



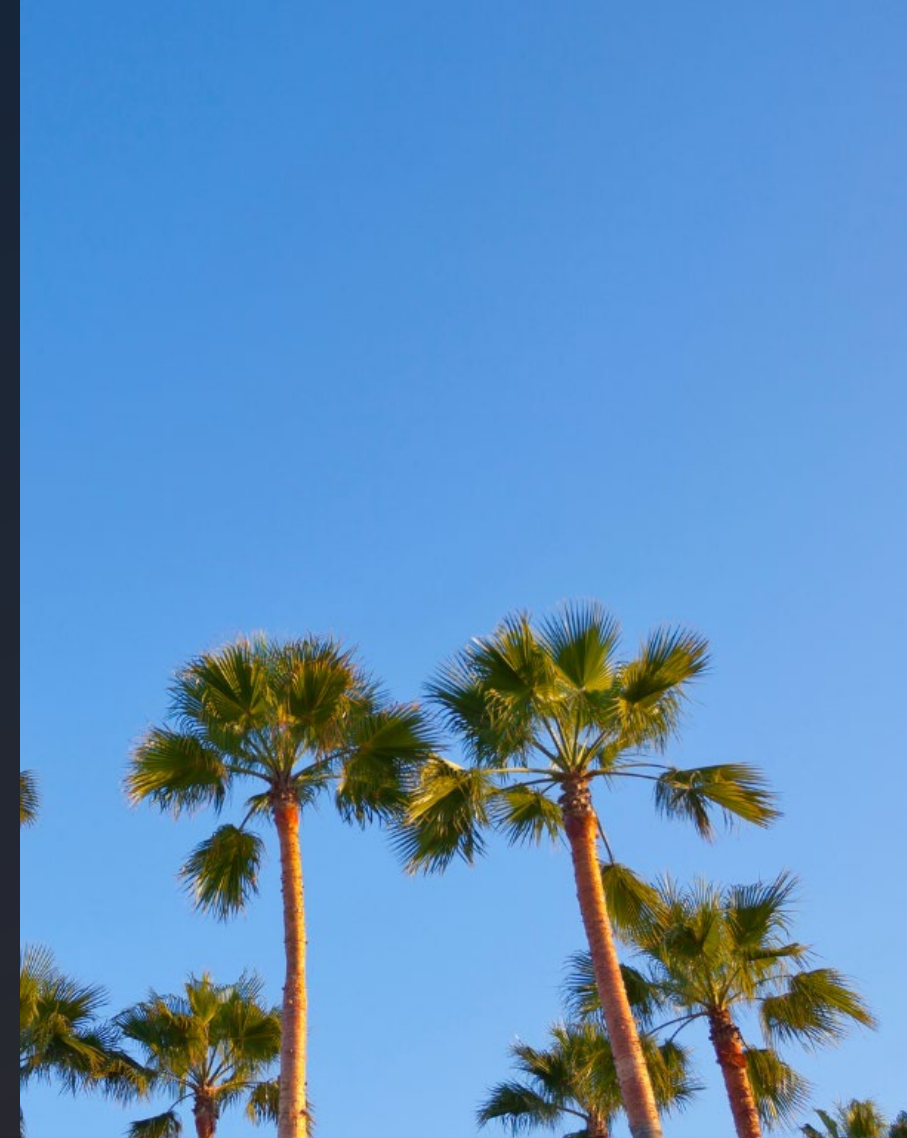
Protection System Performance in IBR Dominated Grids: Insights from RTDS Studies

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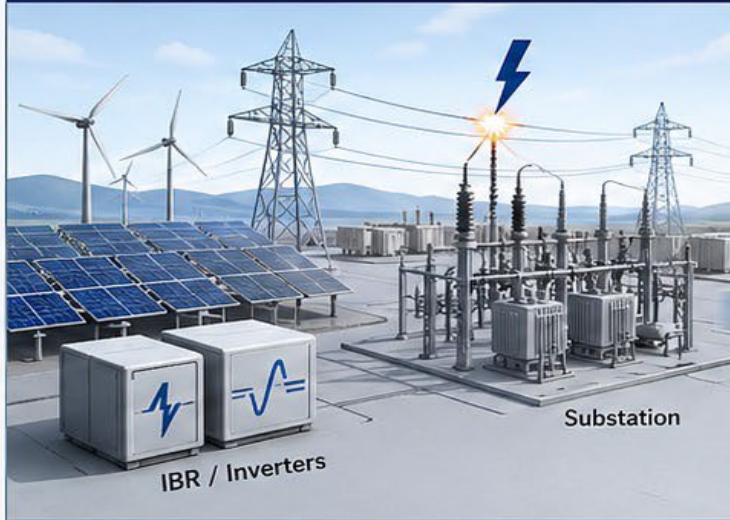


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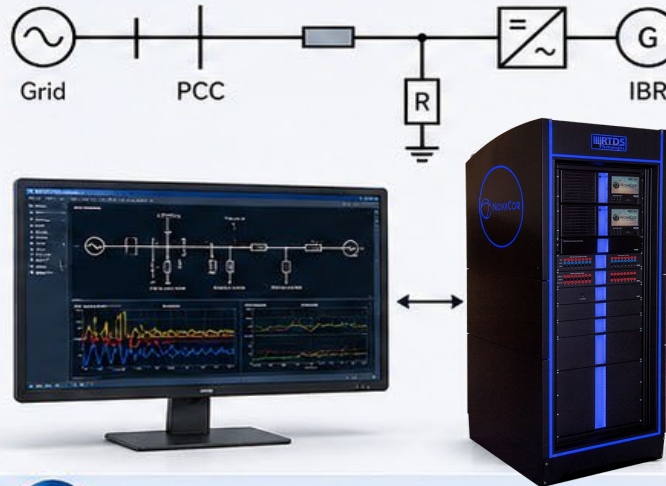
Study Overview

1 IBR-Dominated Grid



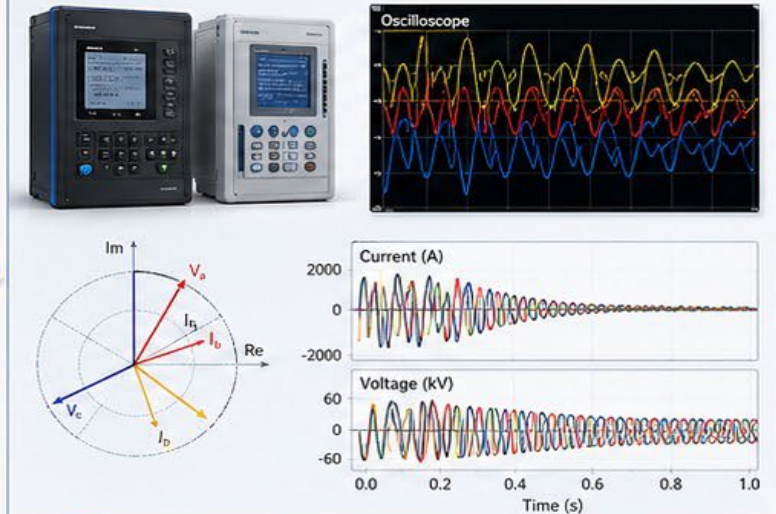
- ⚡ Changing disturbance behavior
- 🛡️ Evolving protection challenges

2 RTDS Study Platform



- 🕒 Real-Time EMT Simulation
- 🛡️ Protection-Oriented Model
- 🌪️ IBR Integration

3 Protection Insights



- 📊 Performance Evaluation
- 🔍 Protection-Relevant Behavior
- 💡 Practical Modeling Lessons

Framework used to study protection-relevant behavior under increasing IBR penetration.

Motivation and Objectives

Why this study matters

- Inverter Based Resources (IBRs) are replacing synchronous generation, changing fault behavior
- Lower fault currents, limited zero-sequence injection, and loss of polarizing voltage
- Legacy distance protection assumptions no longer hold at high IBR levels
- Phasor-domain tools may not capture these effects, EMT simulation is essential

Objectives

- Build a protection-oriented RTDS platform using IEEE 24-bus system
- Study distance relay performance across low, medium, and high IBR penetration
- Observe distance relay behavior, including potential underreach and mis-operation patterns.

RTDS - Study Framework

01 WE BUILD



Detailed IEEE 24-Bus RTDS Model

- ▶ Built from scratch in RSCAD
- ▶ Substations, transformers, breakers, measurements



IBR Scenario Development

- ▶ Conventional and IBR cases
- ▶ Multiple penetration levels
- ▶ Detailed and aggregated IBR representation

02 WE STUDY



Fault Studies 240 Corridor

- ▶ SLG and LL transmission faults
- ▶ Sub 30–Sub 240 and Sub 240–Sub 150



Relay-Facing Measurements

- ▶ 3 ϕ voltage and current signals
- ▶ CT/PT measurement points
- ▶ Signals fed to RSCAD protection elements



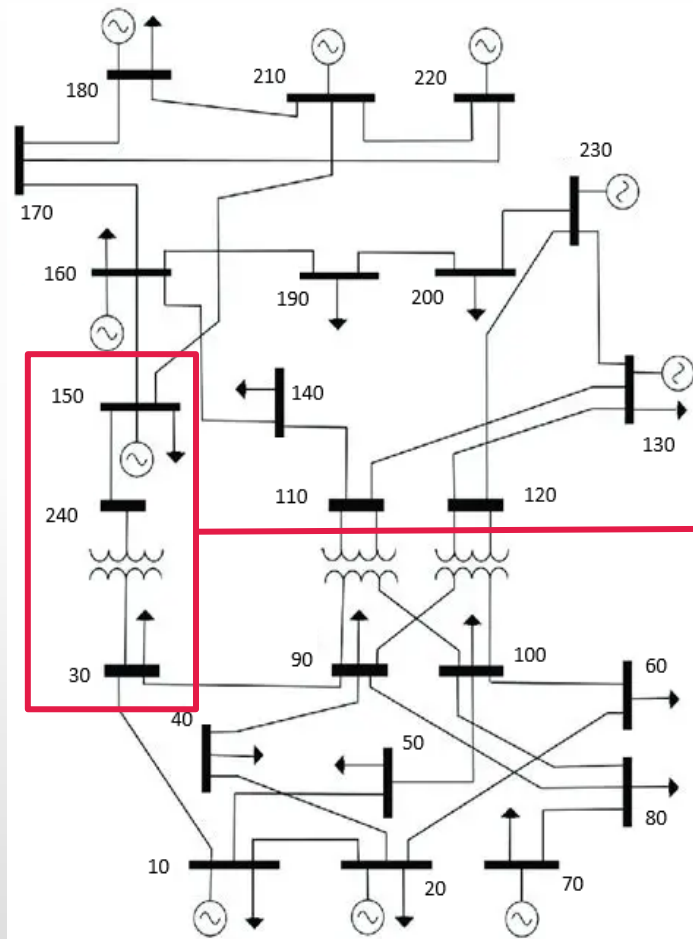
RSCAD Distance Relay Response

- ▶ Legacy distance protection behavior
- ▶ Operation compared across IBR scenarios

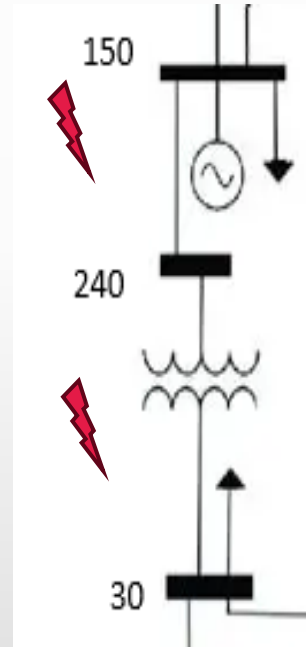
Same RTDS environment, every scenario.

Built to isolate how legacy distance protection responds as IBR penetration changes.

Study System and Protection Corridor



IEEE 24-Bus Reference System



Protection Corridor

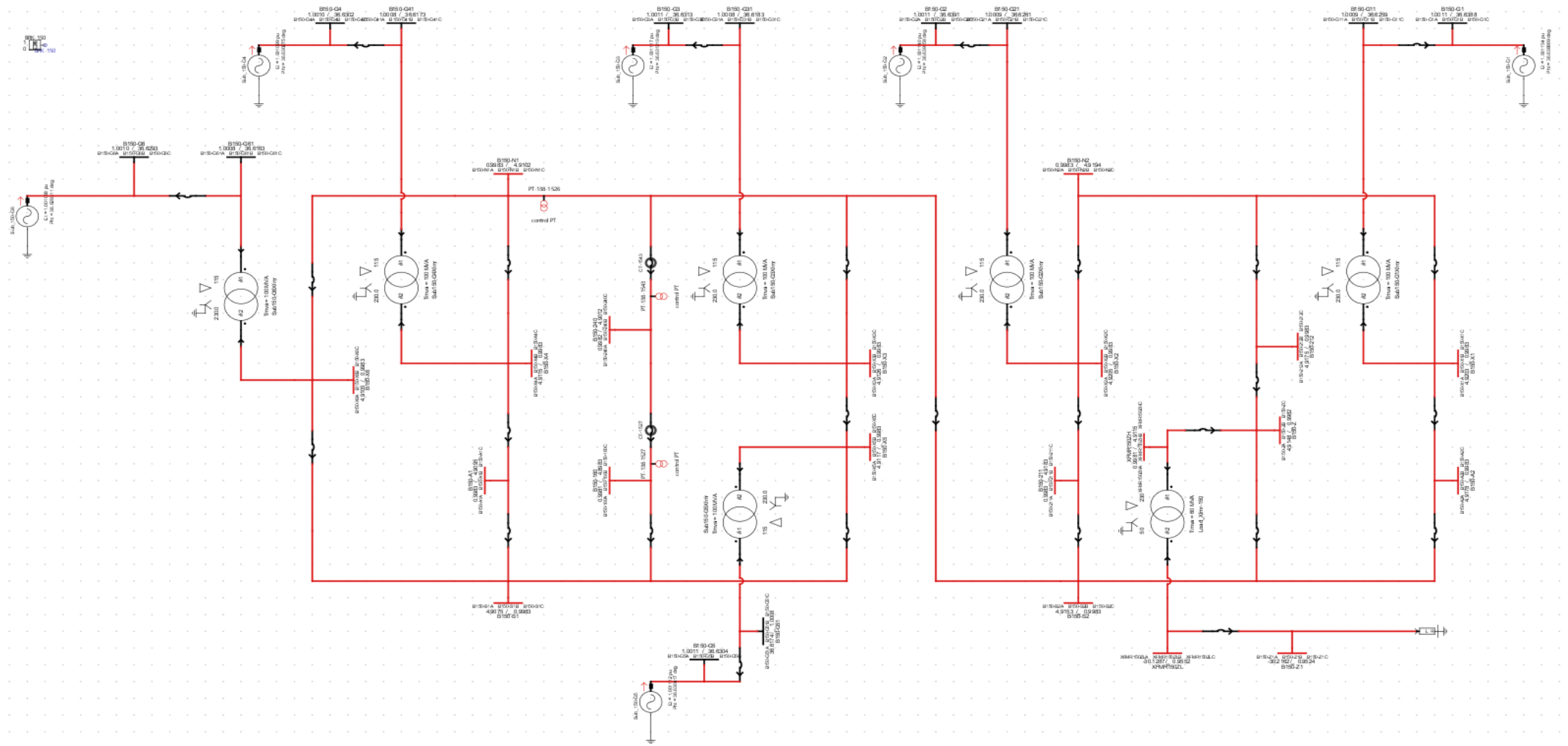
Selected 240 Protection Corridor:

- Sub 150 — Sub 240 — Sub 30

Key features of selected corridor

- CT/PT measurement points
- Fault application region
- Distance relay study corridor

Detailed Substation 150 in RTDS



IBR Scenario Development

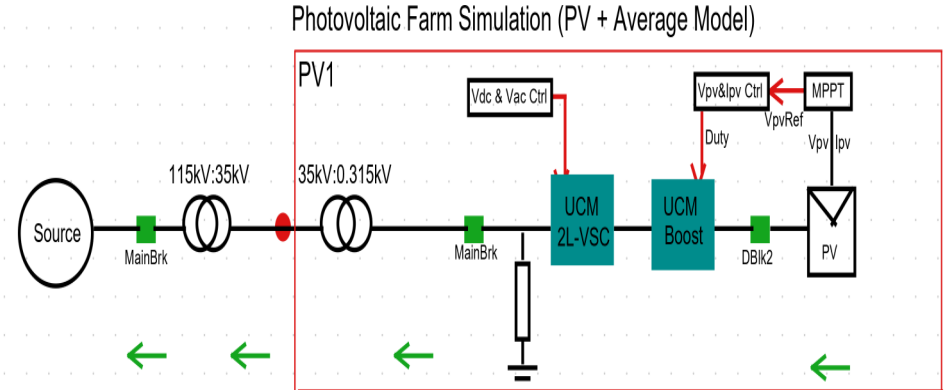
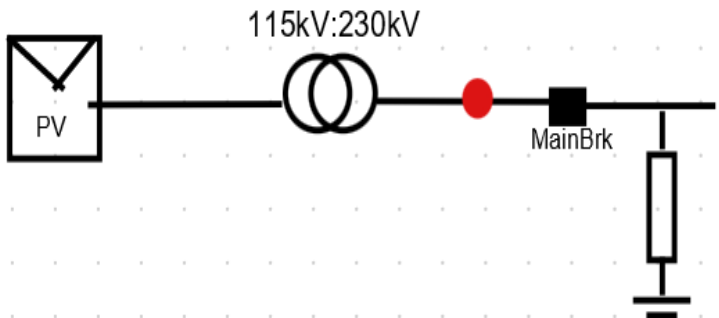
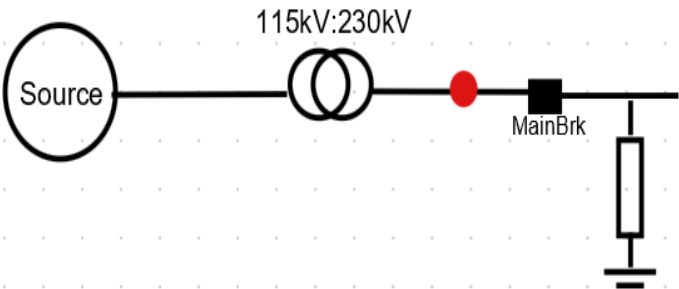
Sub 150 conventional generators were replaced with PV/IBR representations.

Generator Case

- Six 115 kV generator locations at Sub 150
- Baseline source representation
- Local P/V/I recorded before replacement

PV Replacement

- Each generator location replaced with a PV
- Same network connection
- Detailed RTDS PV farm model used

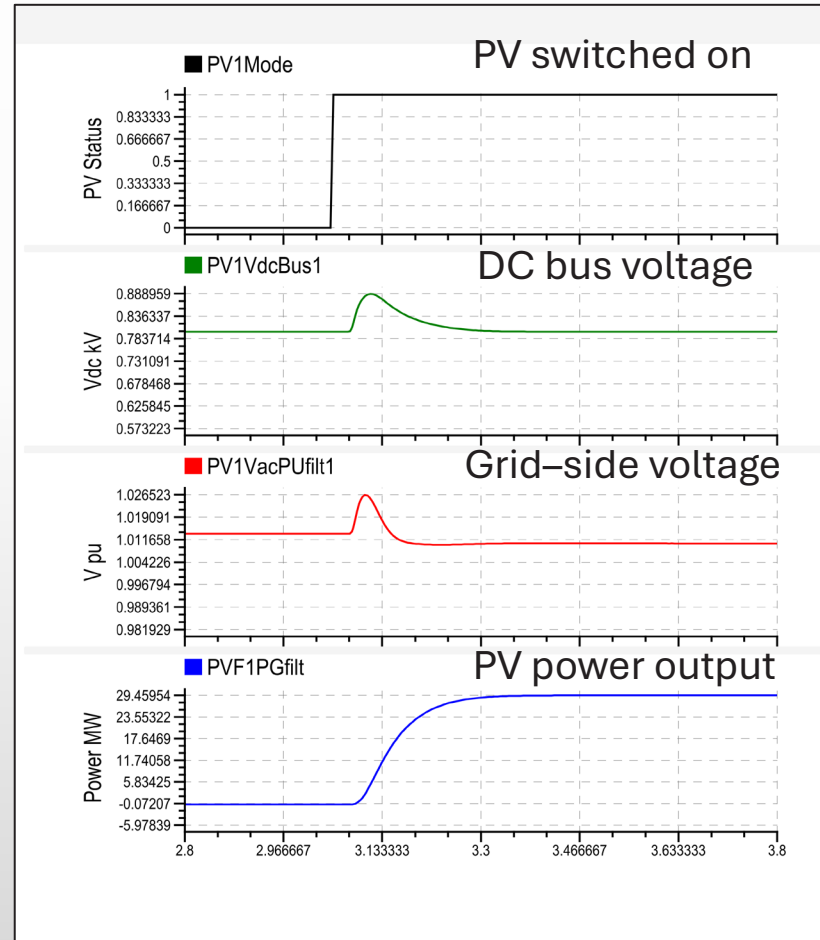


PV Model Response Check

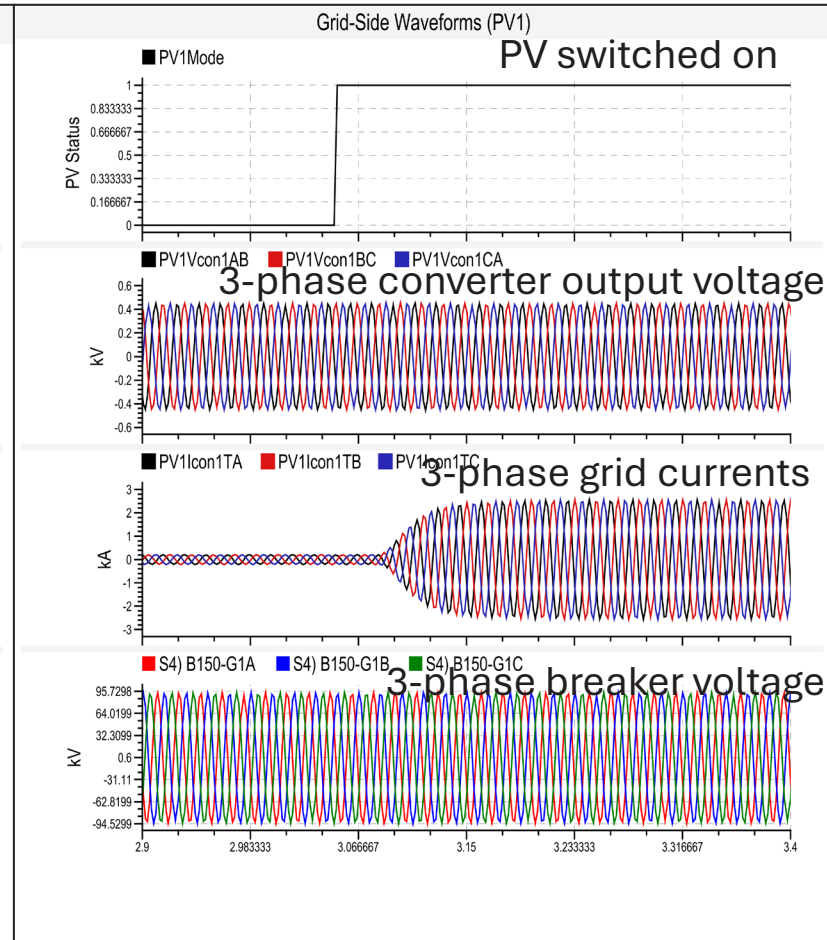
PV model response check

- PV switched on and reached steady operation
- Active power output followed the setpoint
- Grid side voltage and current remained stable before fault application

PV Control and Power Response

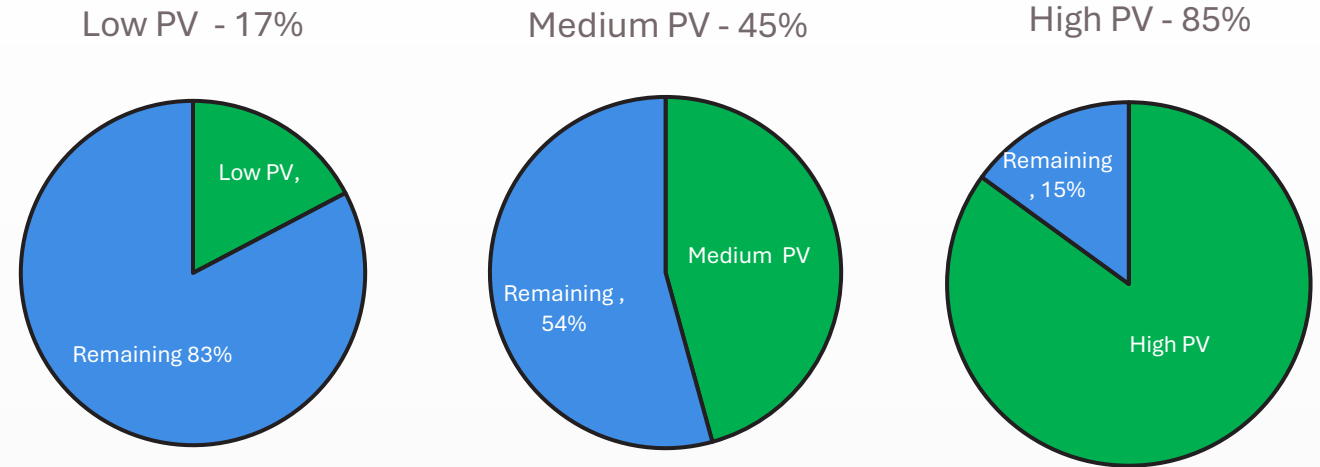


Grid-Side Voltage and Current



PV Penetration Scenarios and Pre-Fault Check

- This PV penetration levels define the study cases
- The local pre-fault check confirms comparable operating conditions before faults are applied.



Local Pre-Fault Check at Sub 150					
Location	Parameter	Gen Case	Low PV case	Medium PV Case	High PV Case
Local Gen 1	Real Power (MW)	29.72	29.62	29.62	29.67
	Voltage (pu)	1.000	0.998	1.006	1.011
	Current (kA)	0.150	0.149	0.147	0.147

Local real power, voltage, and current stayed comparable across cases before applying faults.

Modeling Challenge: Model Detail vs RTDS Capacity

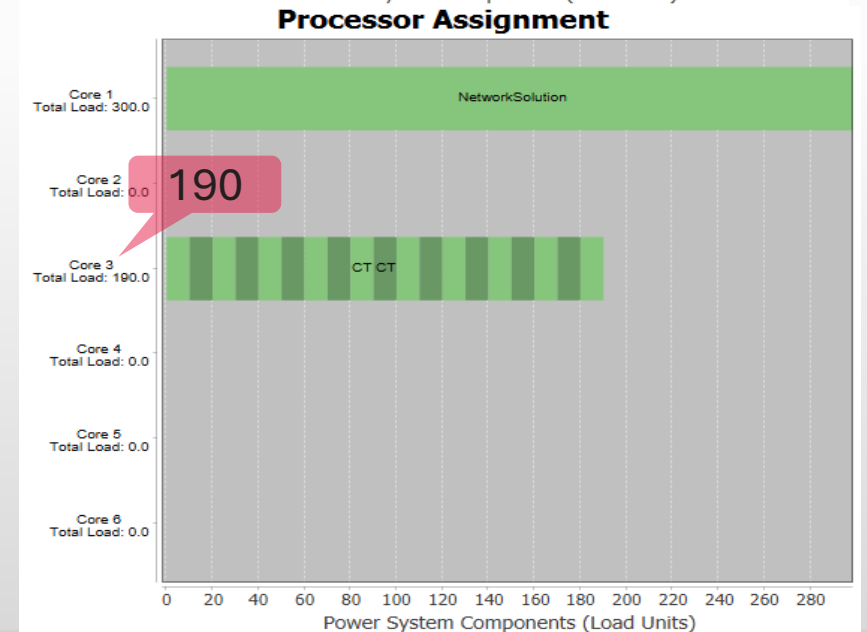
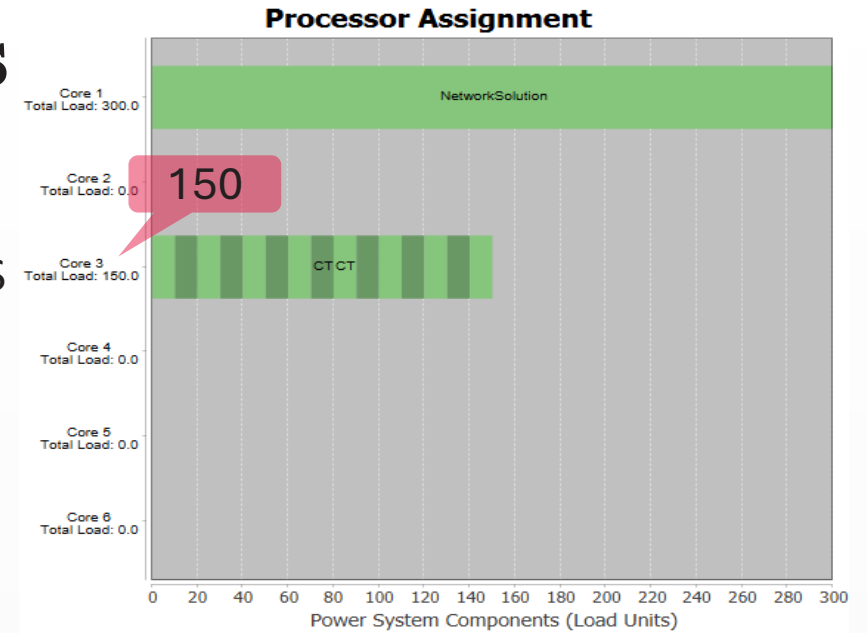
Replacing every generator with detailed PV models was not practical due to RTDS load-unit usage and processor headroom limits.

RTDS Resource Impact

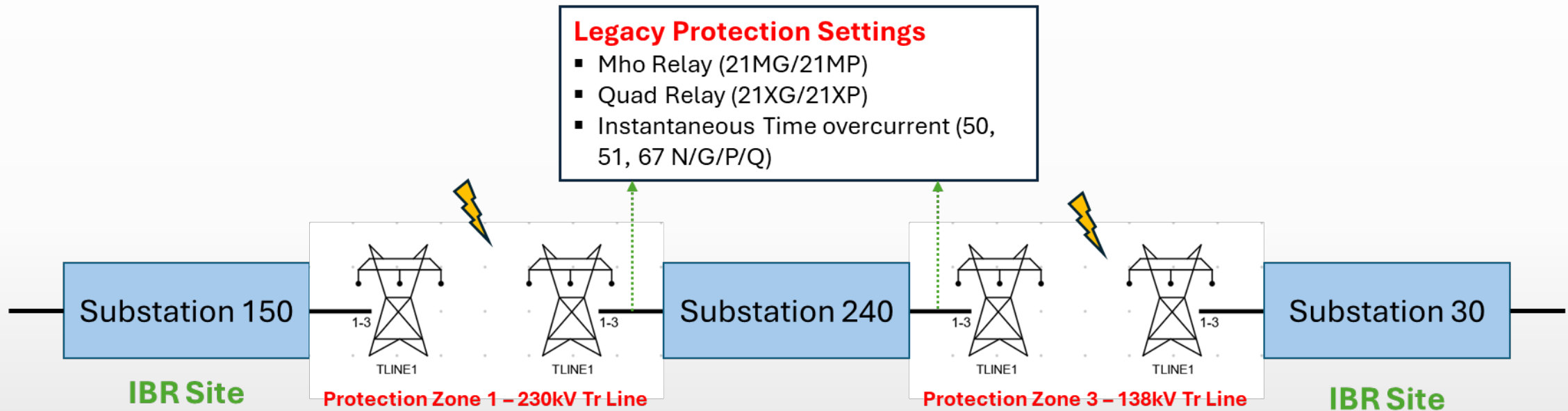
- Original circuit before detailed PV: **~150** load units
- After one detailed PV replacement: **~210** load units
- After transformer optimization: **~190** load units

Area	Original configuration	Model choice
Substation 150	115 kV, 5 x 100 MVA + 1 x 155 MVA	Detailed PV farm models
Substation 30	0.48 kV, 26 MVA total	Distribution-level PV
Other Generators	Remaining generator groups	Aggregated equivalents

Detailed models were used near the protection corridor, and aggregated equivalents were used elsewhere to maintain RTDS capacity.



Fault Scenarios with Varying IBR

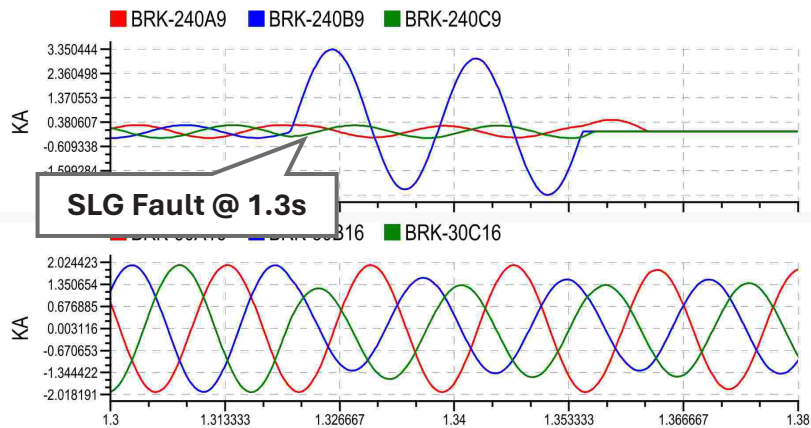


IBR Fault Current Characteristics

No PV penetration

Peak fault current = **3.35 kA**

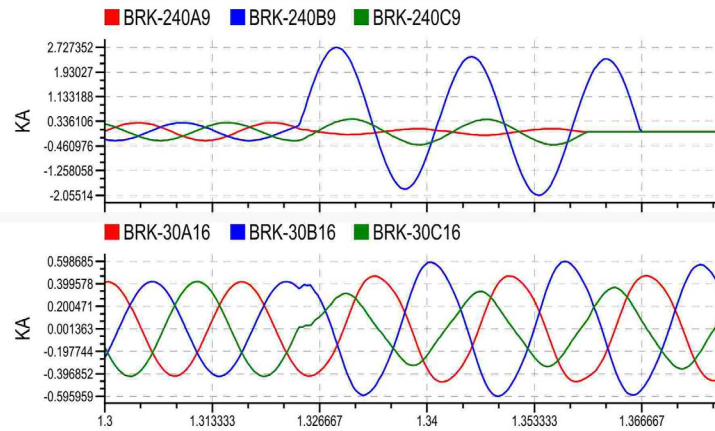
Peak fault current from substation 30 = **1.35 kA**



Medium PV penetration

Peak fault current = **2.72 kA**

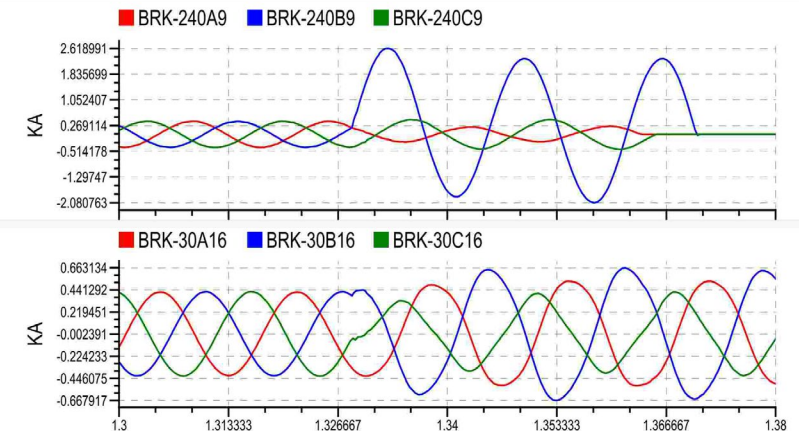
Peak IBR fault current = **0.598 kA**



High PV penetration

Peak fault current = **2.62 kA**

Peak IBR fault current = **0.663 kA**



Current Limiting

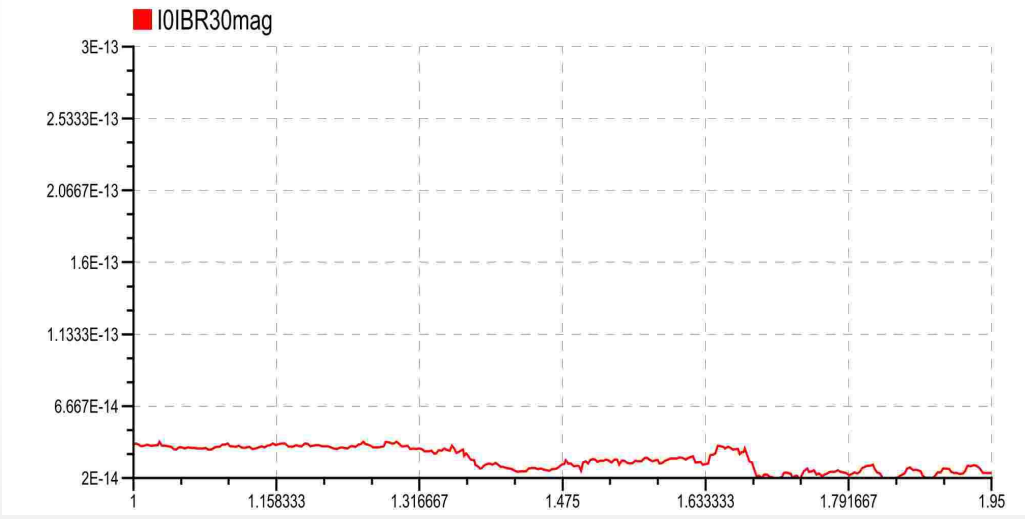
Fault current magnitude decreases significantly with higher IBR penetration compared to the case with no IBRs in the system.

Distance Protection Challenges – Ground Fault Detection

Medium PV penetration



High PV penetration

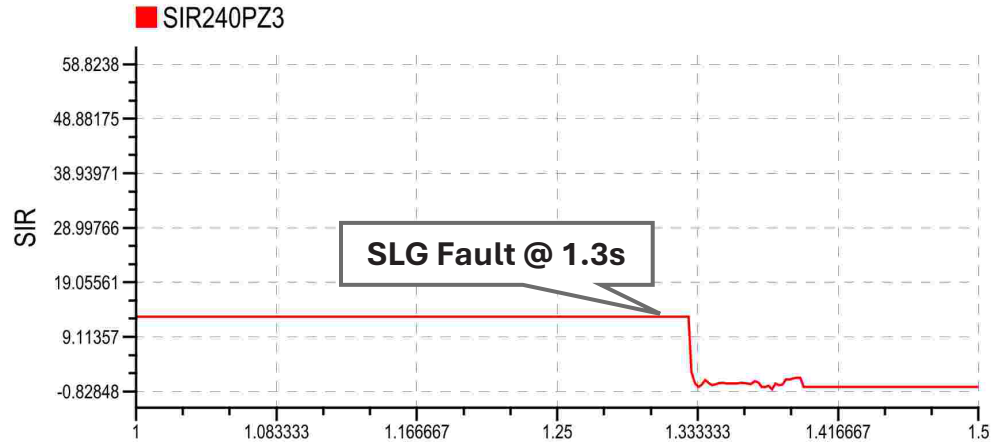


Ground Fault Detection

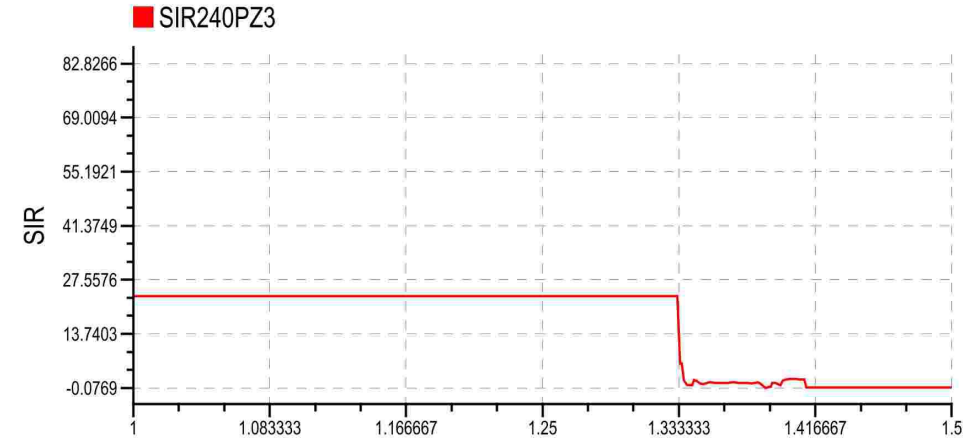
IBRs often inject little or no zero-sequence current during SLG faults, undermining ground distance elements and directional polarization.

The Source Impedance Ratio Problem

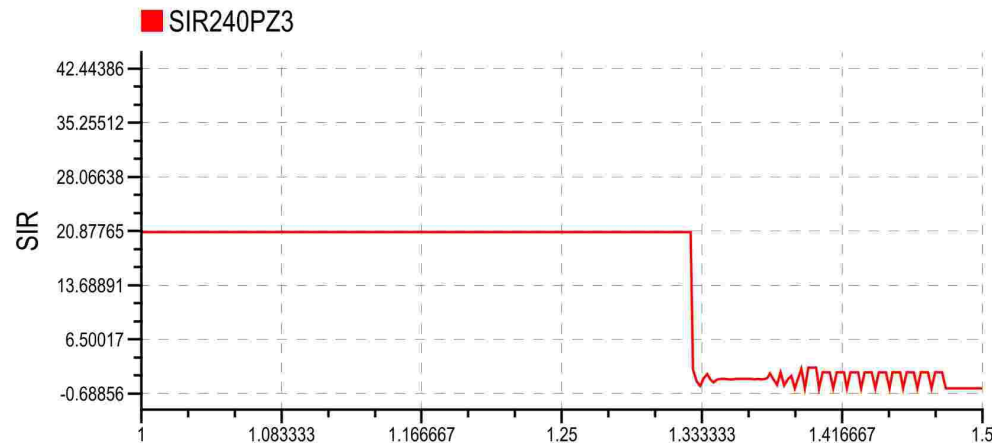
No PV penetration



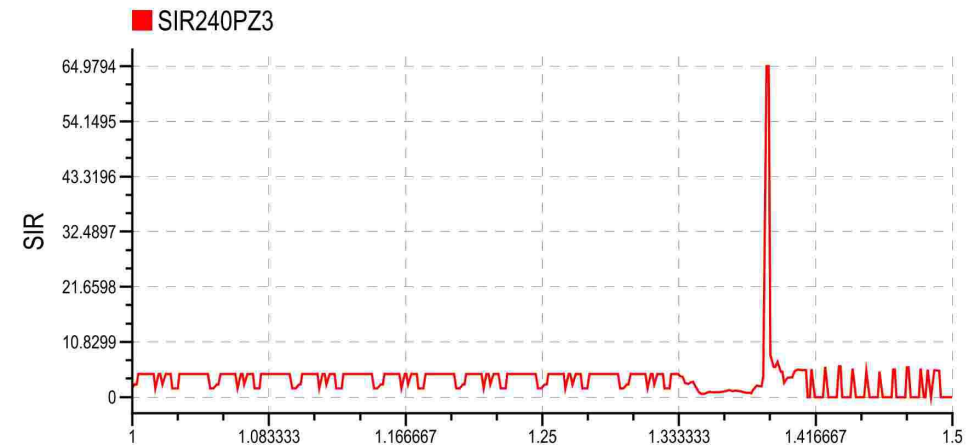
Medium PV penetration



Low PV penetration



High PV penetration



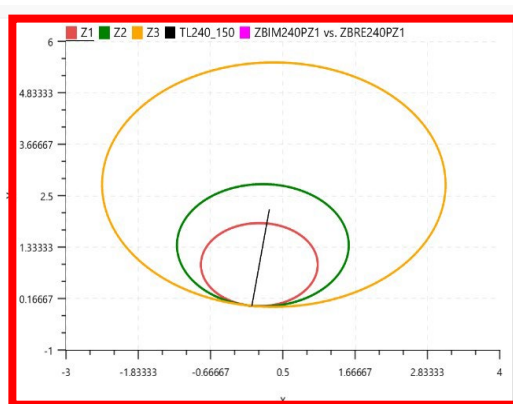
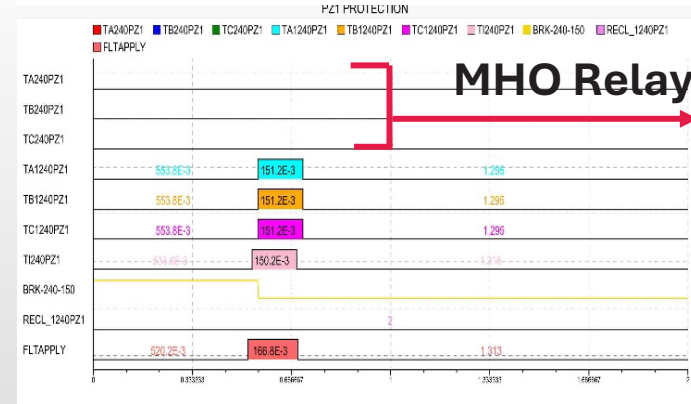
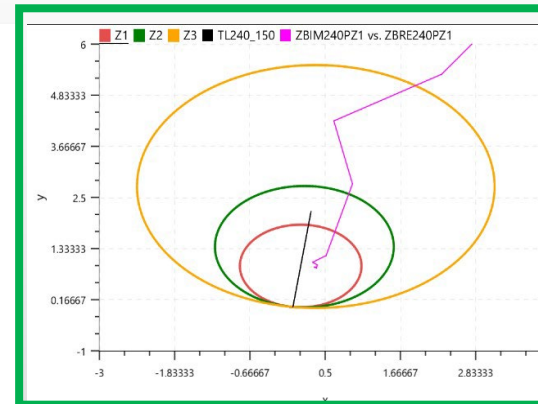
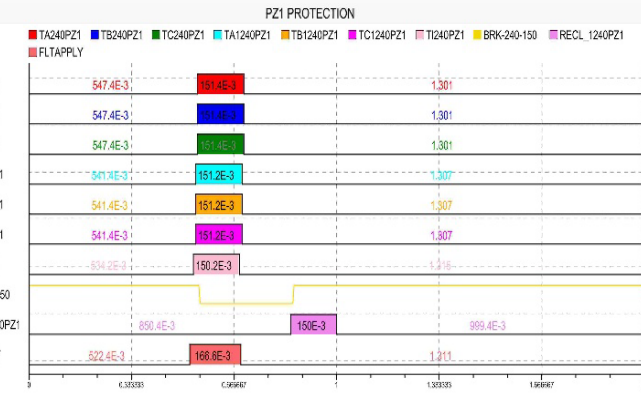
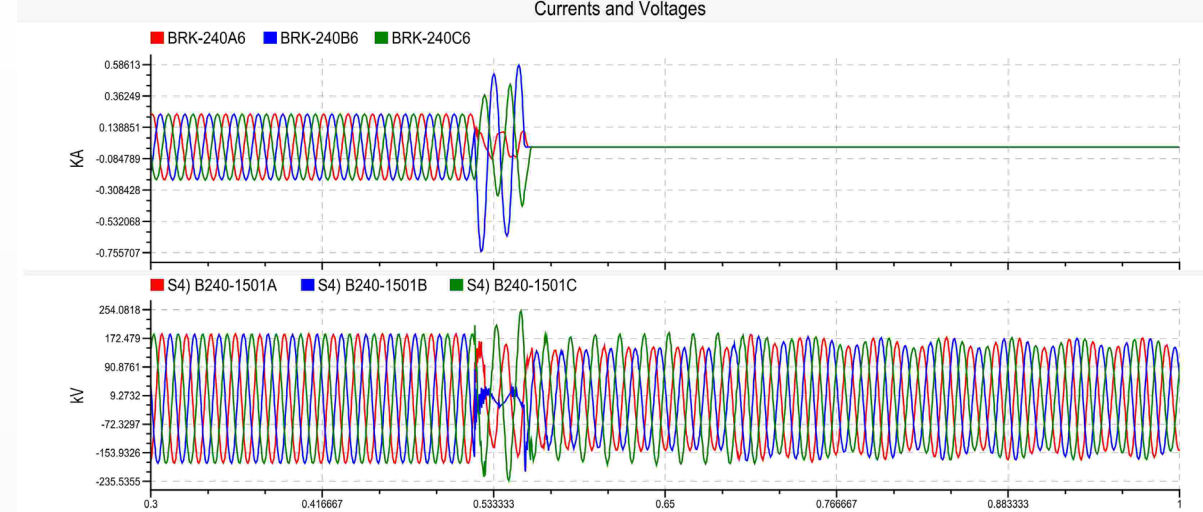
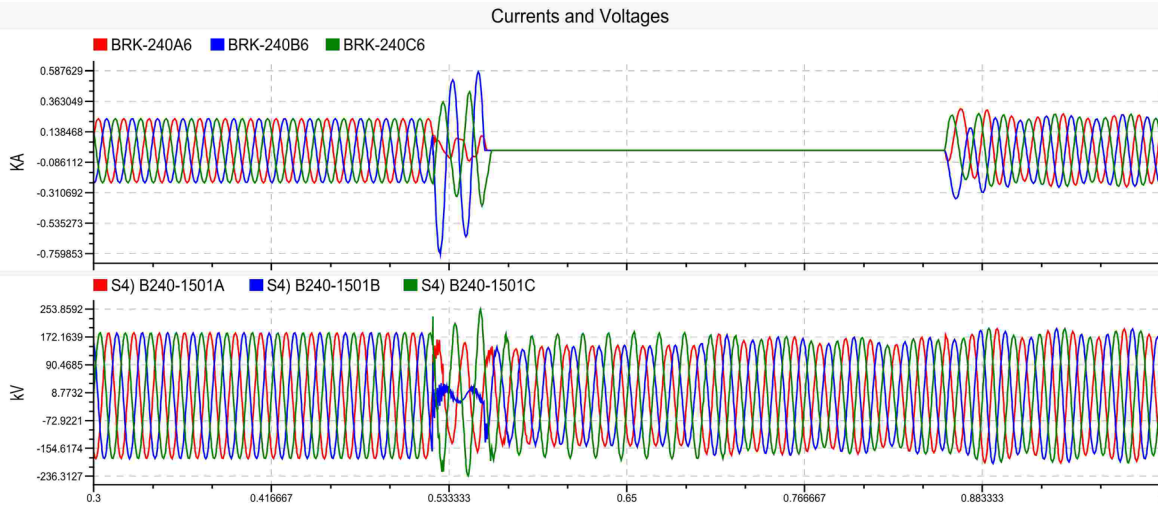
Distance Protection Study with IBRs – Fault Type

Fault @ far end of PZ1 transmission line			No PV penetration		High Penetration	
			Max Fault Current (A)	Mis-operation	Max Fault Current (A)	Mis-operation
L-G	AG	la	1237.81	No	987.6	No
	BG	lb	692.97	No	611.04	Yes
	CG	lc	641.19	No	548.69	No
LL	AB	la	1309.76	No	858.61	Yes
		lb	766.19		496.03	
	BC	lb	939.16	No	693.42	No
		lc	855.68		587.35	
	CA	la	1367.39	No	844.62	Yes
		lc	722.12		560.09	

Distance Protection Study with IBRs – Fault Location

BG fault at 75% transmission line

BG fault at 80% transmission line



Distance protection operates properly

Mis-operation due to lack of fault current

Conclusions & Recommendations

- 1 RTDS IBR models and configurations enabled low, medium, and high PV scenarios for protection performance study.
- 2 IBR fault current characteristics fundamentally differ from traditional sources, challenging the assumptions underpinning distance protection.
- 3 Mitigation requires an adaptive approach: adaptive settings, communication-assisted schemes, or estimation-based differential protection.
- 4 For future studies, RTDS hardware-in-the-loop testing can provide empirical validation of relay behavior under realistic IBR-influenced conditions.

Thank You