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Assessment of Transmission-level Fault Impacts on Distribution Inverter-based Resource (IBR) Operation

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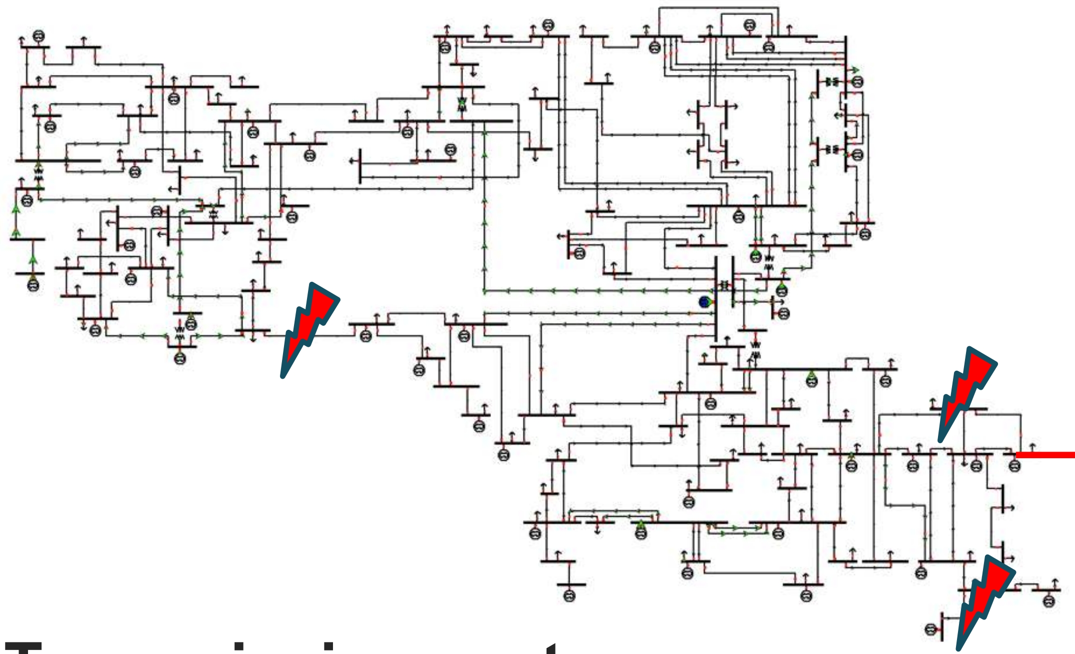
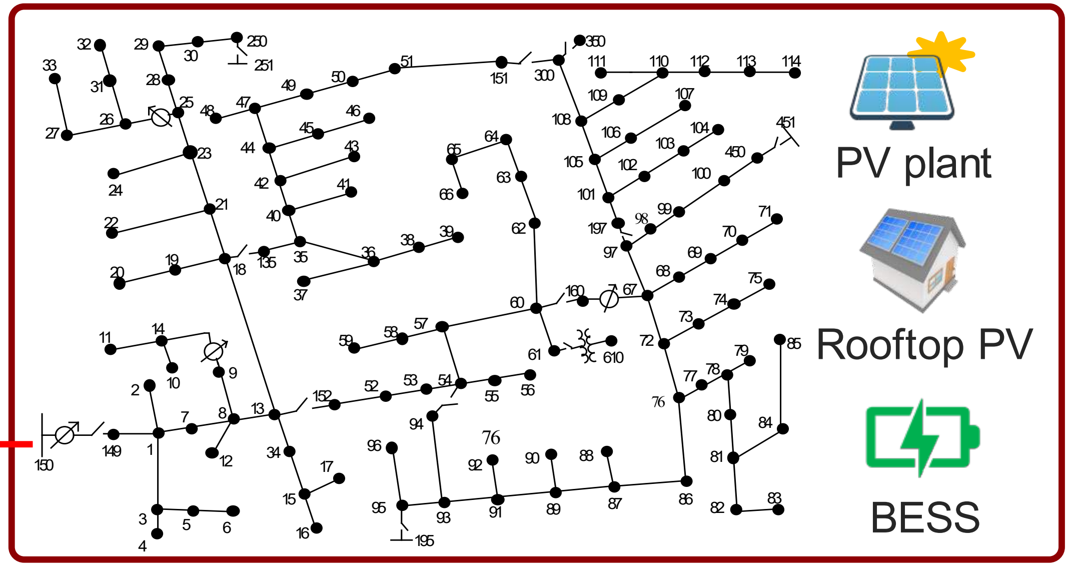
Background

- When a **fault** happens in the transmission system, how will IBRs react and impact the system?

A distribution system with high IBR penetration



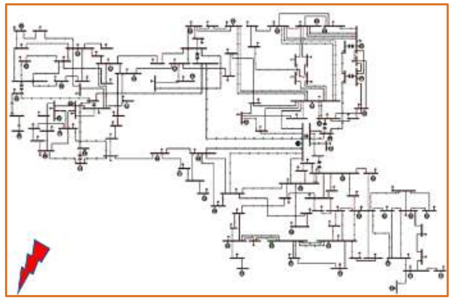
Transmission system



Modeling Considerations:

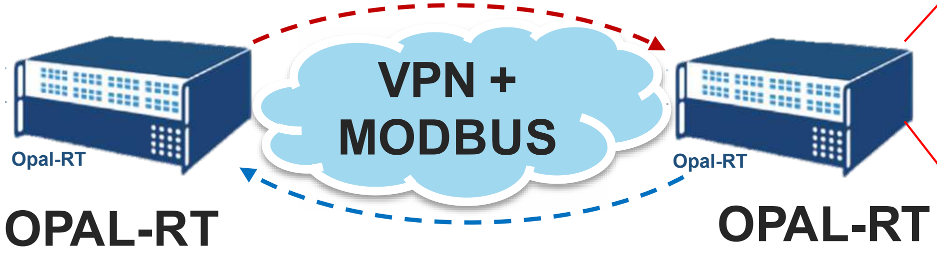
- Different penetrations
- Locations of IBRs
- Types of IBRs

Joint simulation platform

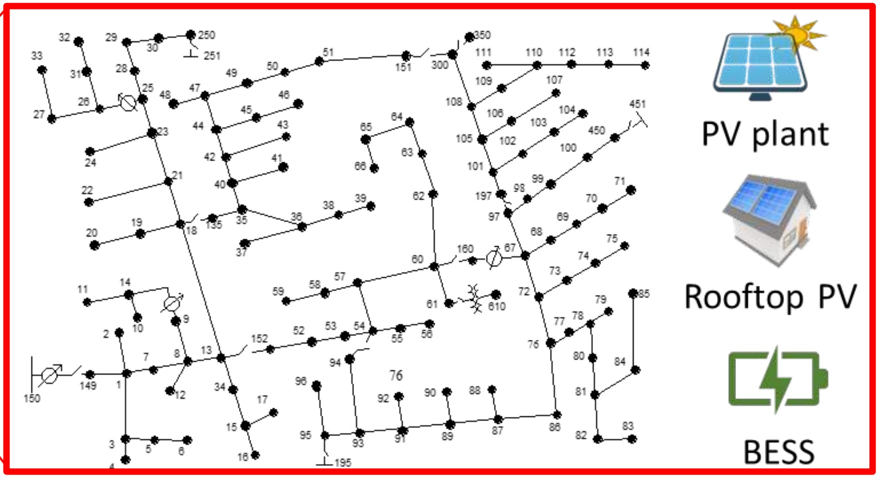


Transmission (Clemson University)

- **Nodal voltage (Magnitude/Angle)**
- **Switch commands**



- **Feeder P/Q**
- **Simulation time**



Distribution (NC State University)

Stage	Transmission	Distribution
1	IEEE 4/39 Bus System	IEEE 123 Bus System with IBRs
2	An actual transmission model from Duke Energy	An actual distribution feeder model from Duke Energy

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First and second stage distribution feeder

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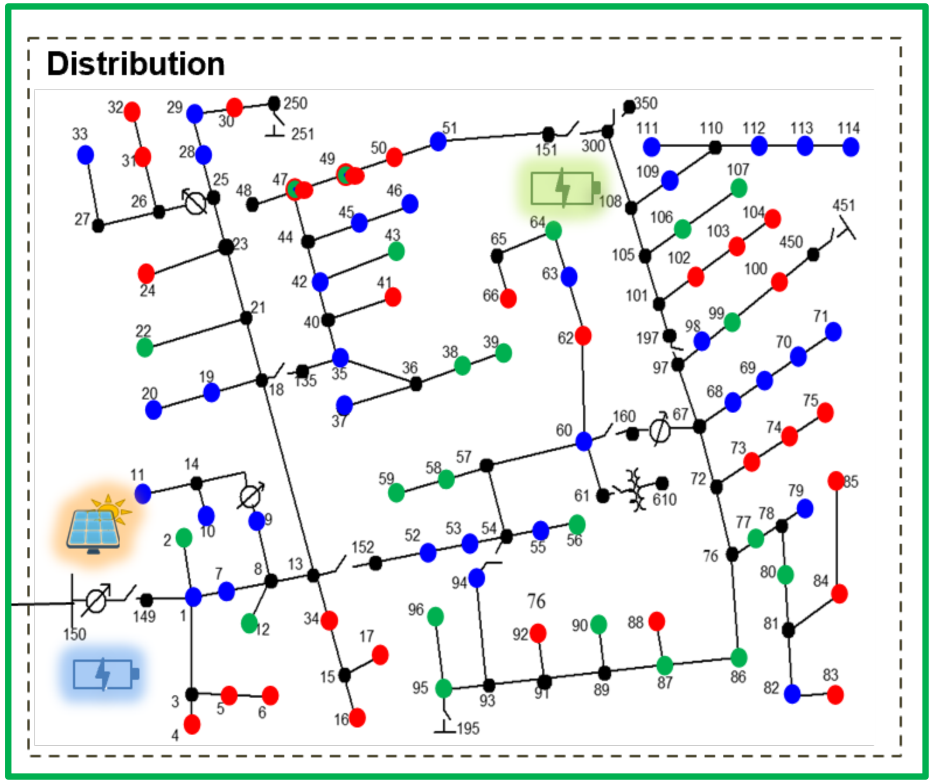
IEEE 123 bus system

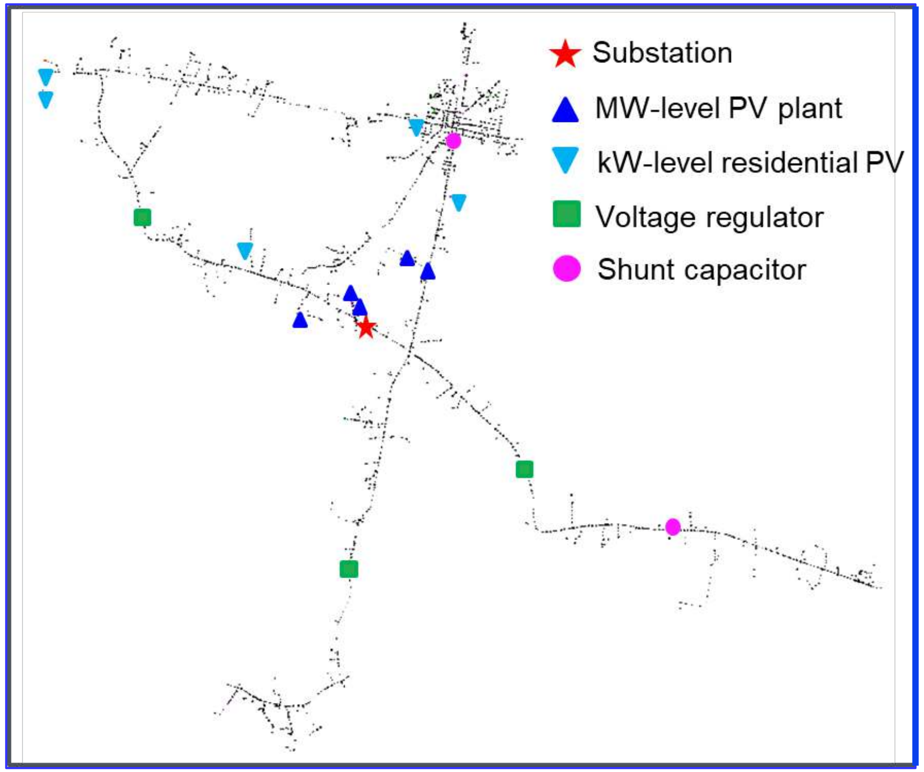


123 nodes, 86 spot loads, 119 lines

3 3-ϕ PV plant / BESS at MW level

86 1-ϕ rooftop PVs at kW level

One actual feeder in NC



2093 nodes, 962 spot loads, 1688 lines

5 3-ϕ PV plants at MW level

5 1-ϕ rooftop PVs at kW level

Distribution system – real-time EMT-TS modeling

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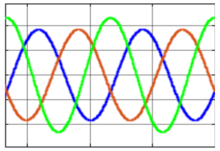
Electromagnetic-Transient (EMT)

-PV Plant, BESS, DG
-Time-step at **μs** level
- Voltages and currents waveforms



Transient Stability (Phasor)

-Grid, Rooftop PV, Loads
-Time-step at **ms** level
-Solves phasors **magnitudes** and **angles**

$$\vec{V} = |V|\angle\theta_v$$

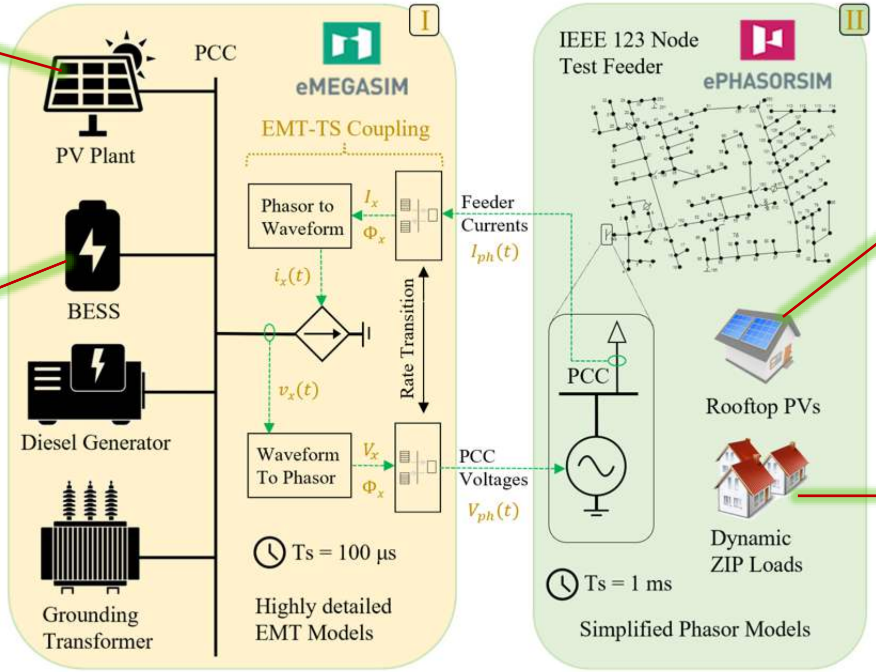
Utility-scale PV plant

- **Fast response power curtailment algorithm**
- Start-up switching logic
- **Reactive power control modes**
- **Disturbance ride-through**

Battery System

Grid-forming mode
- Voltage and frequency regulation
- Three-phase **imbalance control**
- Resynchronization

Grid-following mode
- P and Q power dispatch
- **Disturbance ride-through**



Rooftop PVs

- **Active power curtailment**
- Reactive power control modes
- Frequency-watt droop
- Voltage-active power droop
- **Code-based model**
- **Disturbance ride-through**

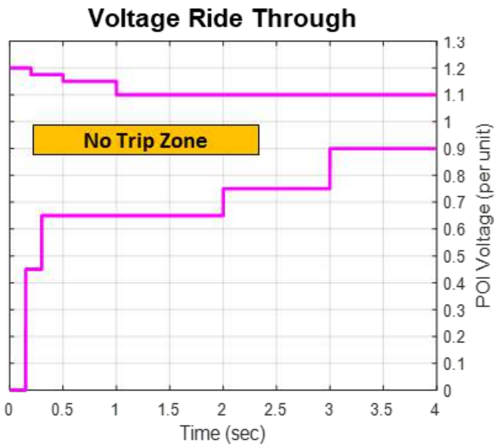
Dynamic ZIP Loads

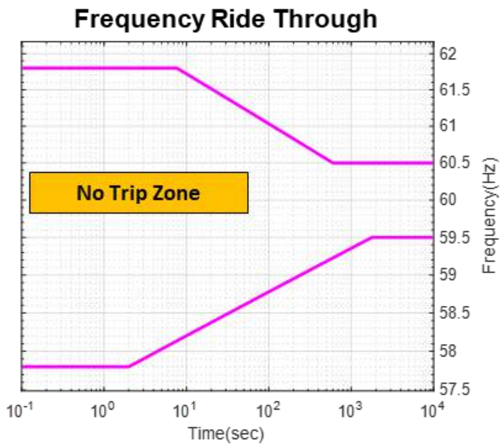
- **Realistic load profile** synthesis
- **HVAC load modeling**
- Load model **parameterization**
- Real-time **Cold Load Pickup** (CLPU) profile generation

Victor Paduani et al., "A Unified Power-Setpoint Tracking Algorithm for Utility-Scale PV Systems With Power Reserves and Fast Frequency Response Capabilities," in *IEEE Transactions on Sustainable Energy*, vol. 13, no. 1, pp. 479-490, Jan. 2022.
Victor Paduani et al., "Maximum Power Reference Tracking Algorithm for Power Curtailment of Photovoltaic Systems." *In Proceedings PESGM 2021*
Bei Xu et al. , "A Novel Grid-forming Voltage Control Strategy for Supplying Unbalanced Microgrid Loads Using Inverter-based Resources," 2022 PESGM.
Victor Paduani et al. , "Novel Real-Time EMT-TS Modeling Architecture for Feeder Blackstart Simulations," *2022 IEEE PESGM.*

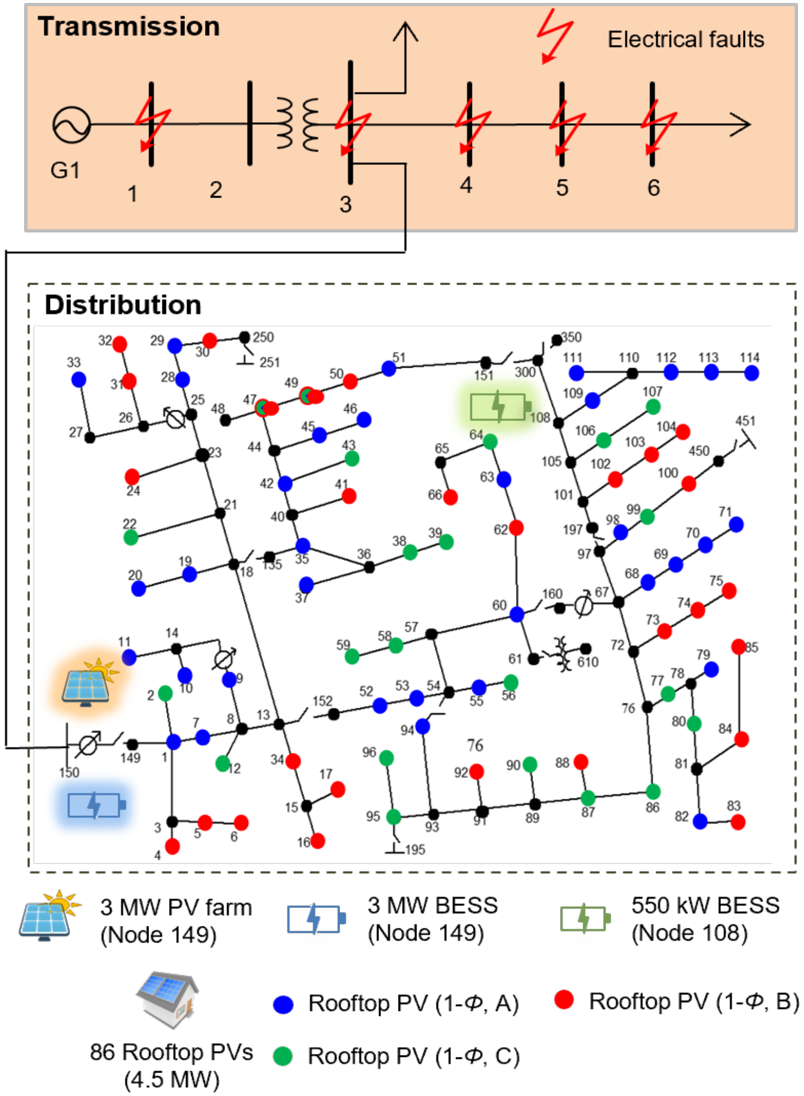
First stage: IEEE 123 bus system with IBRs

- **Modeling of Transmission faults**
  - Symmetrical/unsymmetrical faults
- **Modeling of Distribution IBRs**
  - Different IBR penetrations
  - Fault ride-through





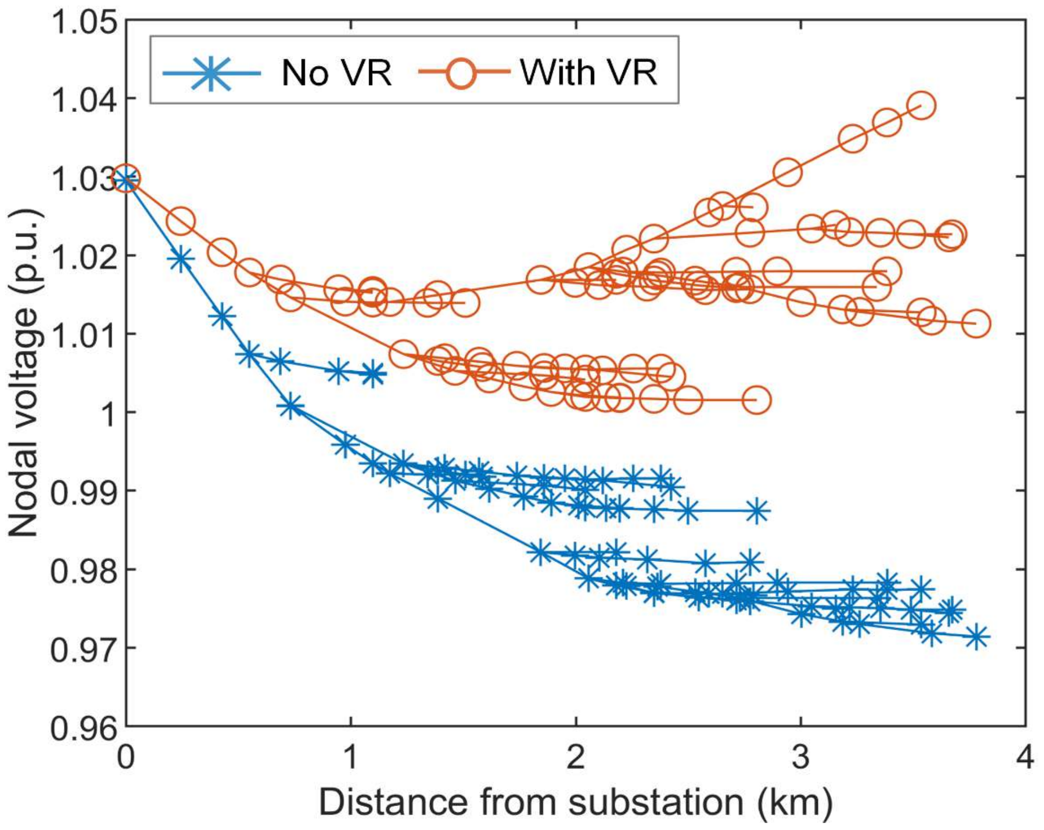
PRC-024-2-Eastern Interconnection Standard



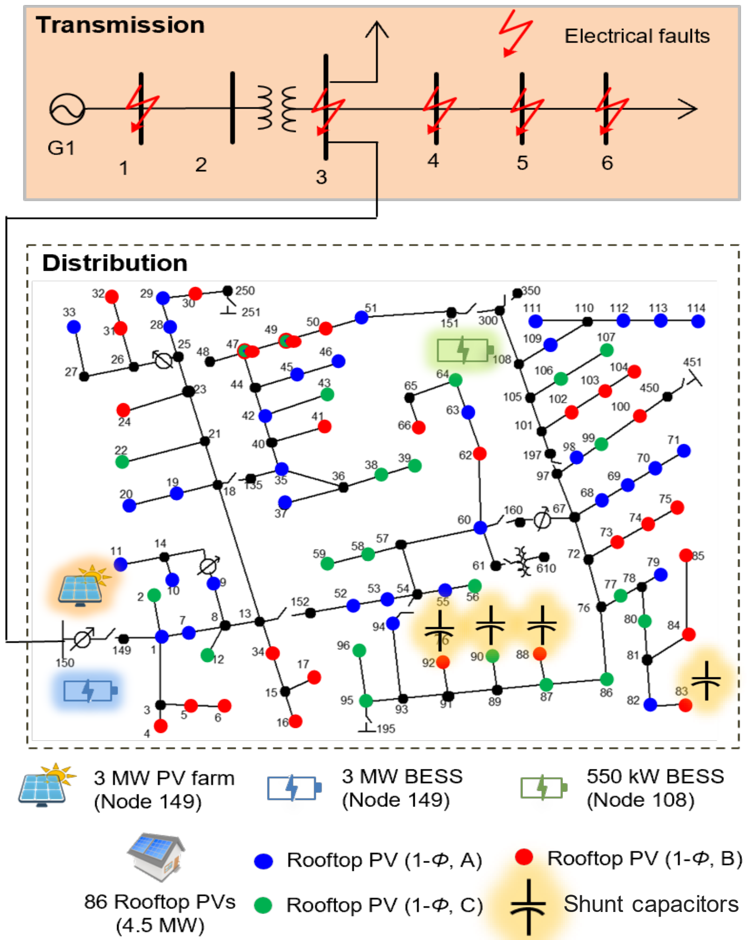
Qi Xiao, et. al. "Assessment of Transmission-level Fault Impacts on 3-phase and 1-phase Distribution IBR Operation." accepted by IEEE PESGM 2024.

Pre-fault nodal voltage profiles

- **Impact of voltage regulation (VR)**



Phase-A nodal voltage of IEEE 123-bus distribution system



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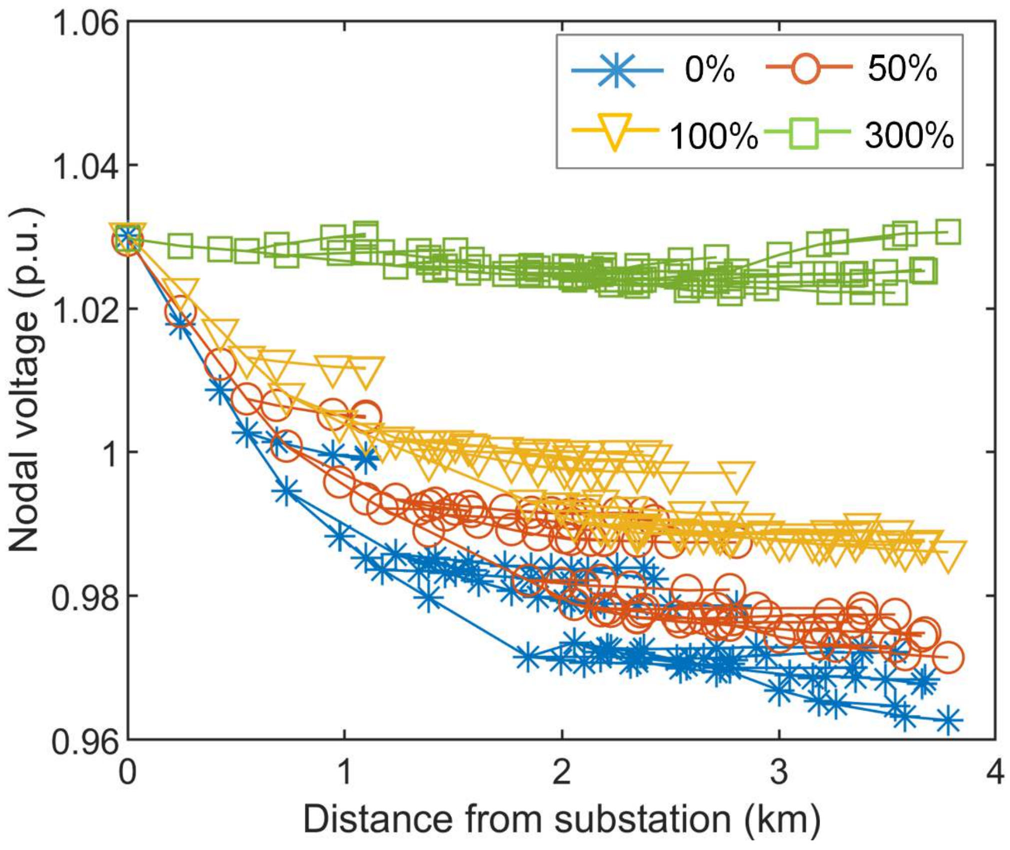
Pre-fault nodal voltage profiles

- **Impact of IBR penetration ratio (P_{IBR} / P_{load})**



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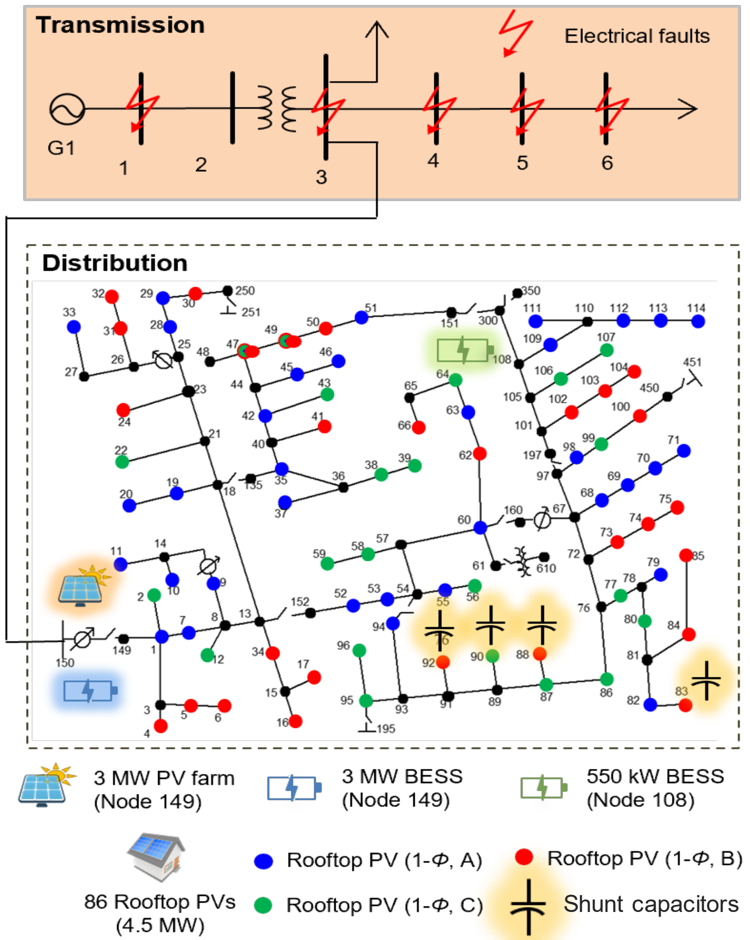

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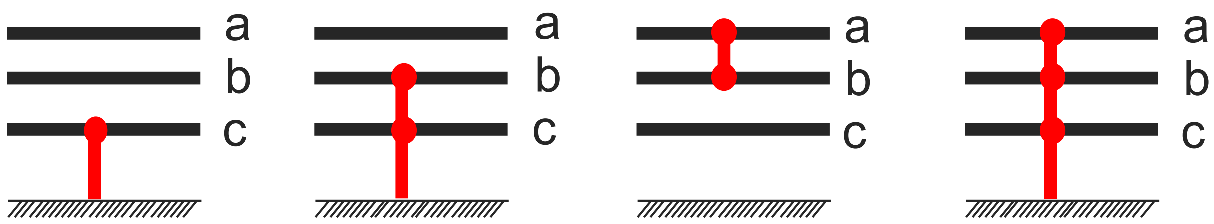
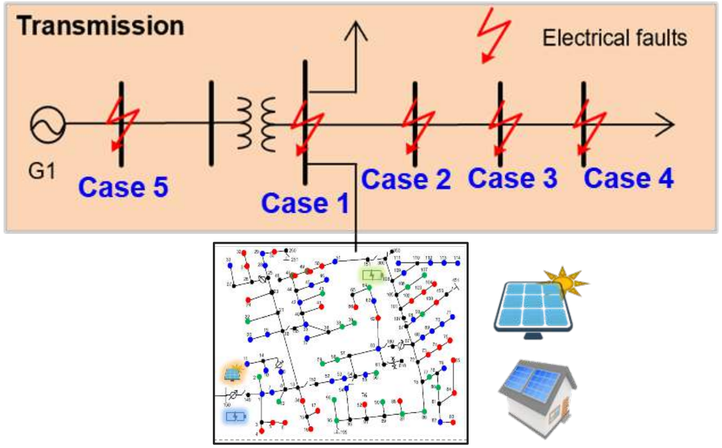
Summary of simulation results (50% IBR penetration ratio)

Trip Percentage of Distributed IBRs

Case	Faulty loc.	Single Line-to-Ground Fault (A-G Fault)				Double Line-to-Ground Fault (A-B-G Fault)				Line-to-Line Fault (A-B Fault)				Three Phase-to-Ground Fault (A-B-C-G Fault)			
		3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)	3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)	3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)	3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)
1	PCC	100	100	0	0	100	100	100	0	0	0	0	0	100	100	100	100
2	Down stream SHORT	100	100	0	0	100	100	100	0	0	0	0	0	100	100	100	100
3	Down stream MEDIUM	0	0	0	0	100	97	100	0	0	0	0	0	100	100	100	100
4	Down stream FAR	0	0	0	0	0	0	0	0	0	0	0	0	33	95	59	89
5	Generator terminal	0	0	0	0	100	0	100	0	100	0	100	0	100	100	100	100



(a) (b) (c) (d)



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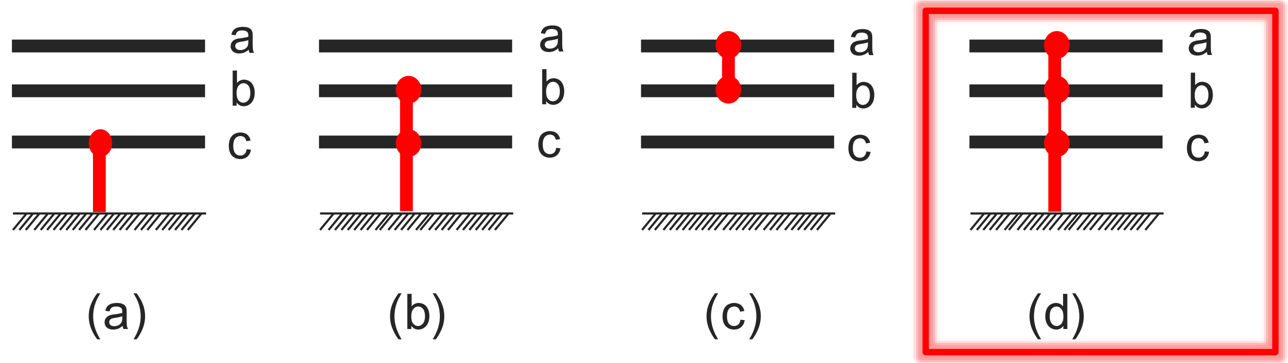
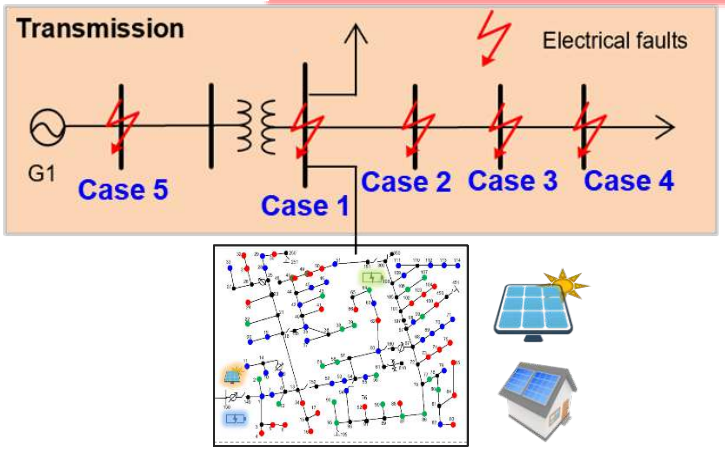
1	PCC	100	100	0	0	100	100	100	0	0	0	0	0	**100**	**100**	**100**	**100**
2	Down stream SHORT	100	100	0	0	100	100	100	0	0	0	0	0	**100**	**100**	**100**	**100**
3	Down stream MEDIUM	0	0	0	0	100	97	100	0	0	0	0	0	**100**	**100**	**100**	**100**
4	Down stream FAR	0	0	0	0	0	0	0	0	0	0	0	0	**33**	**95**	**59**	**89**
5	Generator terminal	0	0	0	0	100	0	100	0	100	0	100	0	**100**	**100**	**100**	**100**





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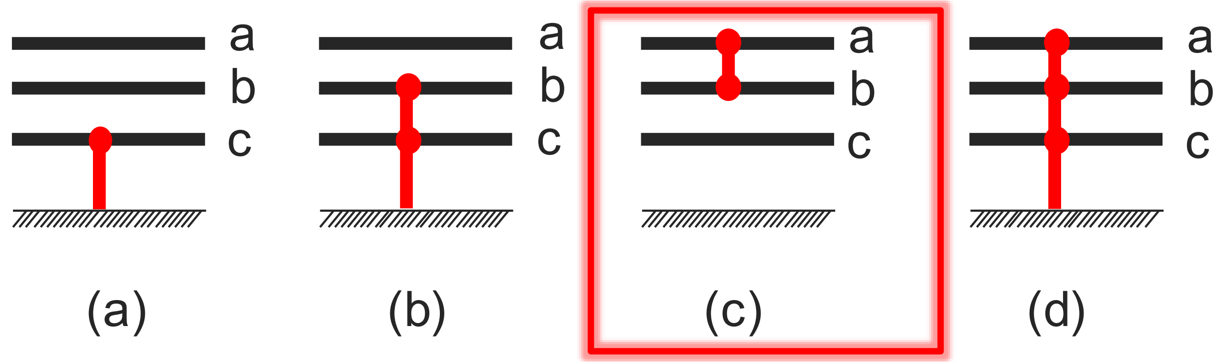
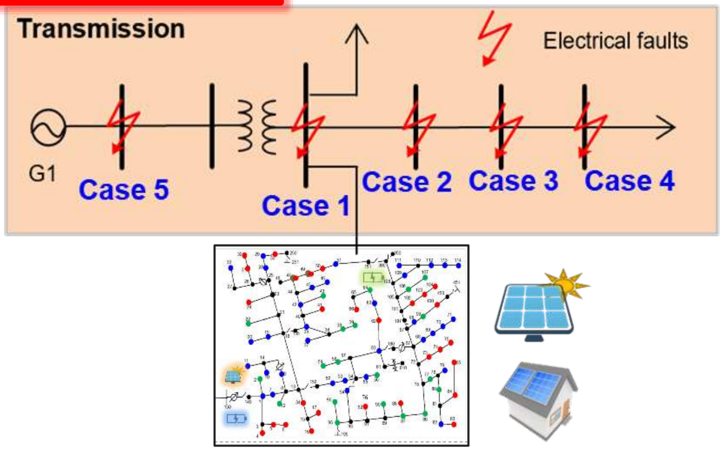
1	PCC	100	100	0	0	100	100	100	0	0	0	0	0	100	100	100	100
2	Down stream SHORT	100	100	0	0	100	100	100	0	0	0	0	0	100	100	100	100
3	Down stream MEDIUM	0	0	0	0	100	97	100	0	0	0	0	0	100	100	100	100
4	Down stream FAR	0	0	0	0	0	0	0	0	0	0	0	0	33	95	59	89
5	Generator terminal	0	0	0	0	100	0	100	0	**100**	0	**100**	0	100	100	100	100





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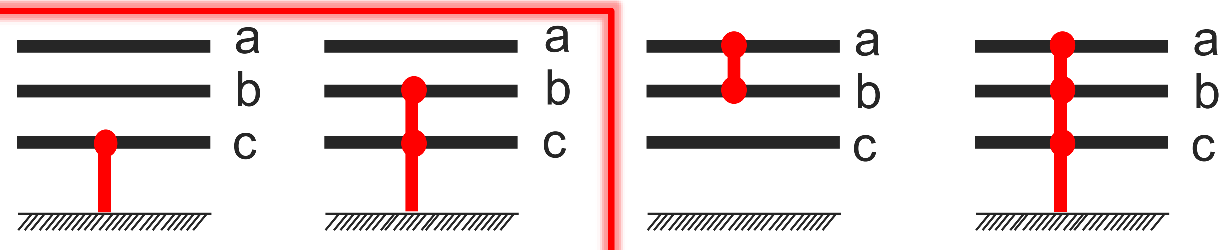
1	PCC	100	100	0	0	100	100	100	0	0	0	0	0	100	100	100	100
2	Down stream SHORT	100	100	0	0	100	100	100	0	0	0	0	0	100	100	100	100
3	Down stream MEDIUM	0	0	0	0	100	97	100	0	0	0	0	0	100	100	100	100
4	Down stream FAR	0	0	0	0	0	0	0	0	0	0	0	0	33	95	59	89
5	Generator terminal	0	0	0	0	100	0	100	0	100	0	100	0	100	100	100	100



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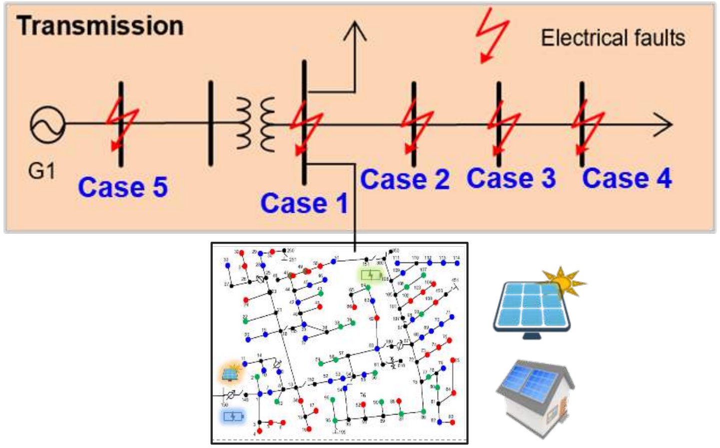

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Summary of simulation results (50% versus 300% penetration ratios)

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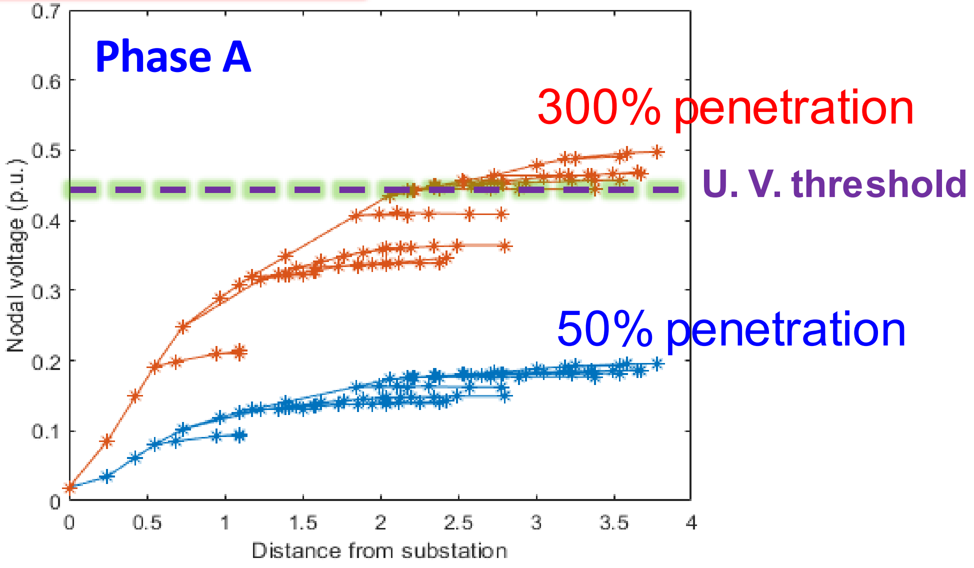
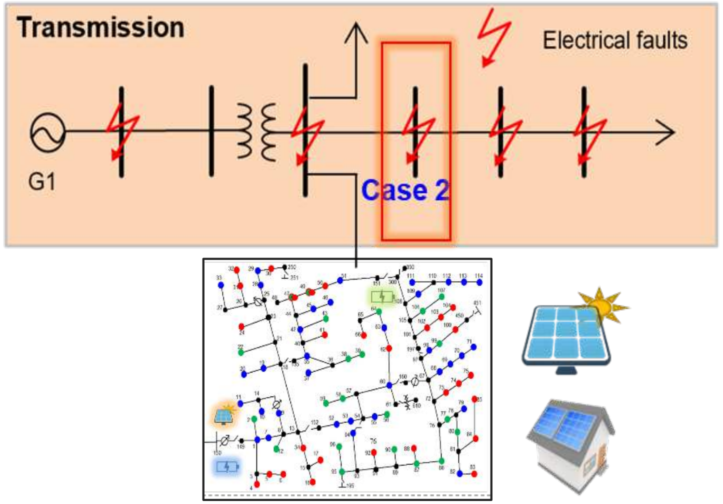
		3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)	3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)	3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)	3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)
1	PCC	100	100/62	0/68	0	100	100/57	100/55	0/41	0	0	0	0	100	100/57	100/50	100/63
2	Down stream SHORT	100	100/57	0/59	0	100	100/54	100/41	0/48	0	0	0	0	100	100/57	100/41	100/52
3	Down stream MEDIUM	0	0	0	0	100	97/0	100	0	0	0	0	0	100	100	100/41	100
4	Down stream FAR	0	0	0	0	0	0	0	0	0	0	0	0	33/0	95/0	59/0	89/0
5	Generator terminal	0	0	0	0	100	0	100/82	0	100	0	100/59	0	100	100	100	100





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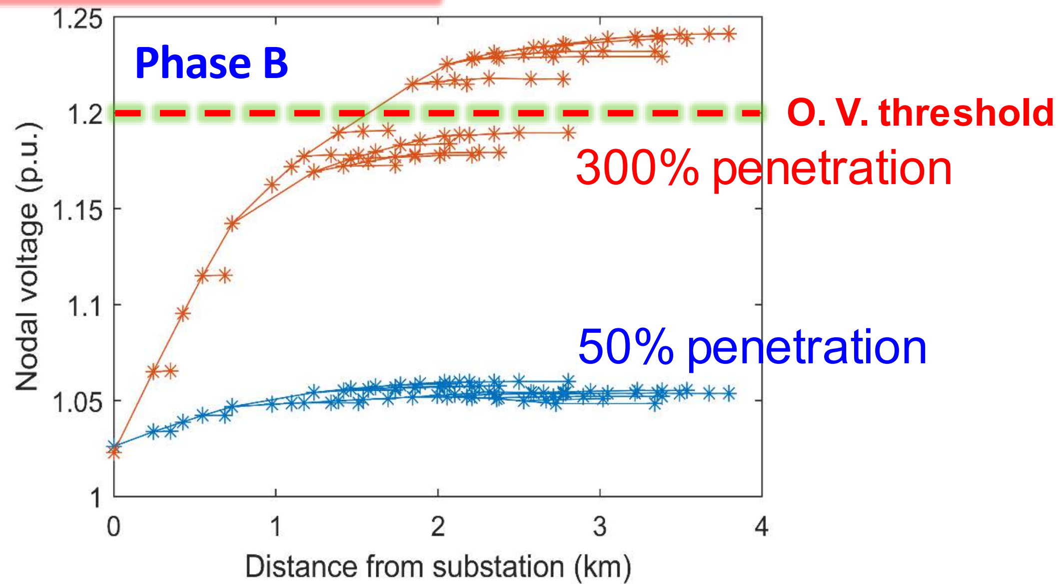
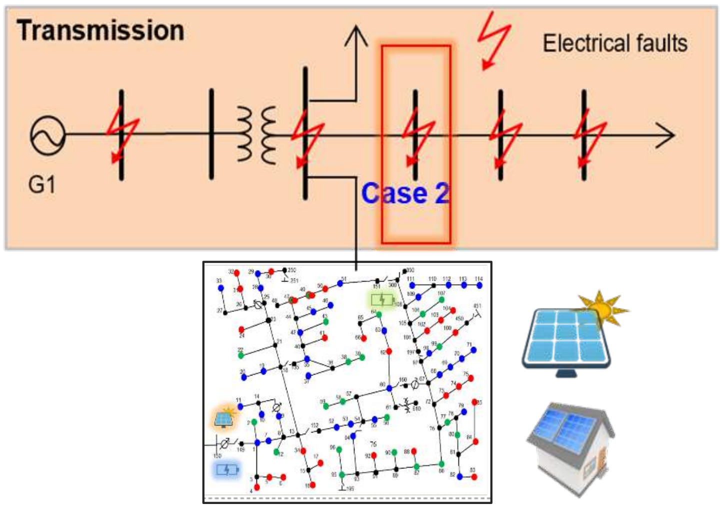
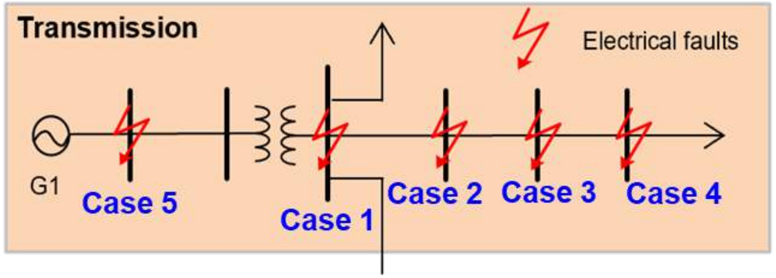
		3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)	3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)	3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)	3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)
1	PCC	100	100/62	0/68	0	100	100/57	100/55	0/41	0	0	0	0	100	100/57	100/50	100/63
2	Down stream SHORT	100	100/57	0/59	0	100	100/54	100/41	0/48	0	0	0	0	100	100/57	100/41	100/52
3	Down stream MEDIUM	0	0	0	0	100	97/0	100	0	0	0	0	0	100	100	100/41	100
4	Down stream FAR	0	0	0	0	0	0	0	0	0	0	0	0	33/0	95/0	59/0	89/0
5	Generator terminal	0	0	0	0	100	0	100/82	0	100	0	100/59	0	100	100	100	100

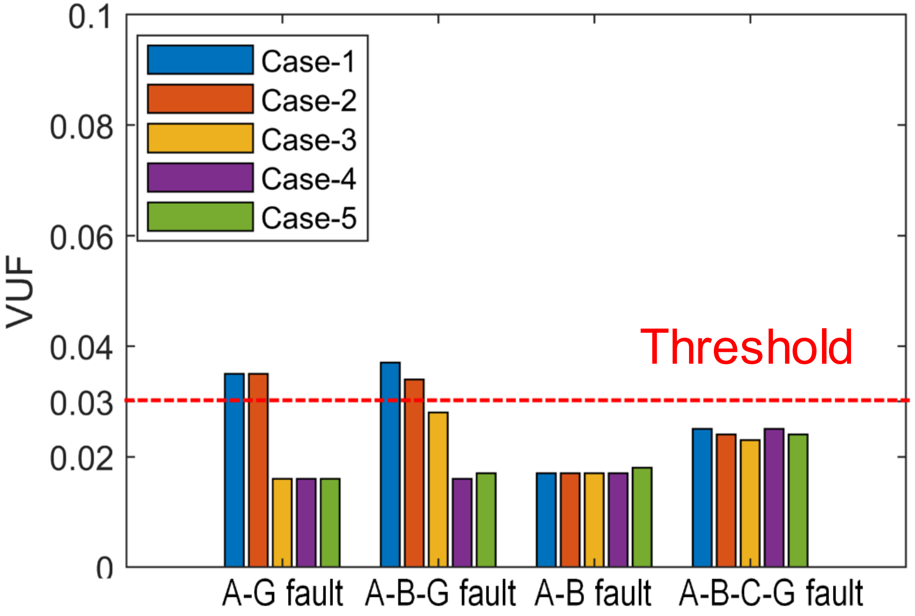




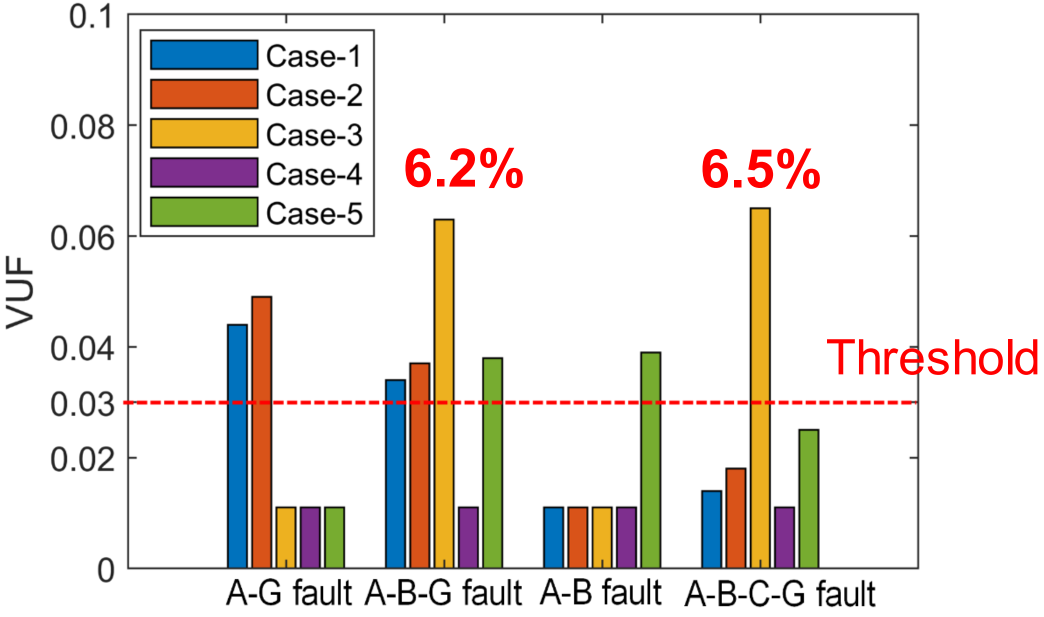
Nodal voltage unbalance

- **Maximum nodal voltage unbalance factor (VUF)**





50% IBR penetration ratio



300% IBR penetration ratio

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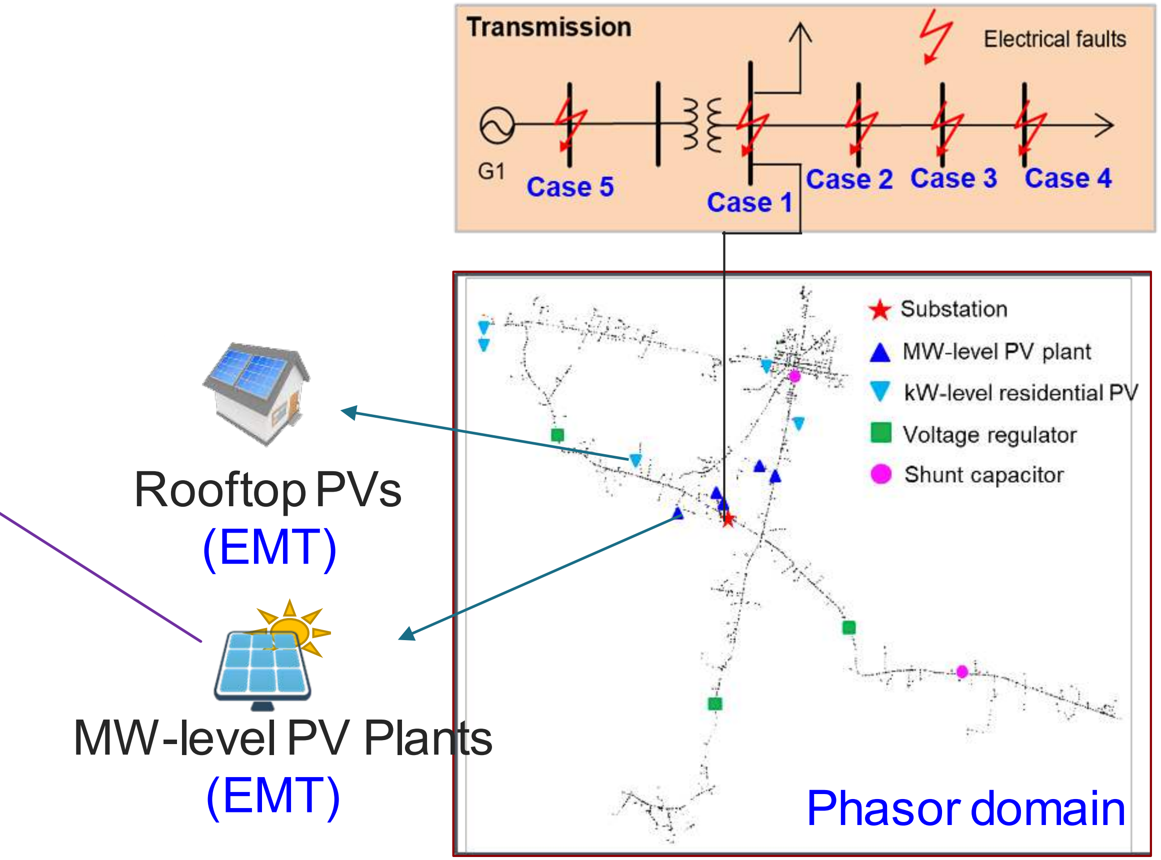
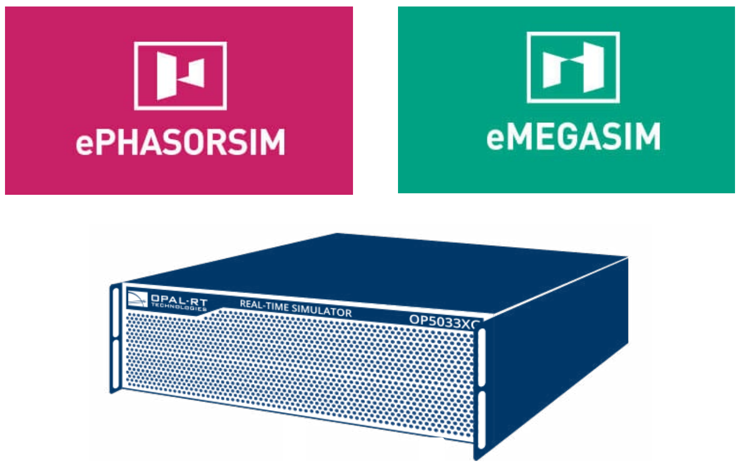
Second stage: an Actual Distribution Feeder





OPAL-RT

- 2093 nodes, 962 spot loads, 1688 lines
- 5 PV plants in MW level, **5** rooftop PVs in kW level

Benchmark Test of Actual Feeder with CYME and OPAL-RT

- The benchmark results are very close

  - Max. voltage error: 0.002 p.u.

  - Max. total active and reactive power error: 0.01 MW / 0.14 Mvar

	Peak Load (21 MVA)					Medium Load (13 MVA)					Light Load (4 MVA)				
	V_{max} (p.u.)	$V_{Min.}$ (p.u.)	P_{total} (MW)	Q_{total} (MVar)	P_{loss} (MW)	V_{max} (p.u.)	$V_{Min.}$ (p.u.)	P_{total} (MW)	Q_{total} (MVar)	P_{loss} (MW)	V_{max} (p.u.)	$V_{Min.}$ (p.u.)	P_{total} (MW)	Q_{total} (MVar)	P_{loss} (MW)
CYME	1.032	0.963	19.88	6.79	0.362	1.038	0.975	12.81	4.987	0.156	1.037	0.993	4.529	0.659	0.020
OPAL-RT	1.031	0.961	19.87	6.93	0.355	1.037	0.973	12.80	5.055	0.157	1.036	0.992	4.593	0.645	0.021
Absolute Error	0.001	0.002	0.01	0.14	0.007	0.001	0.002	0.01	0.068	0.001	0.001	0.001	0.064	0.014	0.001

Summary of simulation results (50% versus 300% penetration ratios)

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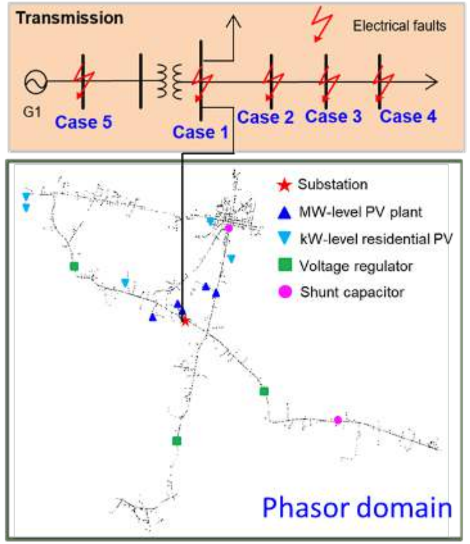
1	PCC	100	100	0	0	100	100	100	0	0	0	0	0	100	100	100	100
2	Down stream SHORT	100	100	0	0	100	100	100	0	0	0	0	0	100	100	100	100
3	Down stream MEDIUM	0	0	0	0	100	100	100	0	0	0	0	0	100	100	100	100
4	Down stream FAR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Generator terminal	0	0	0	0	100	0	100	0	100	0	100	0	100	100	100	100

- Largest nodal voltage differential during faults:

  - actual feeder at 50% and 300%: **0.04 p.u.** and **0.06 p.u.**

  - IEEE 123 bus feeder at 50% and 300%: **0.2 p.u.** and **0.5 p.u.**



Comparison of First and Second Stage Simulation Results

First stage: IEEE 123 bus system (86 1-ϕ rooftop PVs)

Case	Faulty loc.	Single Line-to-Ground Fault (A-G Fault)				Double Line-to-Ground Fault (A-B-G Fault)				Line-to-Line Fault (A-B Fault)				Three Phase-to-Ground Fault (A-B-C-G Fault)			
		3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)	3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)	3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)	3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)
1	PCC	100	100/62	0/68	0	100	100/57	100/55	0/41	0	0	0	0	100	100/57	100/50	100/63
2	Down stream SHORT	100	100/57	0/59	0	100	100/54	100/41	0/48	0	0	0	0	100	100/57	100/41	100/52
3	Down stream MEDIUM	0	0	0	0	100	97/0	100	0	0	0	0	0	100	100	100/41	100
4	Down stream FAR	0	0	0	0	0	0	0	0	0	0	0	0	33/0	95/0	59/0	89/0
5	Generator terminal	0	0	0	0	100	0	100/82	0	100	0	100/59	0	100	100	100	100

Second stage: Actual feeder in NC (5 1-ϕ rooftop PVs)

Case	Faulty loc.	Single Line-to-Ground Fault (A-G Fault)				Double Line-to-Ground Fault (A-B-G Fault)				Line-to-Line Fault (A-B Fault)				Three Phase-to-Ground Fault (A-B-C-G Fault)			
		3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)	3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)	3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)	3-ϕ (%)	ϕ-A (%)	ϕ-B (%)	ϕ-C (%)
1	PCC	100	100	0	0	100	100	100	0	0	0	0	0	100	100	100	100
2	Down stream SHORT	100	100	0	0	100	100	100	0	0	0	0	0	100	100	100	100
3	Down stream MEDIUM	0	0	0	0	100	100	100	0	0	0	0	0	100	100	100	100
4	Down stream FAR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Generator terminal	0	0	0	0	100	0	100	0	100	0	100	0	100	100	100	100

Conclusions

- By leveraging T & D co-simulation platforms, comprehensive research is conducted to investigate the **transmission-level fault impact on the operation of distributed 3-phase and 1-phase IBRs**.
- Two distribution feeders, including **an IEEE standard feeder and an actual feeder**, are integrated into a real-time simulation platform for analysis.
- Different fault types, IBR types, and IBR penetrations are considered for evaluation.
  - **3-phase and 1-phase IBR**: 3-phase IBRs are prone to be tripped during faults, and 1-phase IBRs tend to have larger impact on nodal voltage.
  - In high penetration cases, overvoltage in non-faulty phases and significant node voltage imbalances may occur.

Thank you!

Qi Xiao, et al. "Assessment of Transmission-level Fault Impacts on 3-phase and 1-phase Distribution IBR Operation." *arXiv e-prints* (2023): arXiv-2311.