12})}{X_L - X_C}$$

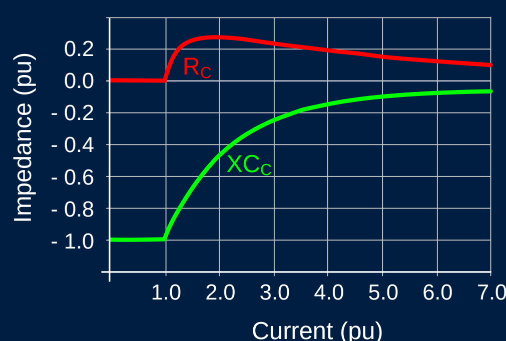
Series Capacitor Protection

- Exposed to large range of fault currents
  - Large fault currents → large voltage drop across the capacitor
- Protected by MOVs and/or spark gaps
  - MOVs clamp the magnitude of the voltage
  - Spark gaps flash during high-voltage conditions



Goldsworthy Equivalent Circuit

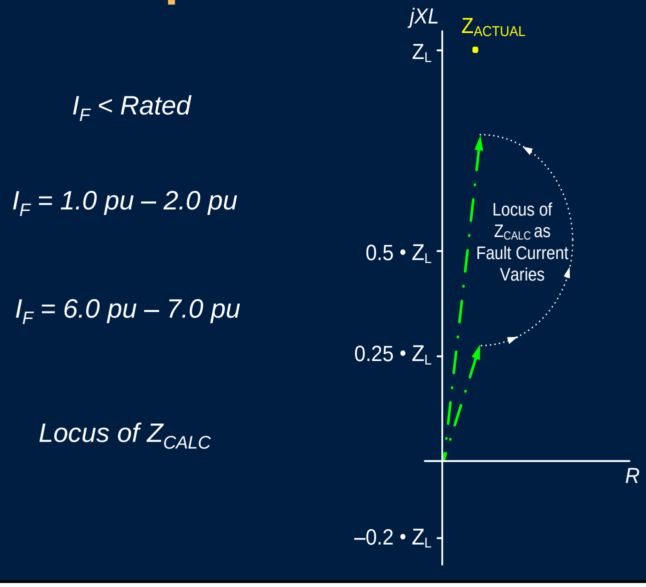




As MOV conducts, effective capacitance decreases

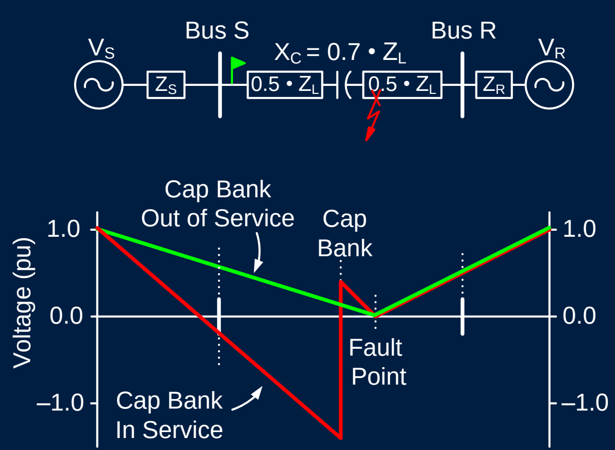
MOV resistance is inversely proportional to series capacitor voltage drop

Effect of R_C and XC_C on Impedance-Based Elements



Voltage Inversion Occurs…

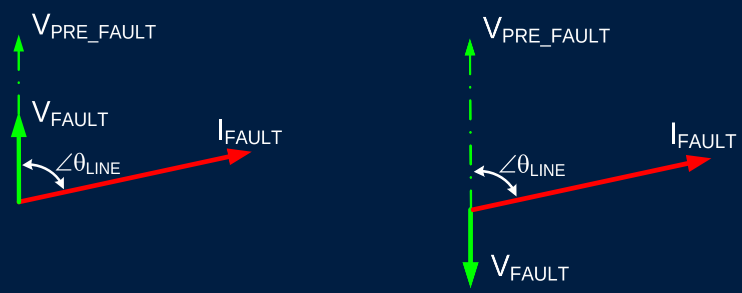
if $Z_{R\_FP} < X_C$ and $Z_S + Z_{R\_FP} > X_C$



Memory Voltage Polarizing Overcomes Voltage Inversion

Bus S
Bank Out of Service

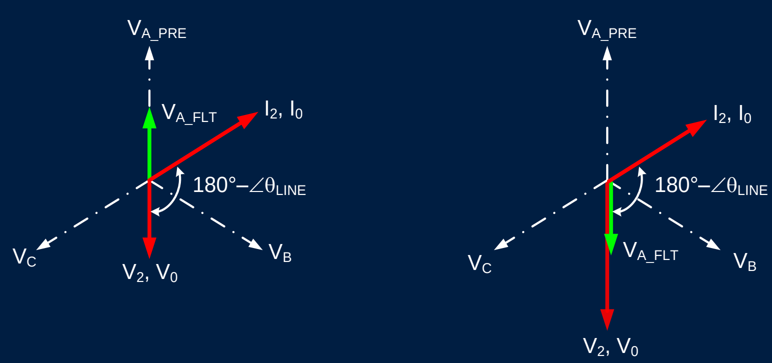
Bus S
Bank In Service



Voltage Inversion Does Not Affect Negative- or Zero-Sequence Directional Elements

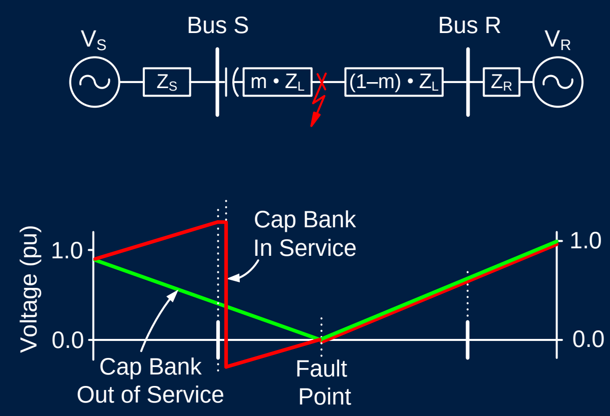
Bus S
Bank Out of Service

Bus S
Bank In Service



Current Inversion Occurs…

if $X_C > Z_S + mZ_L$



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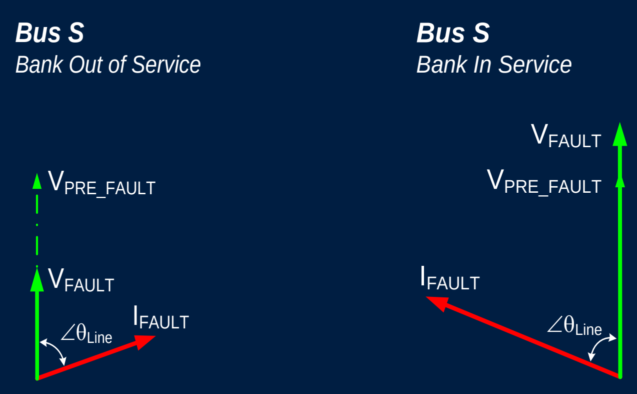
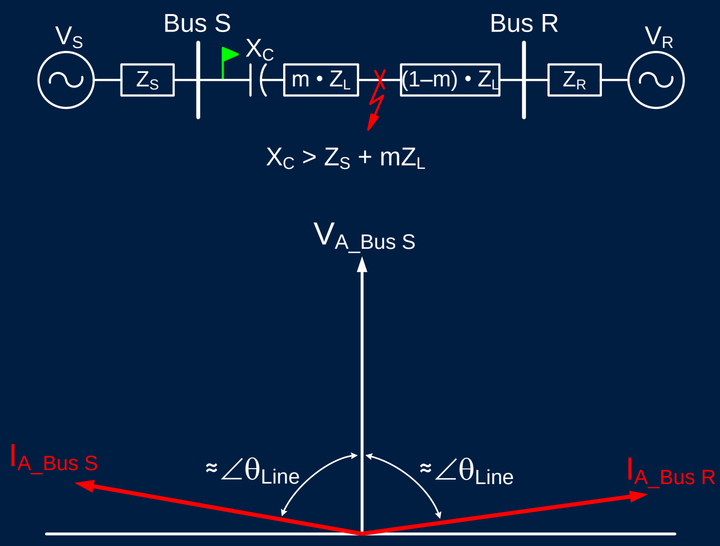
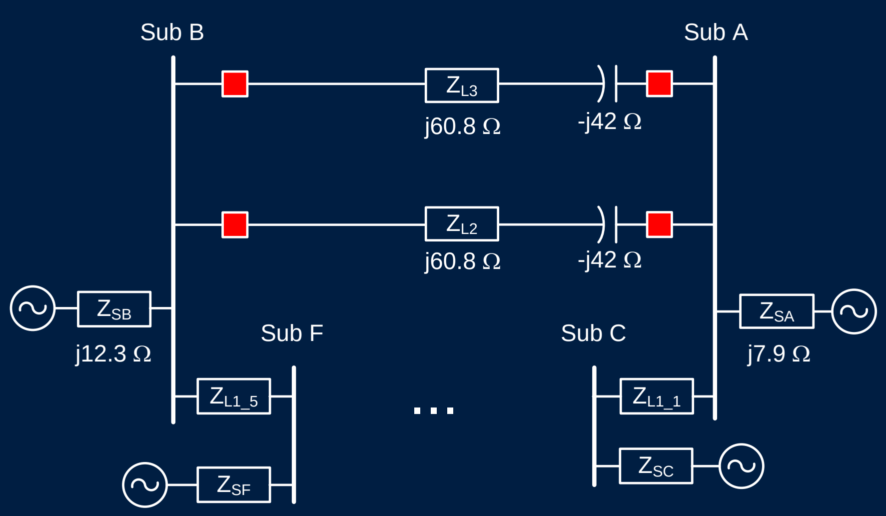


Current Inversion



230 kV System Case Study

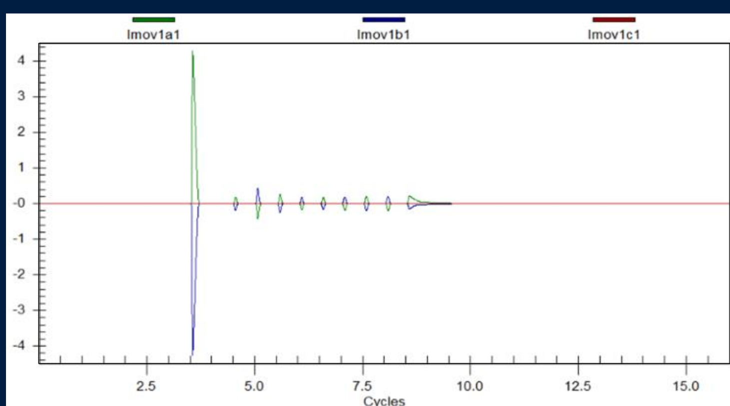


Observations for Close-In Line-to-Line Faults

- Fault current limited by series capacitors
- Voltage drop across capacitor is lower than MOV conduction level
- Nonbypassed series capacitor exposes line protection elements to current inversion

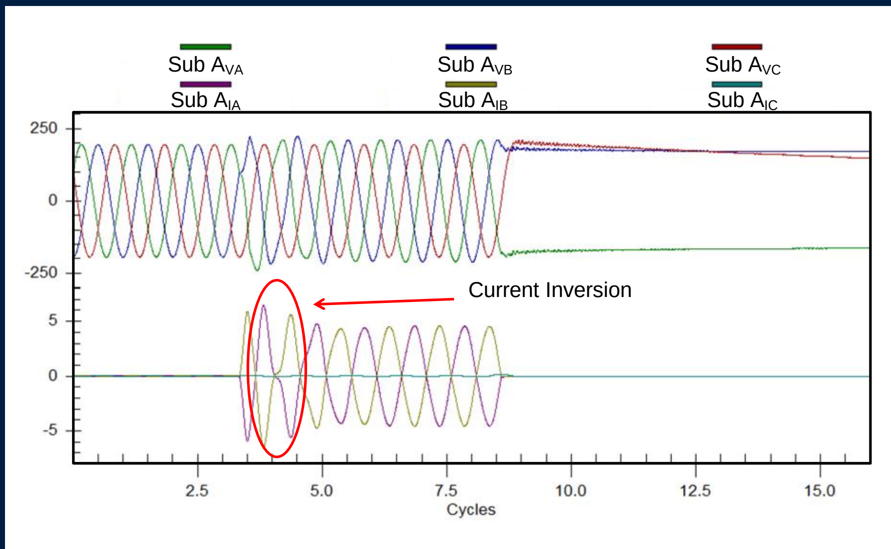
MOV Performance for Close-In Line-to-Line Faults

Peak MOV current of
4.3 kA vs. 5.9 kA bypass level



Distance Element Performance

Close-In Line-to-Line Faults



Distance Element Performance

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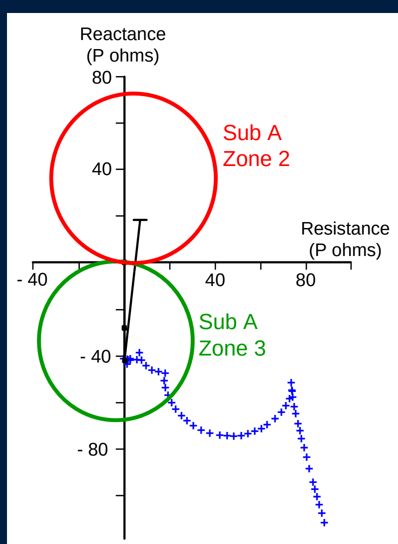
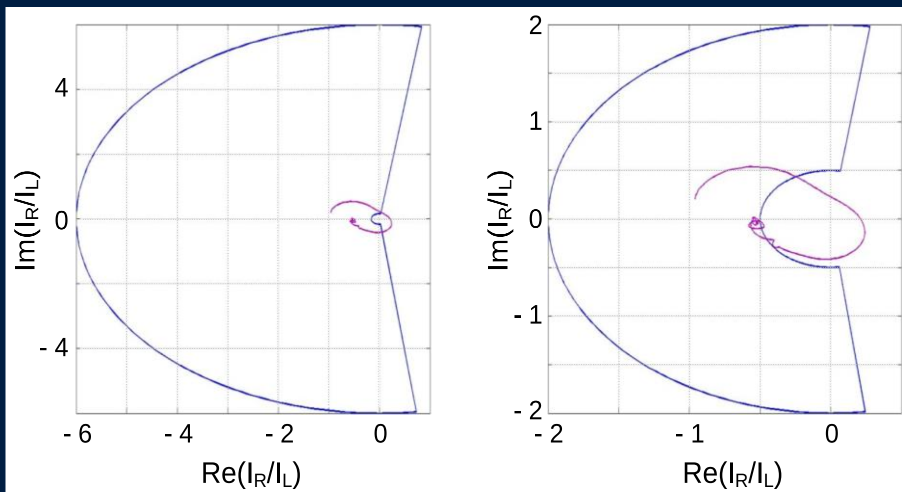


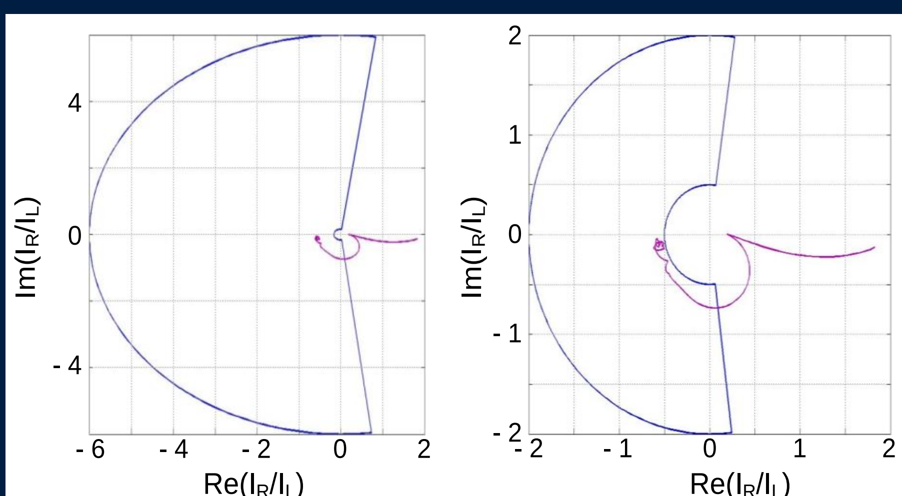
Transient Simulation Results

Case Study One – Heavy Load



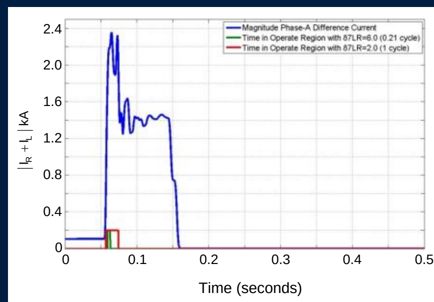
Transient Simulation Results

Case Study Two – Light Load



Transient Analysis

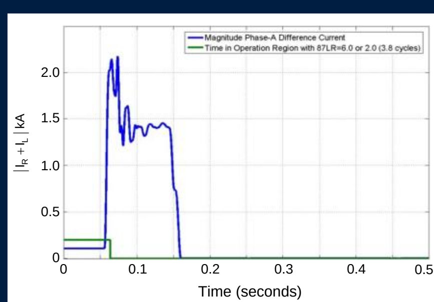
Case Study One – Heavy Load



Analysis	Initial Settings	Adjusted Settings
AB fault, line-side of X_C	87LR = 6.0	87LR = 2.0
Time in operate region and above pickup setting	0.216 cycles	1.005 cycles

Transient Analysis

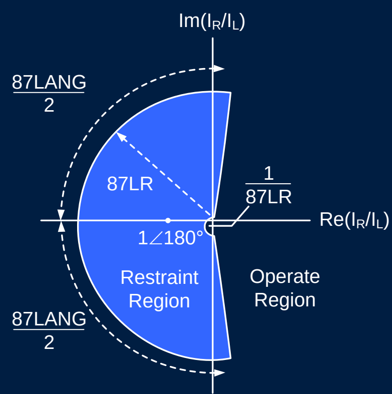
Case Study Two – Light Load



Analysis	Initial Settings	Adjusted Settings
AB fault, line-side of X_C	87LR = 6.0	87LR = 2.0
Time in operate region and above pickup setting	0.303 cycles	0.303 cycles

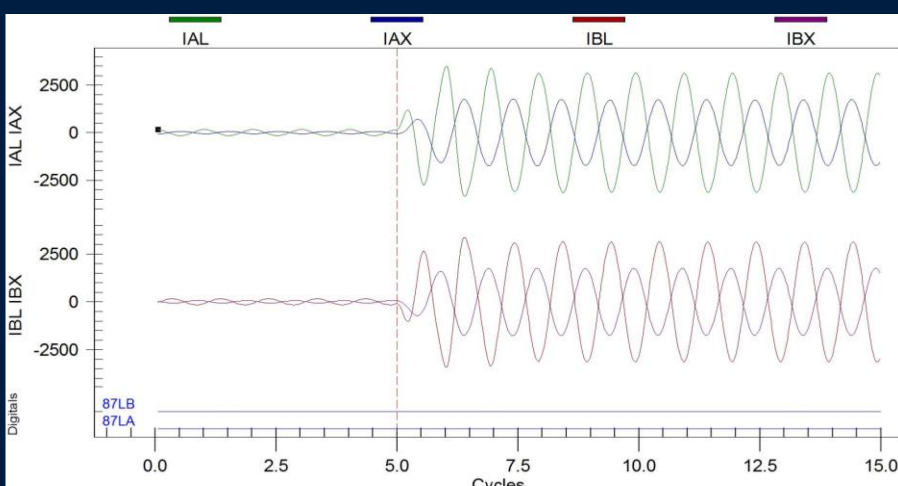
Line Current Differential Is a Potential Solution

- Evaluate performance using RTDS testing
- Develop optimized settings
- Verify security for external fault conditions



Initial RTDS Testing

Close-In Line-to-Line Faults



Initial RTDS Testing

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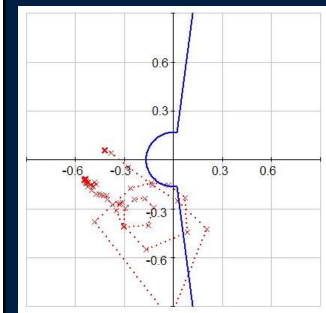
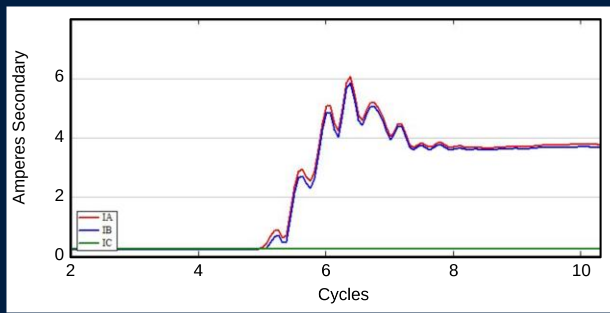
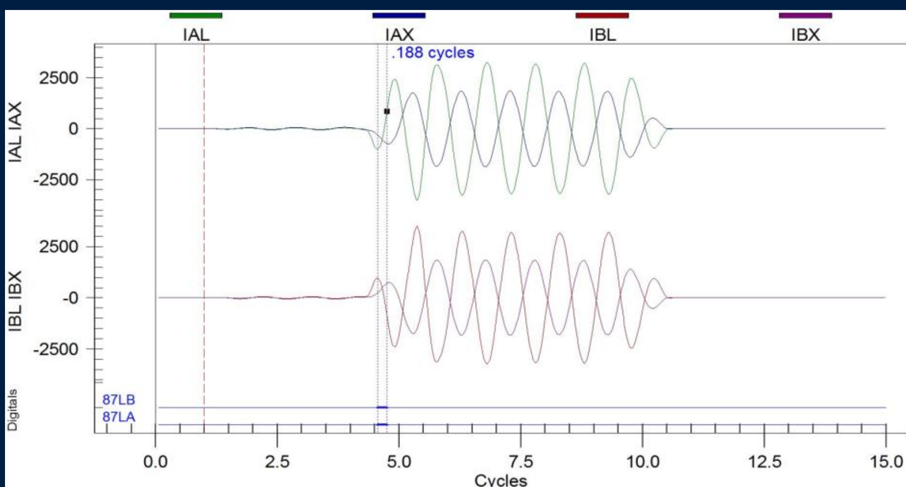




Differential Pickup = 6 A
Blocking Angle = 195°
Blocking Radius = 6.0

Detailed RTDS Testing

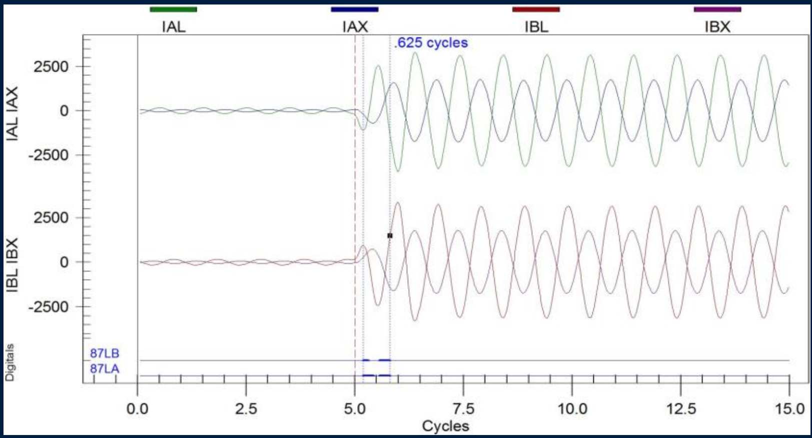
Differential Pickup Setting Reduced From 6 A to 2 A



Detailed RTDS Testing

Blocking Angle Decreased From 195° to 100°

Assertion time increased to 0.625 cycles with momentary dropout



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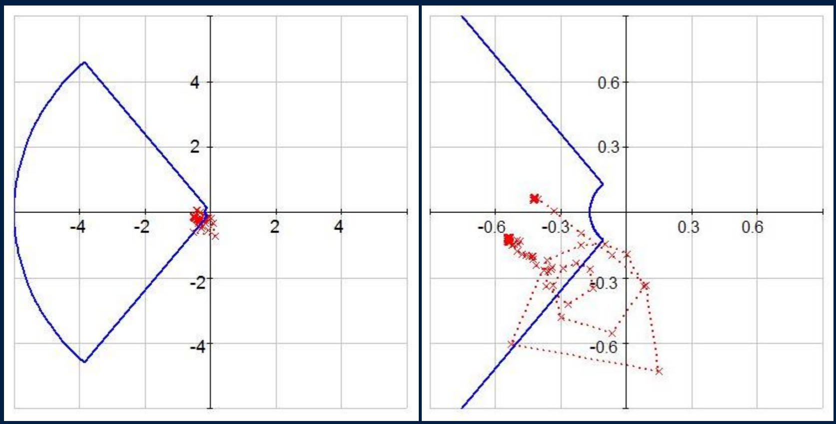
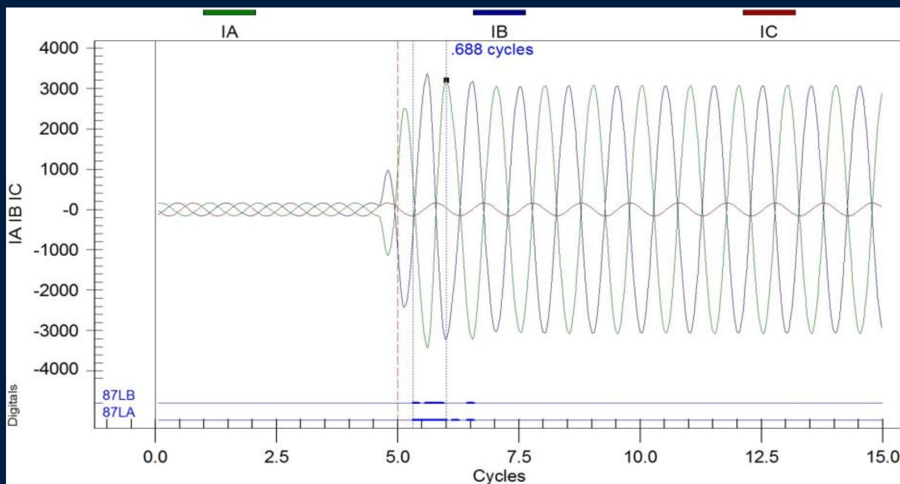


Detailed RTDS Testing

Blocking Radius Decreased From 6 to 2



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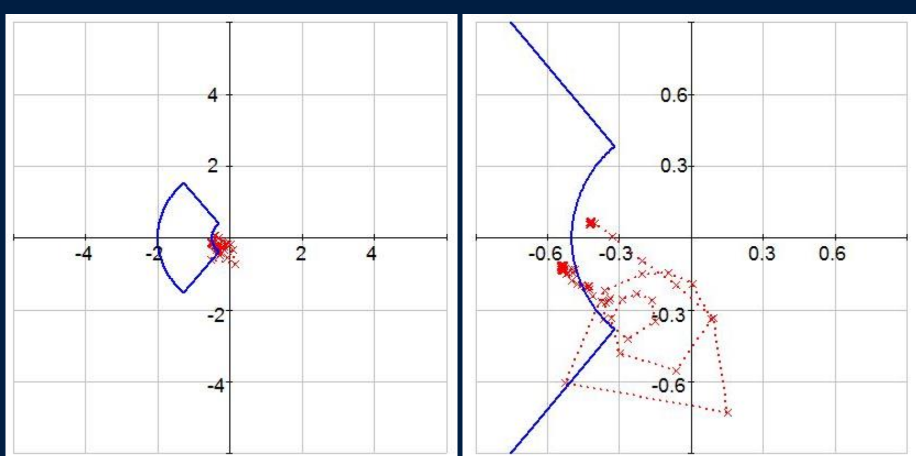


Results of RTDS Testing

Line Current Differential

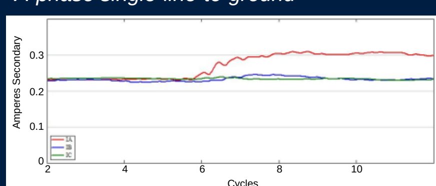
- Dependable solution was found by adjusting
  - Pickup value
  - Blocking angle
  - Blocking radius
- Negative-sequence differential elements cannot be used due to intentional security delay

Differential Element Security

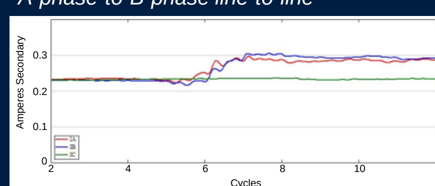
Adjacent Line Faults

Differential currents never exceed pickup setting of 2.0 A

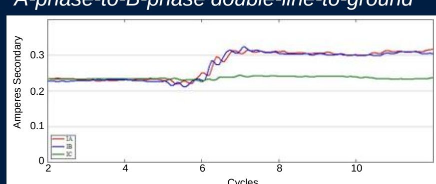
A-phase single-line-to-ground



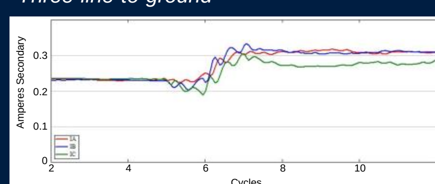
A-phase-to-B-phase line-to-line



A-phase-to-B-phase double-line-to-ground



Three-line-to-ground

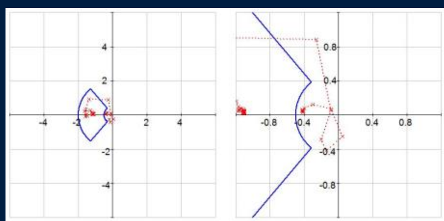


Alpha Plane Security

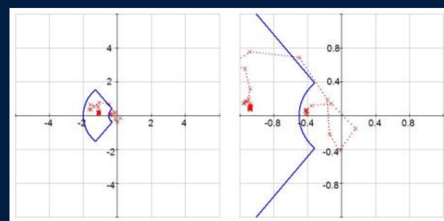
Adjacent Line Faults

Ratio of remote/local current oscillating into the restraint region

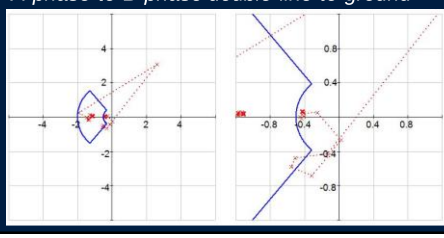
A-phase single-line-to-ground



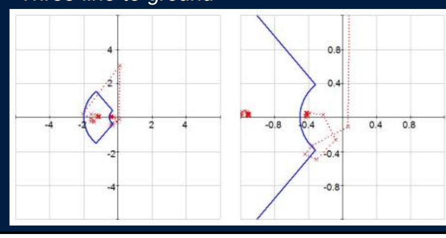
A-phase-to-B-phase line-to-line



A-phase-to-B-phase double-line-to-ground



Three-line-to-ground



RTDS Testing Assumptions

- CT saturation was not possible for adjacent line faults based on analysis
- Communications channels are symmetrical

Conclusion

- Current inversion
  - Distance and directional elements unusable
  - Decreases dependability of differential elements
- Transient simulations and RTDS testing are necessary to evaluate relay performance during current inversion

Questions