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Building A Hardware-In-the-Loop Testing Setup For Evaluating Relays Impacted by High Penetration of Inverter-Based Resources

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CIGRE USNC Grid of The Future Symposium

October 9-12, 202, Kansas City, MO, USA

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Motivations of the Work

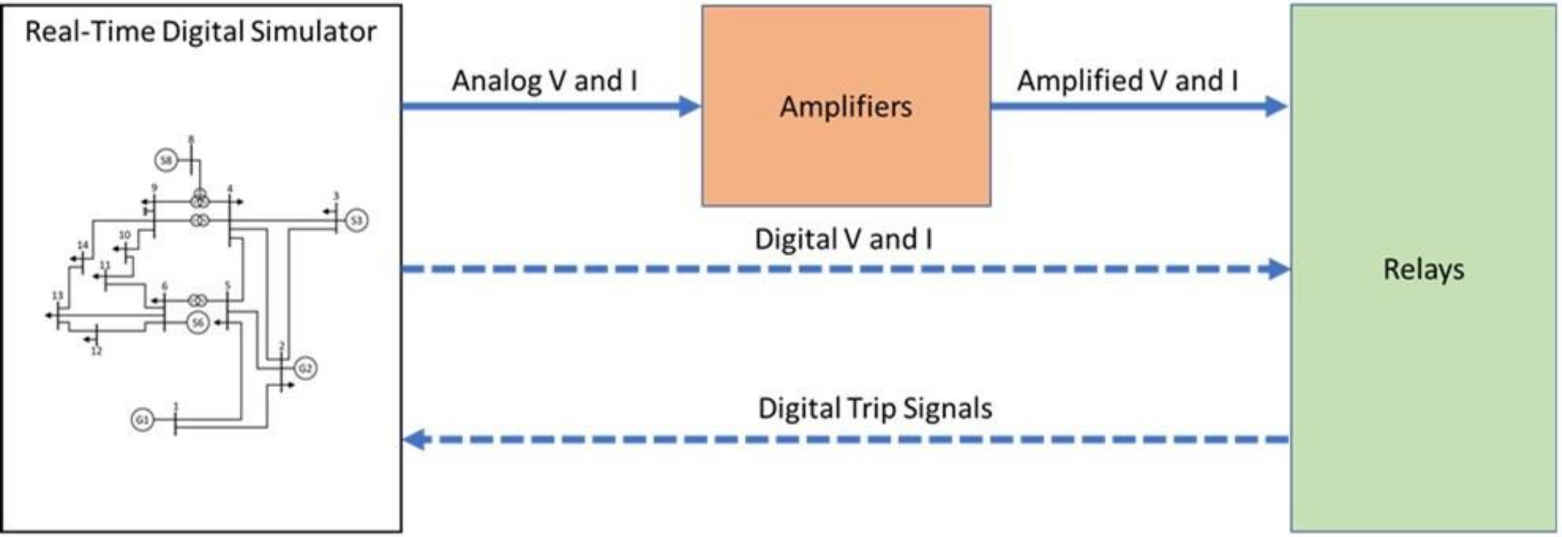
- Take proactive actions to identify and mitigate any potential issues well before their emergence
  - New York State power grid aims to reach carbon neutral by 2040
  - High penetration of inverter-based resources along with the retirement of many existing power plants are expected
  - Existing protective relays and their coordination could be impacted as soon as the penetration of IBRs reaches a critical level
  - Mitigation solutions must be developed and deployed before such a critical level is reached
    - To avoid forced curtailment of IBRs, and
    - To prevent major system disturbances due to relay misoperations

Evaluate IBRs Impact on Relays under Realistic Grid Conditions

Creating a hardware-in-the-loop (HIL) testing setup using real-time digital simulators (e.g., RTDS, Opal-RT) requires:

- Creating system models for realistic future transmission grid conditions
- Accurate IBR models (i.e., models accurately mimic the real IBRs)
  - Vendor-developed models – Project team reached out to many vendors directly and through NYPA and NGrid in this project.
  - Rapid evolvement of the IBR products.
  - At the start of our research project, there were no vendor-developed IBR models available on real-time digital simulators.

HIL Setup Using A Real-Time Digital Simulator for Relay Testing

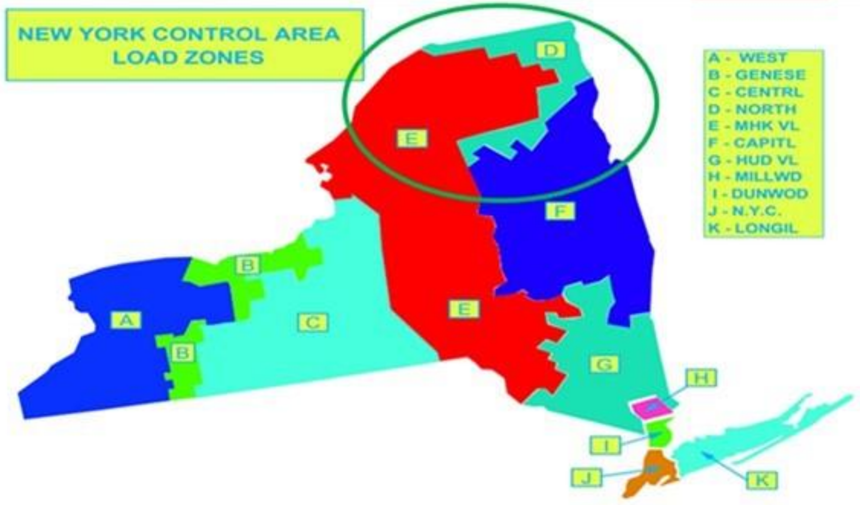


Different system models for real-time digital simulator RTDS were developed for this project

- A base system model
  - Representing the current electric power system
  - Serve as a benchmark system to establish performance of existing relays under current system condition
- Hi-IBRs system models
  - Have high penetration of IBRs
  - For evaluating Hi-IBRs impact on relay performance

Select A Focus Area in A Future New York State Power System

Zones	Existing Capacity (MW)			IBR Level	Projected New IBR Capacity (MW)				S+W Total	IBR Total /	S+W Total / New
	Wind	Solar	Total Gen	now (%)	Wind	Solar	Battery	IBR Total		Total Gen (%)	Total Gen w/o B (%)
A	179	-	3,376	5%	566	2,565	530	3,660	3,309	108%	51%
B	-	-	765	0%	200	965	21	1,186	1,165	155%	60%
C	518	-	6,381	8%	940	3,482	784	5,206	4,941	82%	46%
D	678	-	1,921	35%	847	727	20	1,594	2,252	83%	64%
E	442	-	1,004	44%	1,135	3,180	28	4,342	4,756	433%	89%
F	-	-	4,492	0%	-	1,565	-	1,565	1,565	35%	26%
G	-	-	4,790	0%	-	20	897	917	20	19%	0%
H	-	-	1,088	0%	-	-	1,300	1,300	-	119%	0%
I	-	-	-	#N/A	-	-	400	400	-	#N/A	#N/A
J	-	-	9,618	0%	8,848	-	3,536	12,384	8,848	129%	48%
K	-	32	5,236	0%	18,498	59	388	18,945	18,588	362%	78%



https://www.nyiso.com/documents/20142/1397960/nyca_zonemaps.pdf

- Target year 2030
  - New York State is to reach 70% carbon-free electricity by 2030 and certain area may see a much high penetration
  - Most proposed projects for in-service before/by 2030 in the NYISO queue have a high likelihood to be so
- Focus area (North Country) selection criteria
  - Has high penetration level of IBRs than other areas by 2030
  - Has more weak spots in the area than other areas
  - Preferably within NYPA and NGrid control areas

Load Zone	A	B	C	D	E	F	G	H	I	J	K	Total
Buses	131	70	209	58	150	140	81	29	39	253	76	1236
No. of Top 10% Weak Buses	10	7	28	10	39	14	1	4	0	4	7	124
Weak Buses/Buses (%)	7.6	10.0	13.4	17.2	26.0	10.0	1.2	13.8	0.0	1.6	9.2	10.0

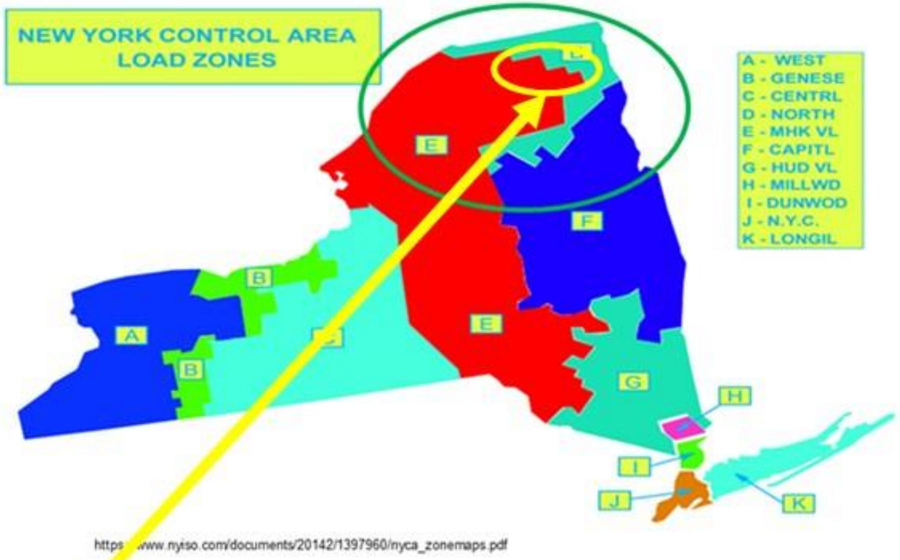
Specific Line Selection

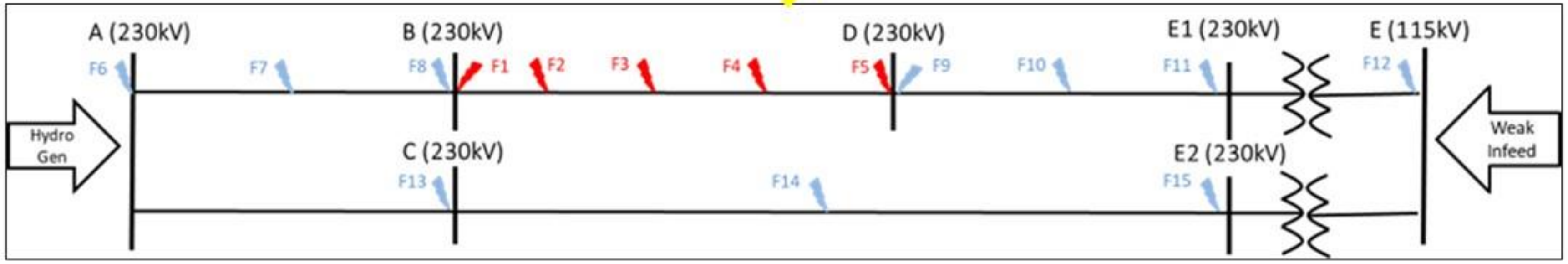
The line selection criteria

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

The results

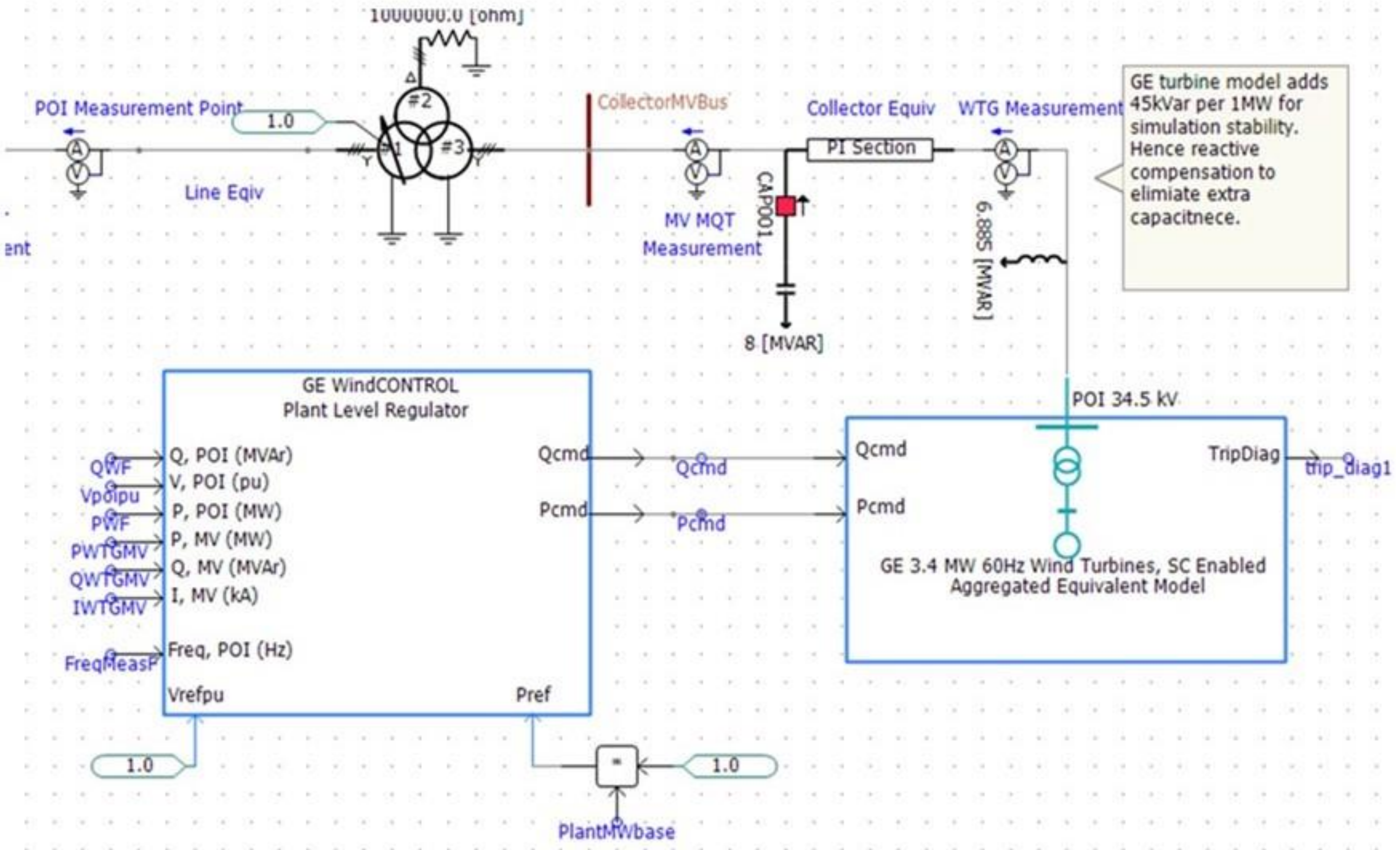
- A 230 kV line B-D was selected;
- A 115 kV line was less represented in detail.





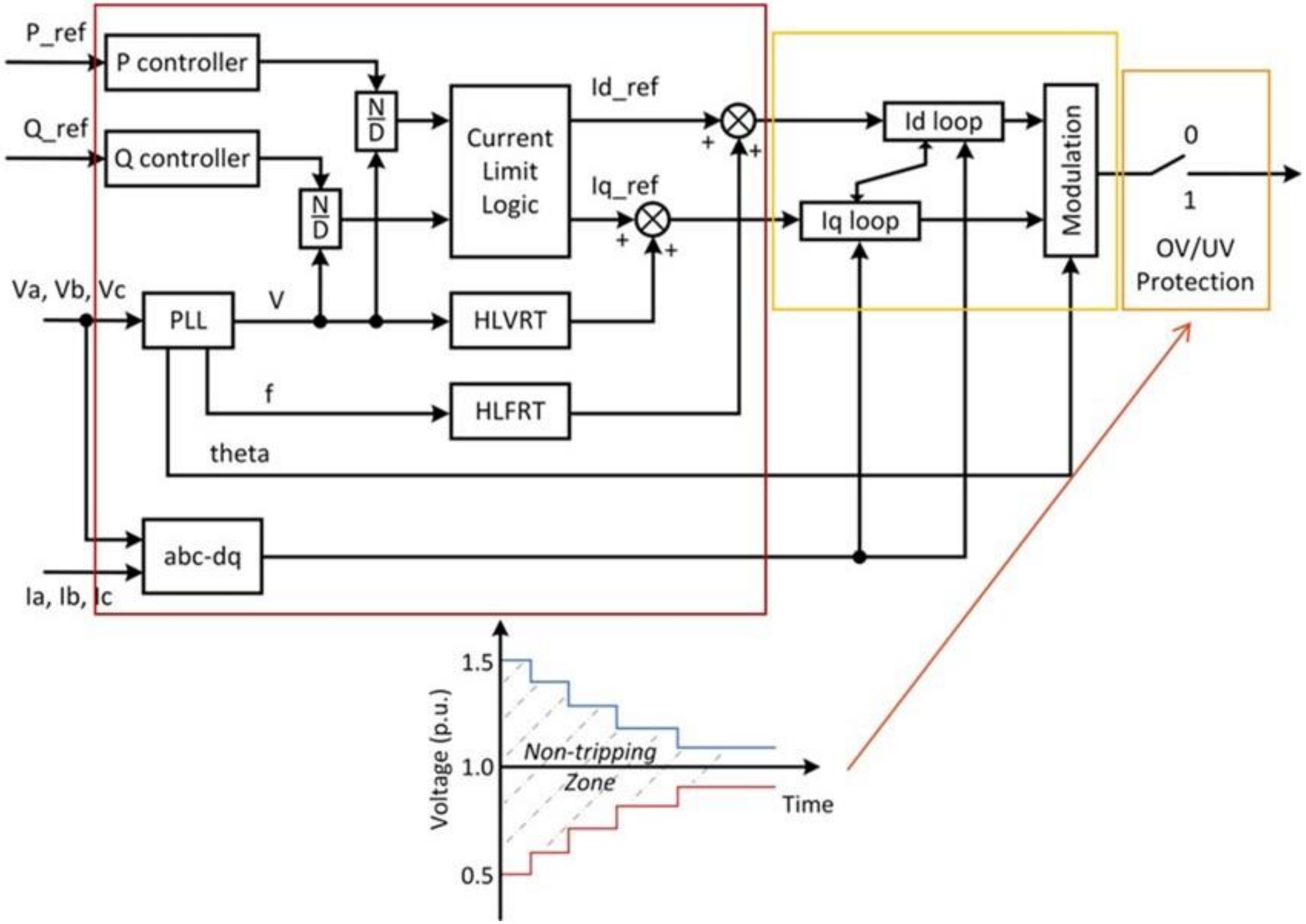
An RTDS IBR Model to Match Vendor Blackbox IBR Model in PSCAD

- Inverter manufacturer developed IBR model is required for power system electromagnetic transient (EMT) studies.
  - Comes commonly in PSCAD black box format.
    - Manufacturers currently have not developed RTDS IBR models.
- Huge challenge to create digital twins of IBR models in RTDS without the knowledge of
  - IBR electrical or mechanical model parameters.
  - IBR controller details.
  - plant controller details.
  - Collector systems, GSU, capacitor banks, etc.

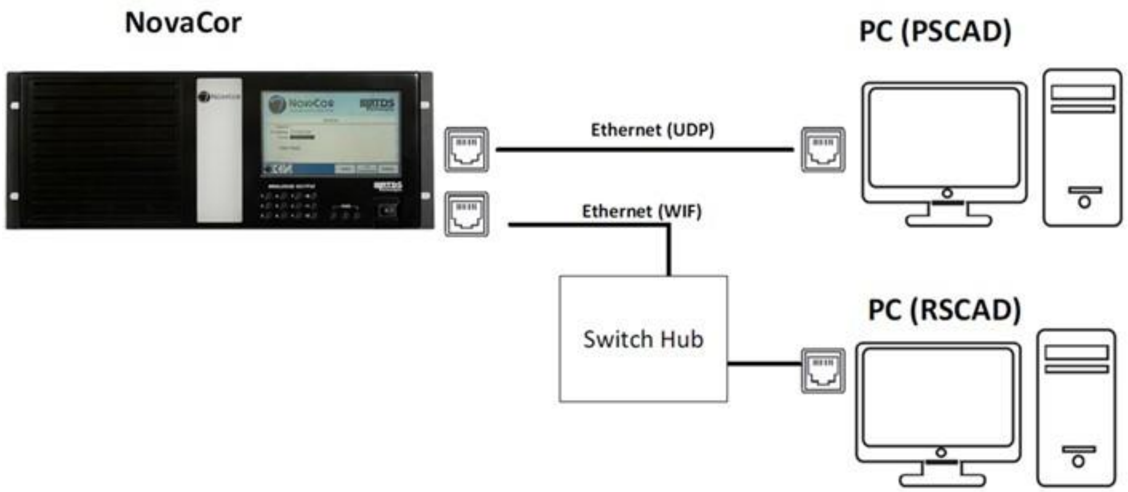


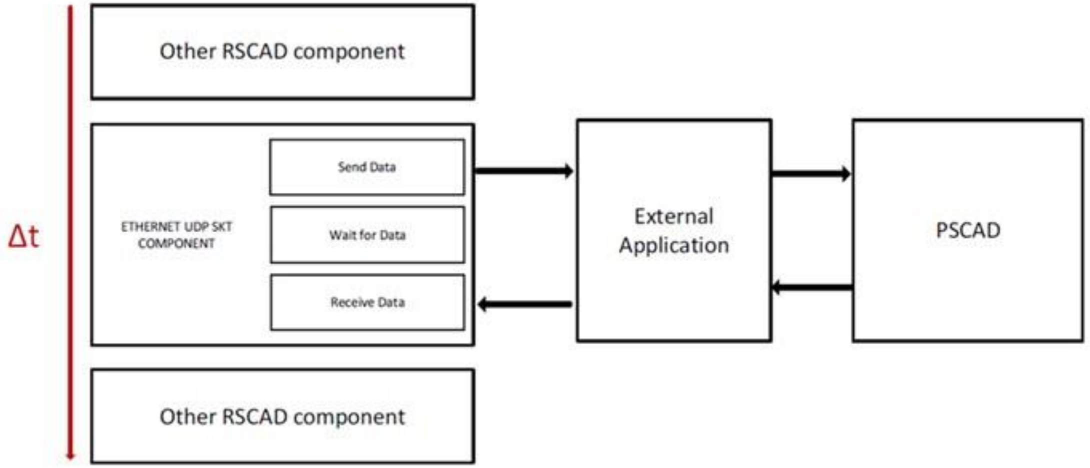
Systematic RTDS IBR Model Tuning and Validation

- Quasi-steady-state response matching
  - Focus on filter time constants, PID gains, voltage-dependent current limits, ramp rates, etc.
- Fault transient response matching
  - Focus on HLVRT, fault, protection functions, etc. (red box)
  - Inner loop control and modulation (yellow box)
  - Tripping logic. (purple box)
- System interactions matching
  - Connect to a self-developed IEEE-14 bus system on RTDS and focus on internal and external fault responses.



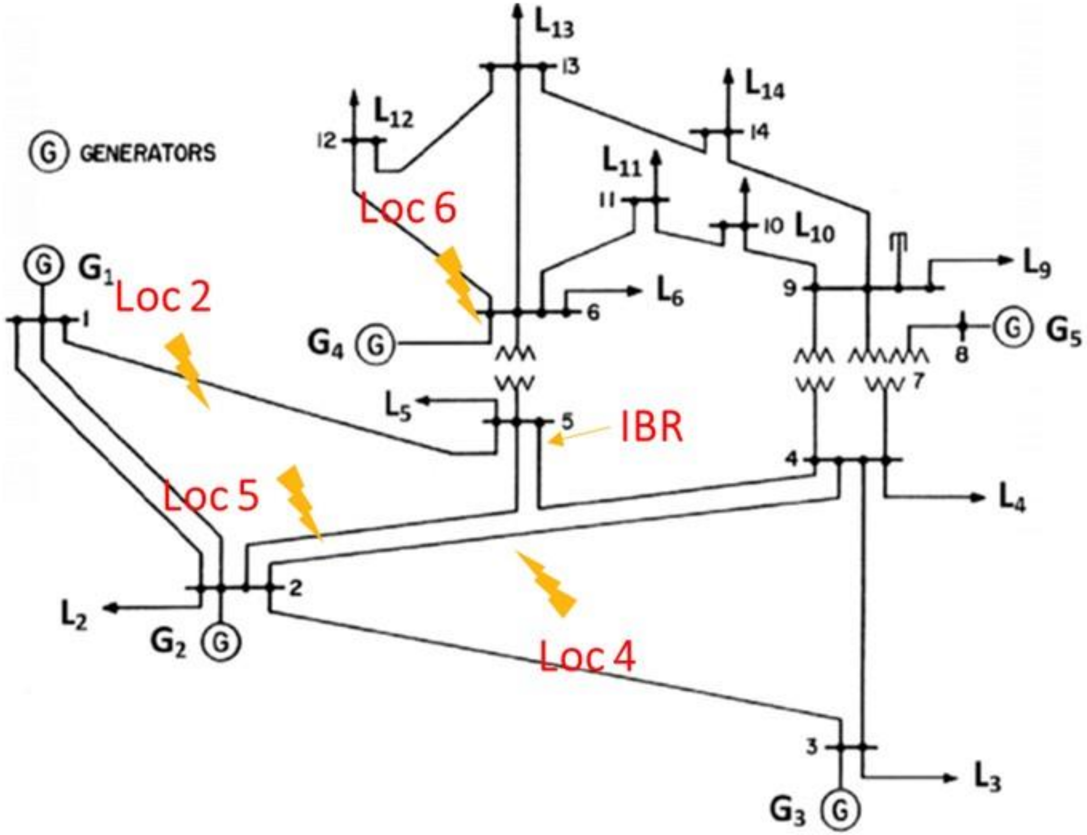
Developed RTDS IBR Model Validation Through RTDS Co-Simulation



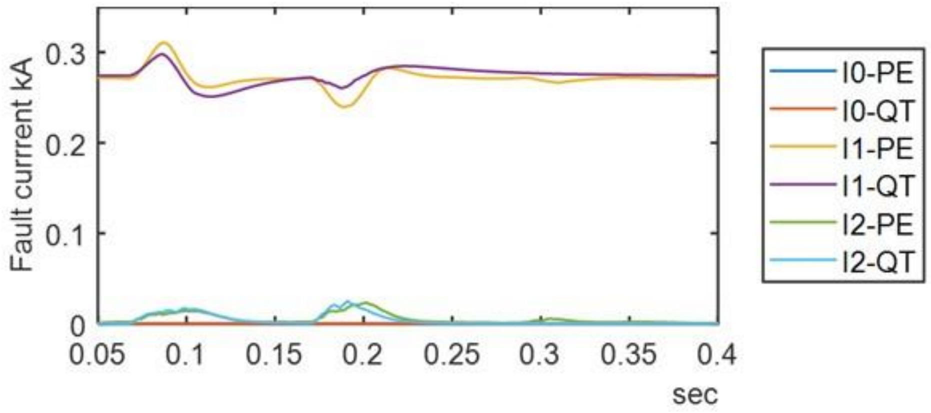


- To save time and avoid subtle model differences between RTDS and PSCAD, the RTDS co-simulation approach was used.
  - Simulate a self-developed IEEE 14-bus power system and the inverter hardware in RTDS
  - Simulate self-developed RTDS IBR controller model
  - Simulate IBR vendor black box controller model in PSCAD
  - UDP interface exchanges analog measurements and control outputs between RTDS and PSCAD.
  - Limitations:
    - Does not support real-time co-simulation
    - RTDS only allows control input

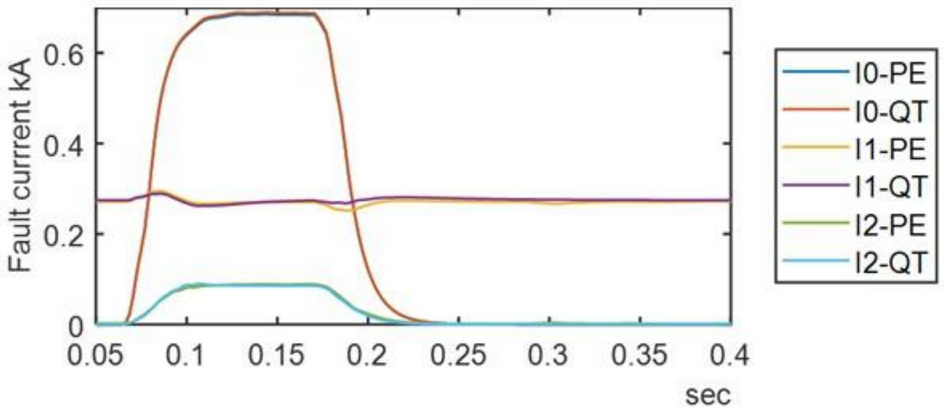
Self-Developed RTDS IBR Model Validation Results (1)



- Fault current at POI: Loc 2 ABC



- Fault current at POI: Loc 2 ABG



Self-Developed RTDS IBR Model Validation Results (2)

- The overall Mean Absolute Error (MAE) is 0.0031 kA (IBR rated current 280A)
- The maximum error is 0.0085 kA.

Fault Cases	I0 MAE	I1 MAE	I2 MAE
FLTLOC_2_AB	0.0000	0.0051	0.0026
FLTLOC_2_ABC	0.0000	0.0070	0.0020
FLTLOC_2_ABG	0.0011	0.0053	0.0022
FLTLOC_2_AG	0.0016	0.0056	0.0021
FLTLOC_4_AB	0.0000	0.0049	0.0025
FLTLOC_4_ABC	0.0000	0.0071	0.0023
FLTLOC_4_ABG	0.0017	0.0055	0.0024
FLTLOC_4_AG	0.0015	0.0063	0.0022
FLTLOC_5_AB	0.0000	0.0054	0.0022
FLTLOC_5_ABC	0.0000	0.0085	0.0025
FLTLOC_5_ABG	0.0023	0.0059	0.0025
FLTLOC_5_AG	0.0026	0.0065	0.0023
FLTLOC_6_AB	0.0000	0.0067	0.0019
FLTLOC_6_ABC	0.0000	0.0055	0.0012
FLTLOC_6_ABG	0.0032	0.0049	0.0021
FLTLOC_6_AG	0.0017	0.0070	0.0020

Main Conclusions

- It is possible to create an HIL setup for properly evaluating the performance of existing relays under realistic future system operation conditions.
- The success in creating such an HIL setup is highly depending on
  - Ability to properly articulate credible future power system operating conditions, and
  - Ability to obtain or self-develop the accurate IBR EMT model for real-time digital simulators.

Thank You!

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Questions?

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