Transmission Line Protection Under High Penetration of Inverter-Based Resources: Impact Assessments and Mitigation Solutions

Juergen Holbach, Henry Chao, Zheyuan Cheng, Yi Hu
Quanta Technology

Bruce Fardanesh, Hossein Hooshyar, Thanh Nguyen, Adam O'Leary
New York Power Authority

Peter Haswell, Louis E. Seiter, Charles T. Hitchings
National Grid

2023 WESTERN PROTECTIVE RELAY CONFERENCE

Presentation Outline

- Project Approach Overview
- Line Selection and Simulation Analysis
- HIL Setup and Testing Results
- Conclusions

Project Approach Overview

Pick up Electric Feeder and Relaying Schemes
- Electric feeder selection
- Relay scheme selection

Create Simulation Models
- IBR RTDS models development
- RTDS System Model with High IBRs

Setup the Lab for Hardware-In-the-Loop (HIL) Test
- Test plan and wiring diagram development
- AGILe Lab HIL test Setup

Assess the Impact
- Perform the test per test plan
- Test results analysis and impact assessment

Develop Mitigation Solutions
- Mitigation solution development
- Mitigation solution verification

- Focus on select where the impact will be felt the most and the earliest
- Develop the model of the selected feeder
- Assess the impact by HIL testing with real relaying products
- Develop mitigation solutions and verify with the same HIL testing setup

Section 2

LINE SELECTION AND SIMULATION ANALYSIS

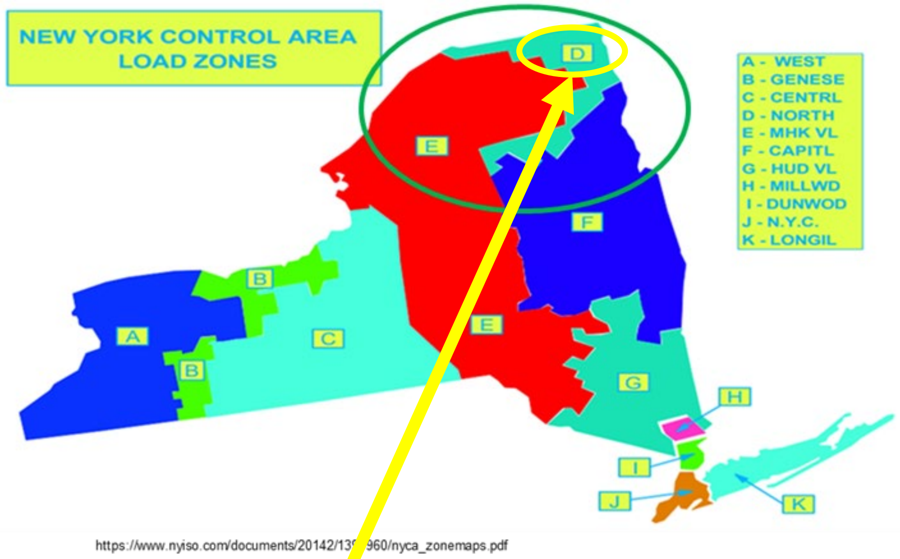
Specific Line Selection

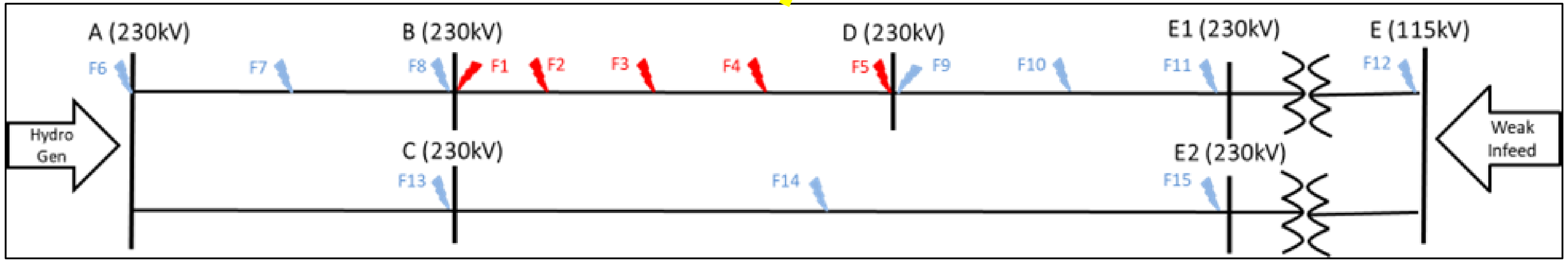
The line selection criteria

- At one of the weak spots in the focus area
- Close to many wind farms, solar farms, and BESS

The results

- A 230 kV line B-D was selected
- A 115 kV line was dropped





Developed Hi-IBR System Models

IBR Projects Added	Capacity (MW)
Franklin Solar	150
Brookside Solar	100
North Country Wind	298
Bull Run Wind	304
Bull Run Solar Energy Center	170
North Ridge Wind	100
Bangor Solar	107
North Country Energy Storage	20
Bull Run II Wind	145

In addition to IBRs added, the Hi-IBR system model (Hi-IBR case #1)

- Reduced large hydro plant output by 50%
- Retired a 315 MW combined cycle generation, and
- The other side is represented by a weak source (SCR=2.5 and X/R < 5)

Two variations of the Hi-IBR case #1 are

- Hi-IBR case #2: take the parallel line C-E2 out-of-service
- Hi-IBR case #3: further disconnect the weak source from case #2

Fault Current Magnitude Changes

- Weak end I1 increased due to increased IBR generation.
- Weak end I2 is decreased for all unbalanced faults.
- I0 fault current is increased for faults involving ground.

Terminal	FaultType	Fault Current Magnitude %Change vs Base Case								
		I1			I2			I0		
		IBR #1	IBR #2	IBR #3	IBR #1	IBR #2	IBR #3	IBR #1	IBR #2	IBR #3
Strong End	AG	-8%	-6%	-11%	50%	57%	65%	23%	22%	16%
Strong End	AB	-19%	-17%	-22%	16%	22%	25%	N/A	N/A	N/A
Strong End	ABG	9%	12%	11%	-4%	1%	-2%	92%	91%	93%
Strong End	ABC	12%	16%	15%	N/A	N/A	N/A	N/A	N/A	N/A
Weak End	AG	29%	21%	33%	-26%	-33%	-28%	24%	22%	15%
Weak End	AB	25%	14%	12%	-43%	-48%	-45%	N/A	N/A	N/A
Weak End	ABG	46%	28%	13%	-52%	-57%	-56%	92%	91%	91%
Weak End	ABC	21%	2%	-20%	N/A	N/A	N/A	N/A	N/A	N/A

Negative Sequence Voltage and Current Angle Difference Changes

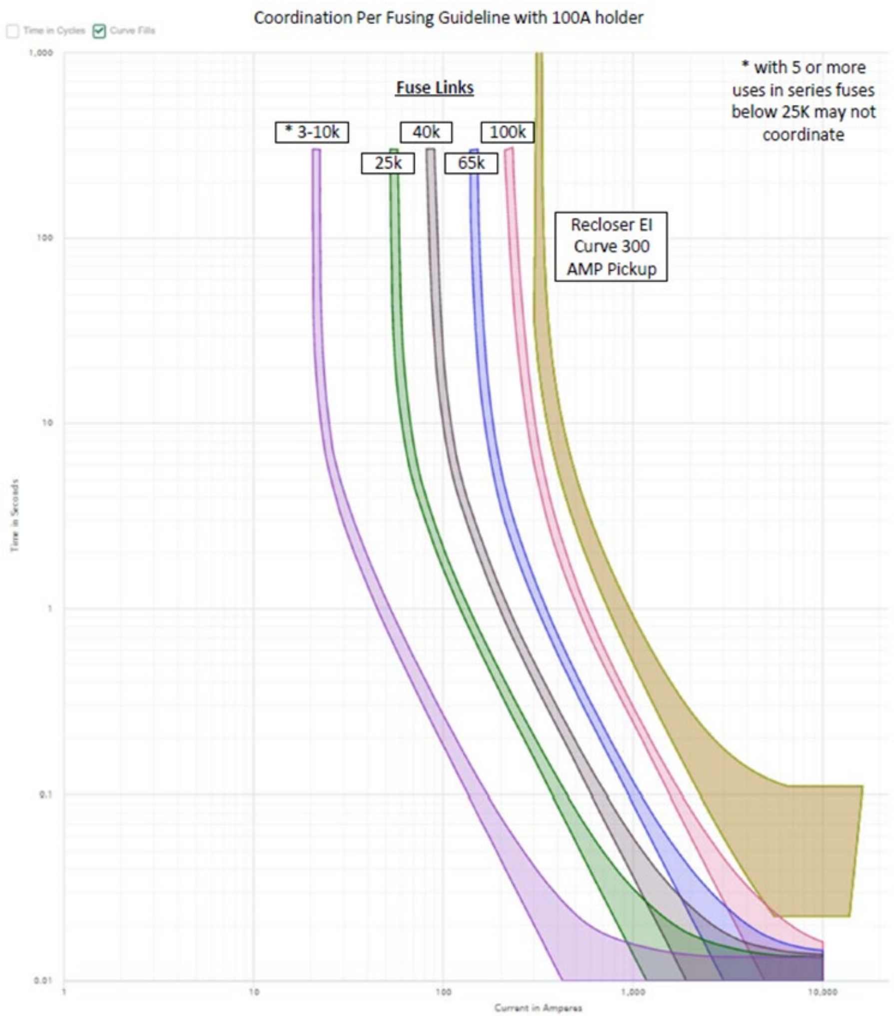
- Negative-sequence voltage and current angle relationship
  - Strong end shown consistent angle difference at around minus 100-degree regardless of fault types and simulation scenarios
  - Weak end saw decrease in the angle difference to as low as around minus 200-degree – much larger deviation then around minus 90 degrees in a system dominated by conventional generation

- No noticeable changes are observed for positive and zero sequence angle relationship.

FaultType	V2– I2 Angle (Deg.)			
	Base	IBR Penetration		
		IBR#1	IBR#2	IBR#3
AG	-97	-143	-164	-198
AB	-97	-143	-166	-199
ABG	-97	-143	-163	-199

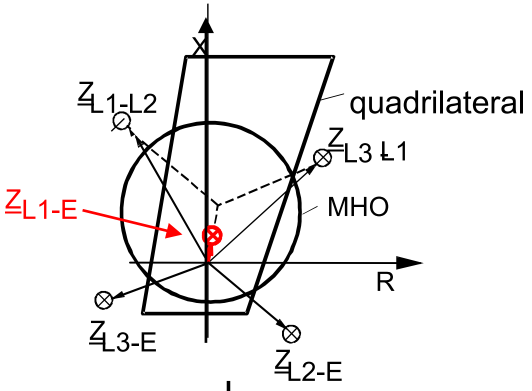
Impact of Declining Fault Current Levels on Protection

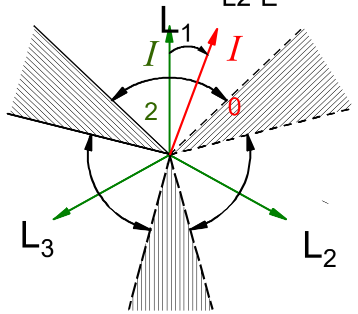
- Impact on Over Current Protection
  - Minimum fault current is critical for pickup settings in overcurrent functions
  - The overcurrent function is typically used as backup protection or for the supervision of unit (differential) and non unit (distance) protection
  - During protection studies, the minimum current is determined by selecting an N-1 contingency that provides the lowest fault current
  - Maximum fault current is used for inverse overcurrent elements to determine the correct time dial (time grading) setting

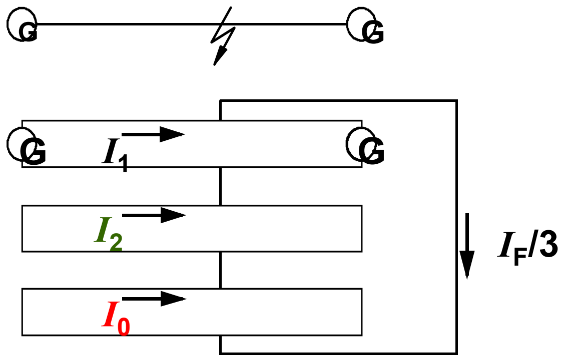


Impact of IBR Fault Current Levels on Protection

- Impact on Distance Protection Loop Selection
  - The selection of the correct fault loop is essential for the performance of the distance relay
  - Different manufacturer implement different algorithms to master this complex task
  - Typical tasks performed are:
    - Impedance comparison
    - Symmetrical component analysis
    - Load compensation
    - Pattern recognition
  - Most assumption used in this algorithm are not correct anymore!





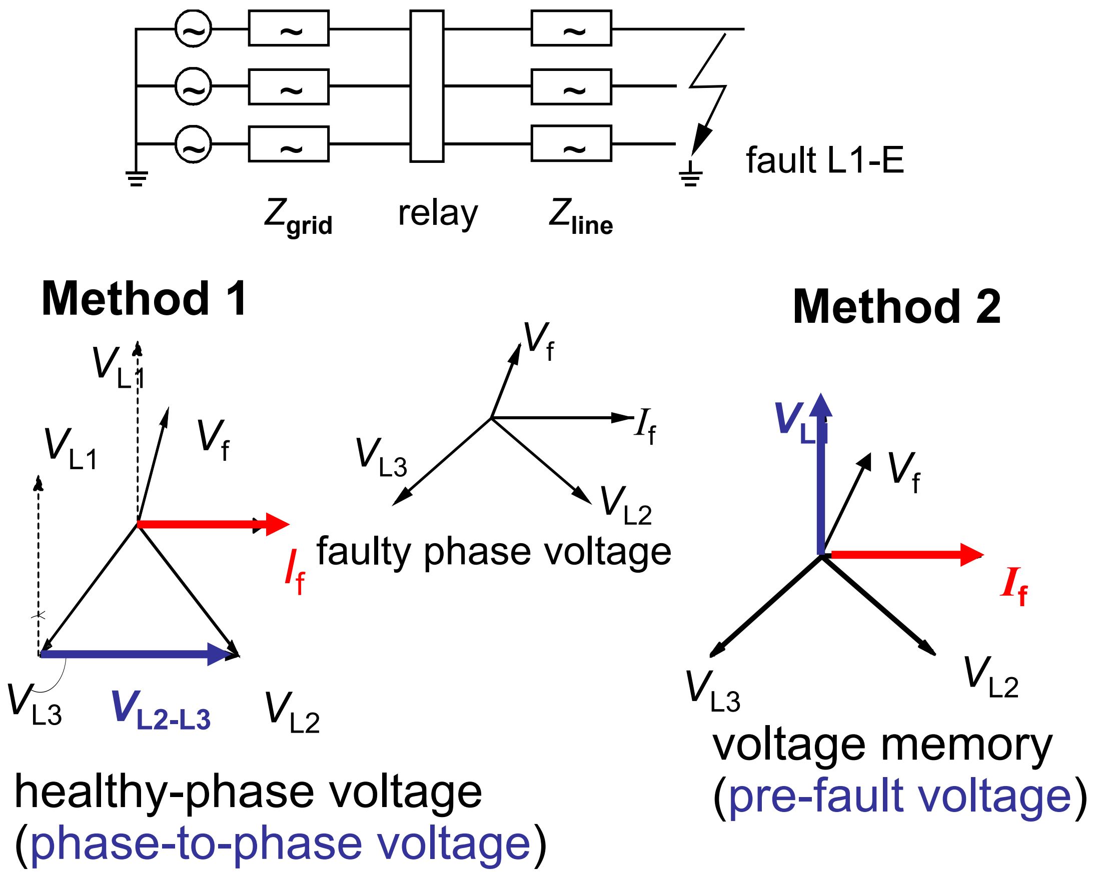


Wrong loop selection causes over or under function of the distance relay.

Impact of IBR Fault Current Levels on Protection

- Impact on Distance Protection Directional Element
  - Direction may be determined together with the impedance measurement,
  - **but** problems may arise in certain cases (e.g. close-in faults).
  - **Separate directional determination required!**
    - ➢ Cross-polarization
    - ➢ Memorized –polarization

  - Both solution assume that system voltage angle will not change during fault



Impact of IBR Fault Current Levels on Protection

- Impact on Distance Protection Accuracy
  - Fault current contribution is limited to 1.0-1.5 pu of rated inverter current
  - Source impedance of inverter based generation is higher than classical synchronous generation
  - The source-to-line-impedance-ratio (SIR) is a value that is used by National Grid to determine whether non-unit protection (distance elements) can be used on a particular line.
  - The SIR ratios will increase in relation to the growing amount of inverter-based generation
  - This is important as when the SIR ratio is above 30, non-unit protection becomes unreliable due to that as the accuracy decreases and operating time increases.

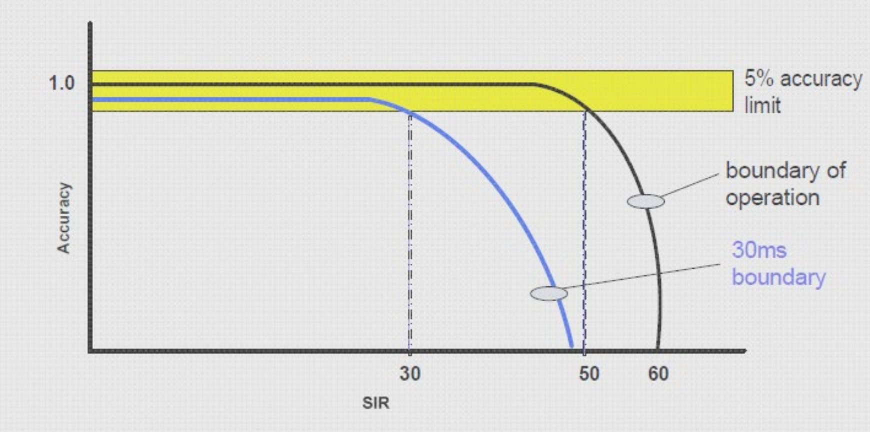
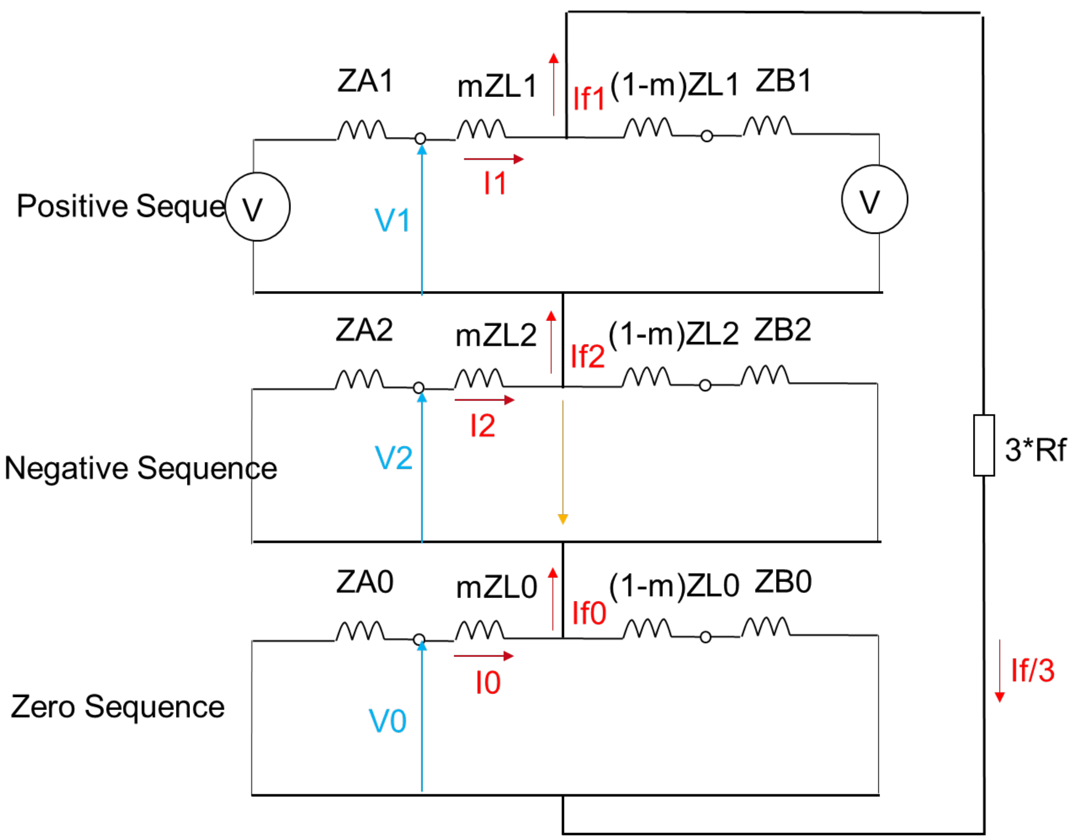


Figure showing the effect of SIR on distance relay performance

Impact of IBR Fault Current Levels on Protection

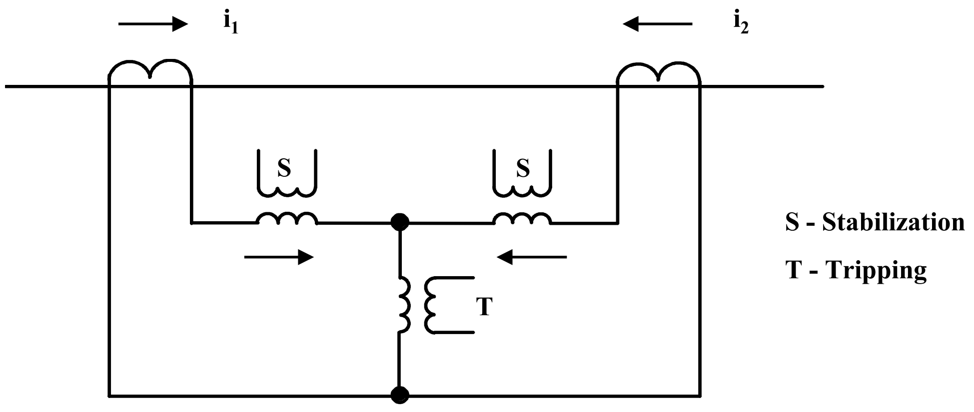
- Directional element based on I2
  - Angle between I2 and V2 is used to determine forward or reverse fault
  - IBR don't typically provide I2
  - The angel between I2 and V2 of an IBR produced I2 is determined by control software in inverter and can have any value

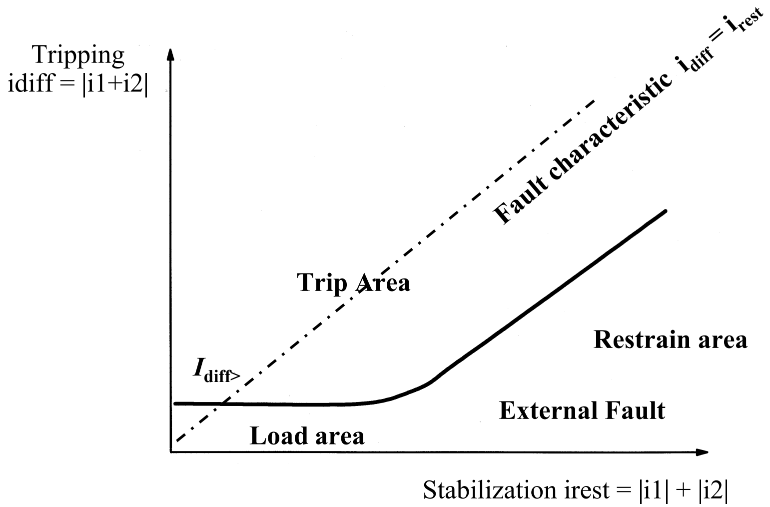
Forward Fault with Synchronous Generator



Impact of Declining Fault Current Levels on Protection

- Impact on Differential Protection
  - The differential protection principle is used for busbar, transformer, and line protection applications
  - The basic principle is not affected by lower fault currents as long as the total fault current exceeds the pickup settings for the differential elements
  - However, the impact of changing fault current characteristics (e.g. phase angle changes) due to the application of inverter based generation requires further study.



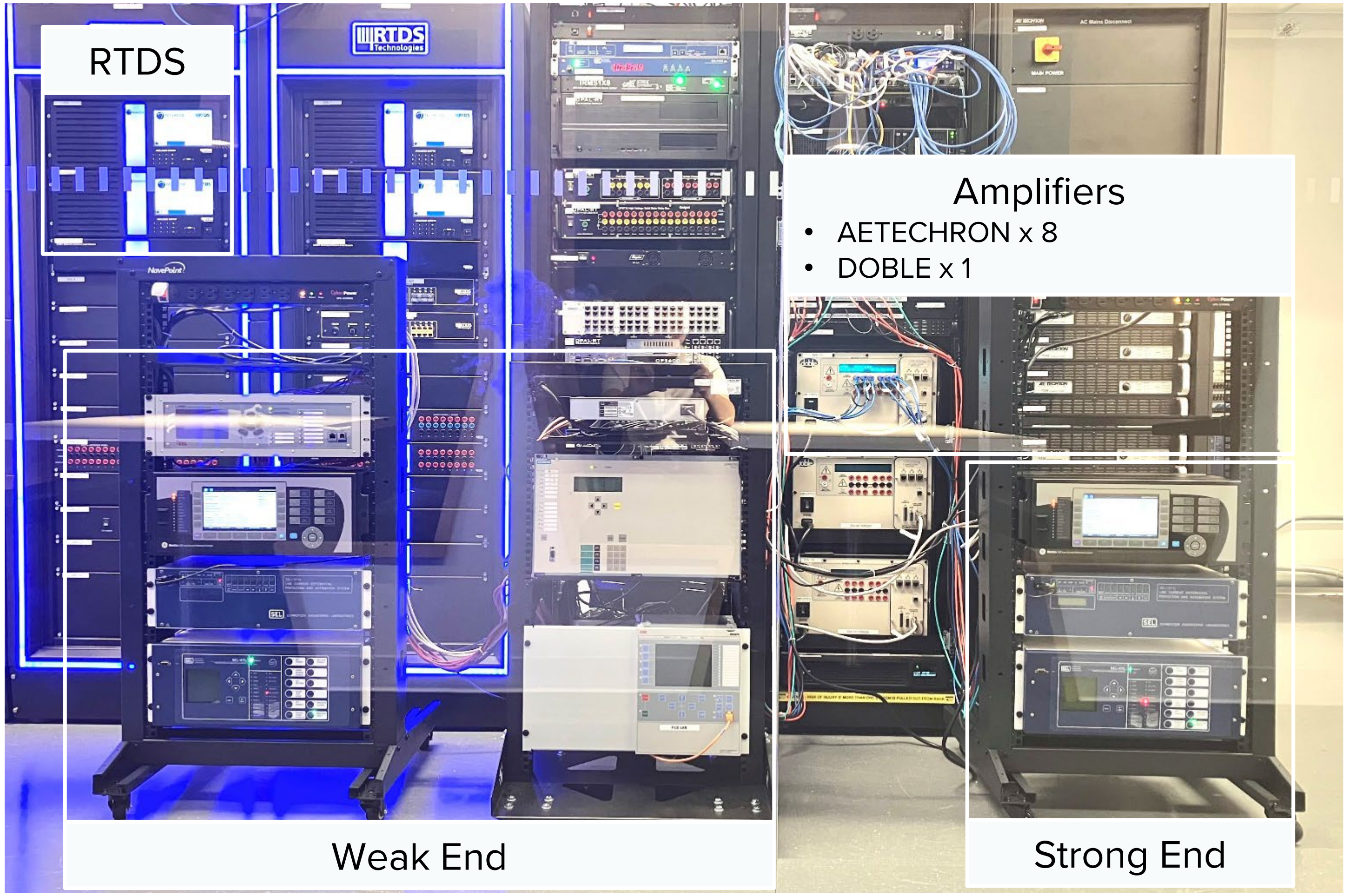


Section 3

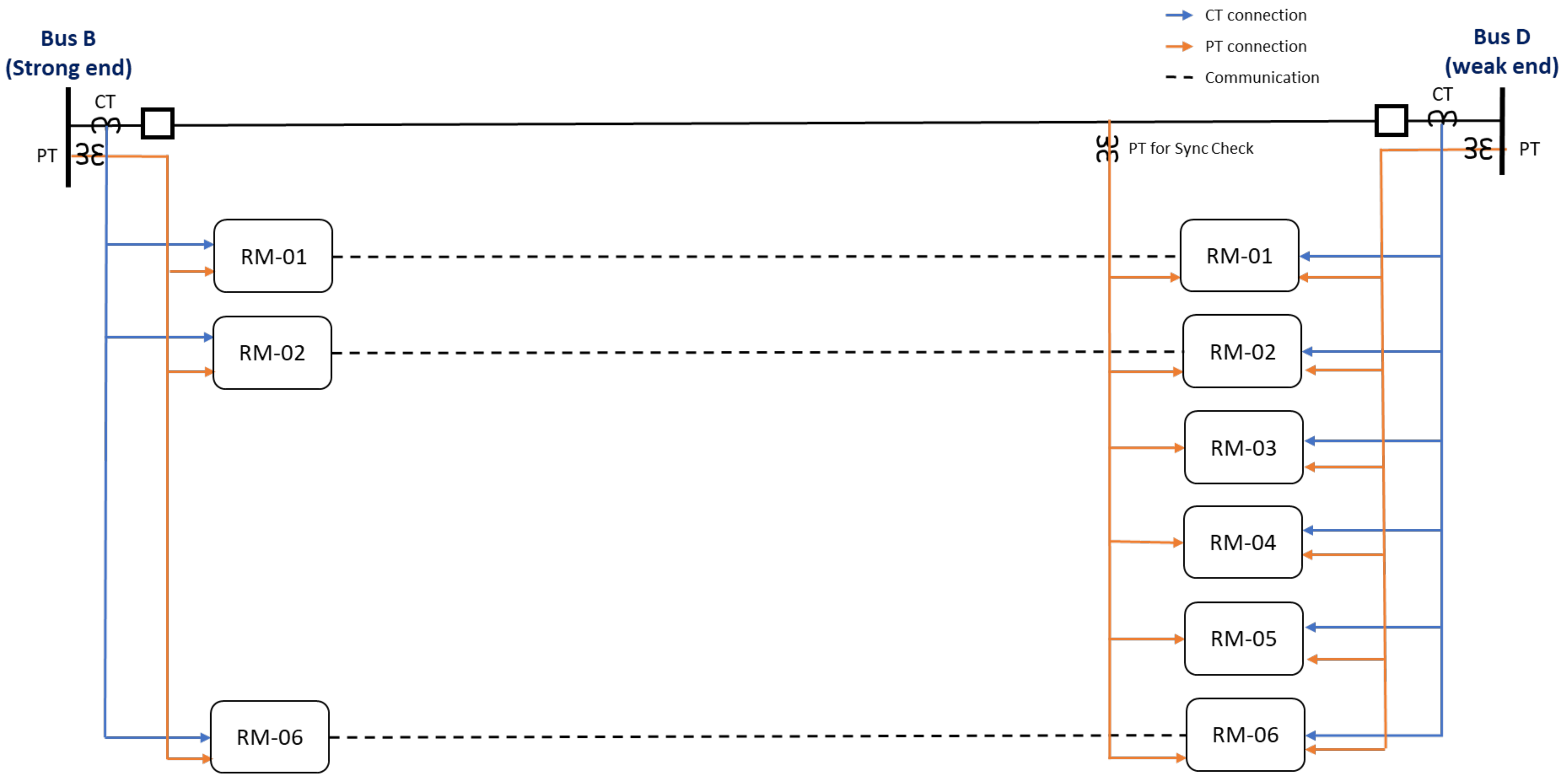
HIL SETUP AND TESTING RESULTS

Protective Relay HIL Testbed

- The HIL testbed includes:
  - 9 relays for 6 relay models from 5 relay manufacturers.
  - RTDS real-time simulator
  - Amplifiers
  - Ethernet switch for network communication
  - Workstations
- The HIL testbed can be accessed remotely.



HIL Relay Testing Setup Diagram



Test Results Details – Zone 1 Misoperations

RM-01		Base	IBR		
FLTLOC	TYP		Case 1	Case 2	Case 3
0%	ABC	0.048	0.046	0.048	0.050
0%	AG	0.056	0.052	0.058	
0%	AB	0.051	0.042	0.054	0.076
0%	ABG	0.054	0.050	0.062	0.063
25%	ABC	0.049	0.049	0.051	0.053
25%	AG	0.057	0.053	0.047	
25%	AB	0.054	0.044	0.046	0.063
25%	ABG	0.053	0.051	0.065	0.062
50%	ABC	0.054	0.050	0.058	0.057
50%	AG	0.056	0.054	0.055	
50%	AB	0.050	0.040	0.063	0.067
50%	ABG	0.049	0.054	0.065	
75%	ABC	0.055	0.051	0.060	0.067
75%	AG				
75%	AB	0.054	0.039	0.075	0.082
75%	ABG	0.050	0.054	0.070	
Legend					
	Undesirable		Mis-operation		

RM-02		Base	IBR		
FLTLOC	TYP		Case 1	Case 2	Case 3
0%	ABC	0.034	0.042		
0%	AG	0.033	0.034	0.034	
0%	AB	0.032	0.036	0.039	0.035
0%	ABG	0.035	0.049	0.045	0.048
25%	ABC	0.039	0.043	0.045	0.063
25%	AG	0.037	0.040		
25%	AB	0.038	0.038	0.043	0.036
25%	ABG	0.042	0.048	0.044	0.042
50%	ABC	0.045	0.042	0.039	0.047
50%	AG	0.042	0.041		
50%	AB	0.043	0.040	0.042	0.042
50%	ABG	0.044	0.051	0.049	0.046
75%	ABC	0.054	0.049	0.063	0.046
75%	AG	0.056	0.048		
75%	AB	0.056	0.066	0.070	0.077
75%	ABG	0.057	0.070	0.070	0.050
Legend					
	Undesirable		Mis-operation		

RM-03		Base	IBR		
FLTLOC	TYP		Case 1	Case 2	Case 3
0%	ABC	0.042	0.043	0.042	0.048
0%	AG	0.043	0.041	0.038	0.034
0%	AB	0.037	0.041	0.034	0.038
0%	ABG	0.050	0.043	0.052	0.044
25%	ABC	0.041	0.042	0.046	0.044
25%	AG	0.042	0.039	0.044	0.032
25%	AB	0.039	0.038	0.035	0.034
25%	ABG	0.044	0.048	0.049	0.046
50%	ABC	0.043	0.044	0.042	0.046
50%	AG	0.042	0.047	0.038	0.041
50%	AB	0.042	0.037	0.042	0.038
50%	ABG	0.041	0.050	0.049	0.043
75%	ABC	0.046	0.051	0.050	0.047
75%	AG	0.038	0.040	0.043	0.038
75%	AB	0.038	0.040	0.042	0.042
75%	ABG	0.043	0.047	0.050	0.049
Legend					
	Undesirable		Mis-operation		

RM-04		Base	IBR		
FLTLOC	TYP		Case 1	Case 2	Case 3
0%	ABC	0.037	0.040	0.040	0.038
0%	AG	0.038	0.037		
0%	AB	0.030	0.036	0.034	
0%	ABG	0.042	0.038	0.047	0.051
25%	ABC	0.041	0.038	0.041	0.045
25%	AG	0.039	0.050		
25%	AB	0.038	0.038	0.034	0.040
25%	ABG	0.077	0.047	0.041	0.044
50%	ABC	0.040	0.046	0.046	0.042
50%	AG	0.042	0.046		
50%	AB	0.038	0.038	0.041	
50%	ABG	0.048	0.054	0.054	0.052
75%	ABC	0.046	0.044	0.048	0.043
75%	AG	0.050			
75%	AB	0.038	0.044	0.041	
75%	ABG	0.049	0.055	0.062	

RM-05		Base	IBR		
FLTLOC	TYP		Case 1	Case 2	Case 3
0%	ABC	0.035	0.012	0.013	0.015
0%	AG	0.034	0.014	0.026	0.022
0%	AB	0.031	0.022		0.019
0%	ABG	0.038	0.013	0.015	0.018
25%	ABC	0.035	0.013	0.017	0.014
25%	AG	0.038	0.014	0.015	0.026
25%	AB	0.031	0.022		0.022
25%	ABG	0.036	0.018	0.014	0.014
50%	ABC	0.034	0.017	0.017	0.032
50%	AG	0.043	0.014	0.014	0.029
50%	AB	0.033	0.027	0.014	
50%	ABG	0.038	0.014	0.017	0.015
75%	ABC	0.040	0.026	0.038	0.058
75%	AG	0.049	0.013	0.047	0.054
75%	AB				
75%	ABG		0.053	0.058	0.036
Legend					
	Undesirable		Mis-operation		

RM-06		Base	IBR		
FLTLOC	TYP		Case 1	Case 2	Case 3
0%	ABC	0.032	0.026	0.026	0.037
0%	AG	0.032	0.030	0.041	
0%	AB	0.028	0.025	0.038	0.052
0%	ABG	0.034	0.037	0.044	0.067
25%	ABC	0.031	0.026	0.030	0.036
25%	AG	0.034	0.032	0.048	
25%	AB	0.030	0.030	0.042	0.053
25%	ABG	0.032	0.034	0.055	0.066
50%	ABC	0.031	0.054	0.050	0.055
50%	AG	0.036	0.044	0.046	
50%	AB	0.030	0.043	0.050	0.059
50%	ABG	0.030	0.059	0.064	0.062
75%	ABC	0.050	0.056	0.057	0.056
75%	AG	0.039	0.050	0.053	
75%	AB	0.037	0.057	0.054	0.070
75%	ABG	0.045	0.060	0.067	0.073
Legend					
	Undesirable		Mis-operation		

- Root Cause for Zone 1 misoperations
  - Use of Zone 5 as instantaneous zone → missing stabilization
  - Wrong fault loop selection
  - Wrong direction determination
- Mitigation
  - Only use Zone 1 as instantaneous element
  - Select CCVT transient filter
  - Use specialized logic (proposed solution from manufacturer)

Test Results Details – Zone 2 Misoperations

- Root Cause for Zone 2 misoperations
  - Wrong fault loop selection
  - Wrong direction determination

- Mitigation
  - Use specialized logic (proposed solution from manufacturer)

RM-02		Base	IBR		
FLTLOC	TYP		Case 1	Case 2	Case 3
100%	ABC	0.530	0.532	0.531	0.533
100%	AG	0.526	0.530		
100%	AB	0.529	0.535	0.532	0.535
100%	ABG	0.529	0.532	0.531	0.532
115%	ABC	0.530	0.530	0.530	0.536
115%	AG	0.533	0.535		
115%	AB	0.535	0.534	0.535	0.531
115%	ABG	0.537	0.539	0.533	0.538
130%	ABC	0.541			
130%	AG				
130%	AB				
130%	ABG			0.811	0.744
Legend					
	Undesirable		Mis-operation		

RM-03		Base	IBR		
FLTLOC	TYP		Case 1	Case 2	Case 3
100%	ABC	0.537	0.538	0.540	0.555
100%	AG	0.531	0.529	0.538	0.541
100%	AB	0.531	0.536	0.538	0.542
100%	ABG	0.529	0.538	0.537	0.534
115%	ABC	0.533	0.536	0.536	0.550
115%	AG	0.534	0.542	0.539	0.533
115%	AB	0.535	0.547	0.537	0.545
115%	ABG	0.534	0.539	0.532	0.542
130%	ABC	0.530			
130%	AG	0.533			
130%	AB				
130%	ABG				
Legend					
	Undesirable		Mis-operation		

RM-04		Base	IBR		
FLTLOC	TYP		Case 1	Case 2	Case 3
100%	ABC	0.528	0.533	0.532	0.534
100%	AG	0.531			
100%	AB	0.531	0.533	0.532	
100%	ABG	0.530	0.529	0.529	
115%	ABC	0.535	0.534	0.534	0.534
115%	AG	0.532			
115%	AB	0.534	0.539	0.538	
115%	ABG	0.532	0.538	0.536	
130%	ABC				
130%	AG				
130%	AB				
130%	ABG				
Legend					
	Undesirable		Mis-operation		

RM-05		Base	IBR		
FLTLOC	TYP		Case 1	Case 2	Case 3
100%	ABC	0.527	0.522	0.513	0.523
100%	AG	0.530	0.515	0.529	0.527
100%	AB	0.529			
100%	ABG	0.526	0.522	0.525	0.527
115%	ABC	0.530	0.529	0.526	0.535
115%	AG	0.528	0.554	0.541	0.541
115%	AB	0.545			
115%	ABG	0.543	0.559	0.538	0.534
130%	ABC				
130%	AG				
130%	AB				
130%	ABG				
Legend					
	Undesirable		Mis-operation		

RM-06		Base	IBR		
FLTLOC	TYP		Case 1	Case 2	Case 3
100%	ABC	0.514	0.515	0.516	0.525
100%	AG	0.516	0.525	0.551	
100%	AB	0.517	0.528	0.527	
100%	ABG	0.518	0.515	0.590	
115%	ABC	0.515	0.516	0.545	0.526
115%	AG	0.514	0.529		
115%	AB	0.522	0.526	0.530	
115%	ABG	0.522	0.550		
130%	ABC				
130%	AG				
130%	AB				
130%	ABG	0.662			
Legend					
	Undesirable		Mis-operation		

Test Results Details – Zone 4 Misoperations

RM-02		Base	IBR		
FLTLOC	TYP		Case 1	Case 2	Case 3
100%	ABC	1.023	1.024	1.023	1.025
100%	AG	1.021	1.019		
100%	AB	1.021	1.026	1.025	
100%	ABG	1.022	1.032	1.025	1.023
115%	ABC	1.023	1.030	1.030	1.024
115%	AG	1.022	1.021		
115%	AB	1.025	1.030	1.033	
115%	ABG	1.026	1.029	1.033	1.046
130%	ABC	1.025	1.029	1.031	1.025
130%	AG	1.025			
130%	AB	1.028	1.026	1.032	
130%	ABG	1.023	1.030	1.032	1.026
145%	ABC	1.029	1.030	1.031	1.025
145%	AG	1.022			
145%	AB	1.028		1.032	
145%	ABG	1.027	1.032	1.034	
160%	ABC	1.030	1.034	1.031	1.054
160%	AG	1.026			
160%	AB	1.029		1.032	
160%	ABG	1.030		1.034	
Legend					
	Undesirable		Mis-operation		

RM-03		Base	IBR		
FLTLOC	TYP		Case 1	Case 2	Case 3
100%	ABC	1.032	1.038	1.039	1.054
100%	AG	1.034	1.028	1.038	1.040
100%	AB	1.026	1.035	1.037	1.041
100%	ABG	1.029	1.038	1.035	1.034
115%	ABC	1.037	1.034	1.034	1.050
115%	AG	1.033	1.042	1.038	1.032
115%	AB	1.031	1.046	1.036	1.043
115%	ABG	1.032	1.040	1.031	1.041
130%	ABC	1.031	1.037	1.036	1.057
130%	AG	1.031	1.032	1.031	1.057
130%	AB	1.033	1.039	1.038	1.042
130%	ABG	1.034	1.042	1.031	1.041
145%	ABC	1.034	1.050	1.041	1.052
145%	AG	1.035	1.037	1.037	1.070
145%	AB	1.041	1.047	1.042	1.038
145%	ABG	1.034	1.040	1.037	1.042
160%	ABC	1.033	1.054	1.044	1.054
160%	AG	1.032	1.040	1.041	1.058
160%	AB	1.039	1.065	1.045	1.065
160%	ABG	1.034	1.037	1.038	1.037
Legend					
	Undesirable		Mis-operation		

RM-04		Base	IBR		
FLTLOC	TYP		Case 1	Case 2	Case 3
100%	ABC	1.023	1.028	1.027	1.028
100%	AG	1.024			
100%	AB	1.027	1.028	1.029	
100%	ABG	1.023	1.037	1.022	
115%	ABC	1.025	1.029	1.030	1.026
115%	AG	1.023			
115%	AB	1.027	1.030	1.030	
115%	ABG	1.025	1.024	1.022	
130%	ABC	1.028	1.032	1.030	1.028
130%	AG	1.026			
130%	AB	1.028	1.033	1.033	
130%	ABG	1.027	1.028	1.024	
145%	ABC	1.031	1.033	1.031	1.024
145%	AG	1.026			
145%	AB		1.034	1.034	
145%	ABG	1.032		1.066	
160%	ABC	1.032	1.036	1.034	1.026
160%	AG	1.030			
160%	AB			1.037	
160%	ABG				
Legend					
	Undesirable		Mis-operation		

RM-05		Base	IBR		
FLTLOC	TYP		Case 1	Case 2	Case 3
100%	ABC	1.027	1.022	1.016	1.017
100%	AG	1.027	1.012	1.012	1.014
100%	AB	1.026			
100%	ABG	1.029	1.022	1.018	1.015
115%	ABC	1.026	1.026	1.022	1.022
115%	AG	1.028	1.014	1.014	1.014
115%	AB	1.031			
115%	ABG	1.030	1.016	1.016	1.017
130%	ABC	1.025	1.020	1.021	1.020
130%	AG	1.028	1.018	1.014	1.026
130%	AB	1.027			
130%	ABG	1.026	1.022	1.015	1.026
145%	ABC	1.030	1.029	1.025	1.022
145%	AG	1.028	1.023	1.015	1.025
145%	AB				
145%	ABG	1.026	1.023	1.024	1.022
160%	ABC	1.025	1.030	1.021	1.027
160%	AG	1.023	1.025	1.030	1.026
160%	AB				
160%	ABG	1.026	1.022	1.025	1.026
Legend					
	Undesirable		Mis-operation		

RM-06		Base	IBR		
FLTLOC	TYP		Case 1	Case 2	Case 3
100%	ABC	1.022	1.024	1.024	1.023
100%	AG	1.022	1.023	1.051	
100%	AB	1.023	1.024	1.025	
100%	ABG	1.026	1.023		
115%	ABC	1.022	1.024	1.024	1.022
115%	AG	1.022	1.022		
115%	AB	1.024	1.026	1.030	
115%	ABG	1.022	1.027		
130%	ABC	1.022	1.024	1.025	1.024
130%	AG	1.023	1.031		
130%	AB	1.023	1.028	1.030	
130%	ABG	1.024			
145%	ABC	1.023	1.026	1.024	1.023
145%	AG	1.023			
145%	AB	1.024	1.031	1.046	
145%	ABG	1.028			
160%	ABC	1.024	1.028	1.026	1.054
160%	AG	1.022			
160%	AB	1.027	1.046	1.046	
160%	ABG	1.027			
Legend					
	Undesirable		Mis-operation		

- Root Cause for Zone 4 misoperations
  - Wrong fault loop selection
  - Wrong direction determination
- Mitigation
  - Use specialized logic (proposed solution from manufacturer)
  - Use stabilization logic to stabilize intermittent pick-up

Evaluated Vendor-Recommended Mitigation Solutions

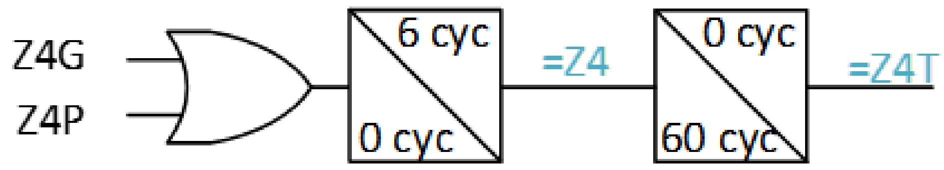
- Relay model RM-02 – Vendor suggested to only use zone 1 for high-speed tripping instead of using Quadrilateral characteristics with zone 5 (it has the same reach as zone 1) for high-speed tripping
  - Zone 2 to 5 are used for delayed trip applications
- Results show some improvement
  - Reduced the total number of misoperations from 8 to 4 for zone 2, mostly for Hi-IBR case #2
  - Similar results for zone 4

- Another relay model RM-04
  - Vendor recommended to disable the CCVT transient compensation for zone 1 misoperation
- Results mixed
  - Solution solves the underreach issue for Hi-IBR case #1 and #2, but does not for Hi-IBR case #3, and
  - The solution created the overreach misoperation issues

Evaluated Proposed Mitigation Solutions

- For mitigating incorrect directional determination – Use most reliable polarizing quantity for directional element
  - Ground directional polarization priorities: $V_0 \geq I_0 \geq V_2$
  - Phase directional polarization priorities: $V_1 \geq V_2$
  - Decrease the sensitivity of the negative-sequence based directional elements
- Results show great improvement but not 100%

- For mitigating unstable fault type selection – Use a sample-and-hold logic
  - The logic as shown below to sustain the Zone 4 pickup triggered by Z4G or Z4P
- Results show significant improvement but not 100%



Section 4

CONCLUSIONS

Conclusions

- This directional elements and fault type identification logic are the most impacted relay protection functions.
- The key negative impact on distance protection is the under-reach issue. Our investigation suggests that the unconventional angle relationship between voltage and current is the leading cause for this project.
- No obvious negative impact is observed on the current differential protection.
- High IBR penetration negatively impacts most of relay models tested in this project, but the severity level varies significantly.
- We developed two mitigation strategies for directional and fault identification issues, respectively. These mitigation solutions have shown to be effective in reducing the number of misoperations. Still, they are insufficient to correct all reported misoperations, and some relay models lack the necessary setting customization to implement the proposed mitigation strategy.
- Further investigation will be needed to determine whether setting customization would be sufficient to mitigate the identified issues. If not, new relaying algorithms/methods must be developed and implemented to address the identified issues fully.