SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Project Presentation

Scalable/Secure Cooperative Algorithms and Framework for Extremely-high Penetration Solar Integration (SolarExPert)

University of Central Florida

Award # DE-EE0007998

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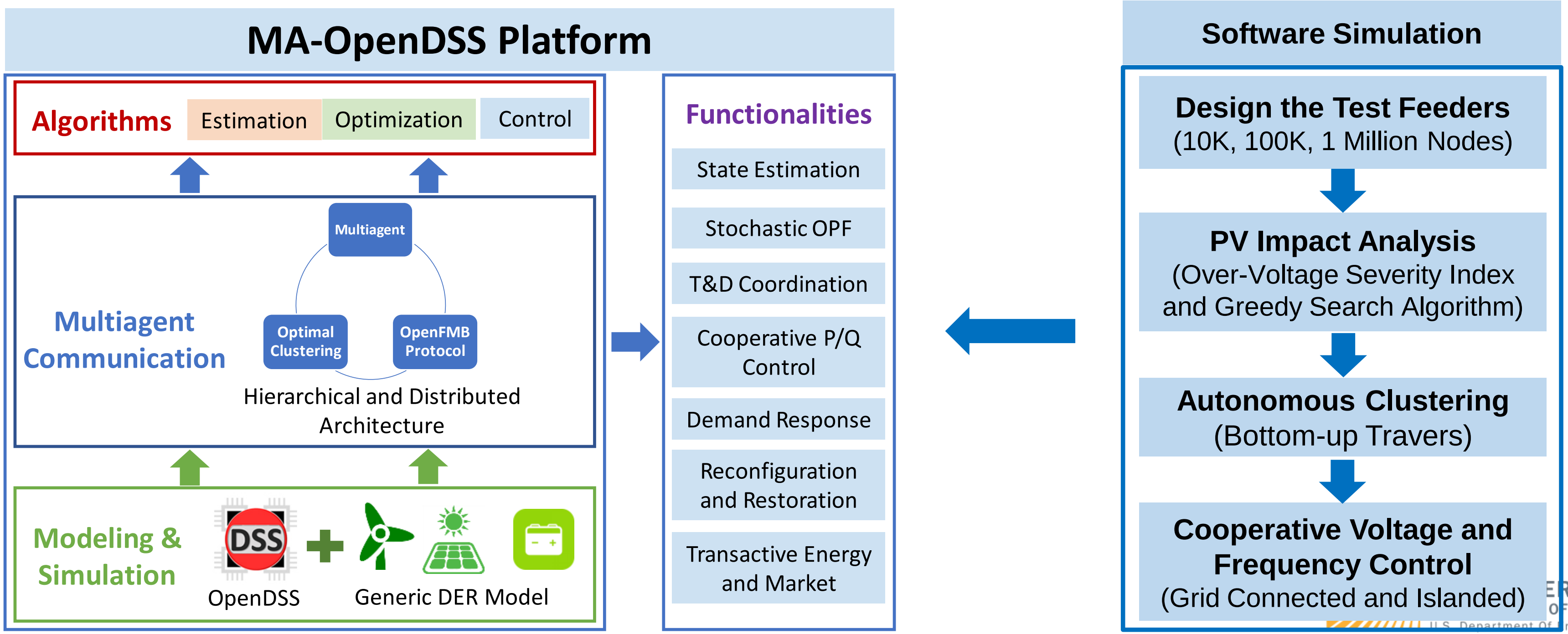
Other Contributors: NREL, HNEI, Duke, GE, Siemens, OPAL-RT

Milestone 1 – System Architecture

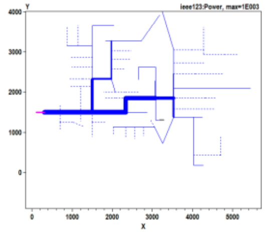
- Multi-Agent OpenDSS Platform
  - Basic version through EPRI OpenDSS: https://sourceforge.net/projects/electricdss/
  - Latest version: https://www.cs.ucf.edu/~qu/MA-OpenDSS.php



Milestone 1 – System Architecture

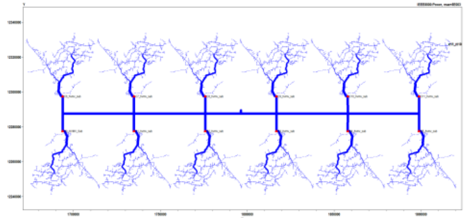
- Multiple 100K-node test feeders

1. IEEE and EPRI systems



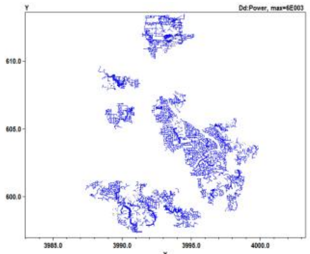
IEEE 123-node

11K-node (IEEE 8500+EPRI Ckt 7)

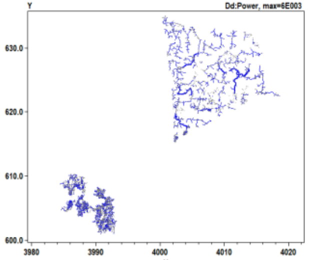


100K-node (12 of IEEE 8500-node systems)

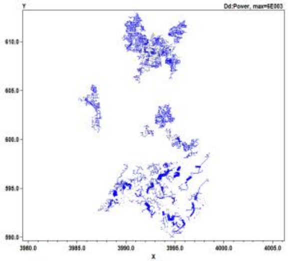
2. NREL synthetic systems



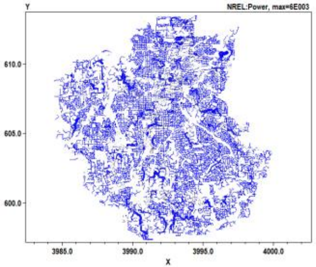
i) 100K-node (urban/ suburban)



ii) 100K-node (rural + urban/ suburban)



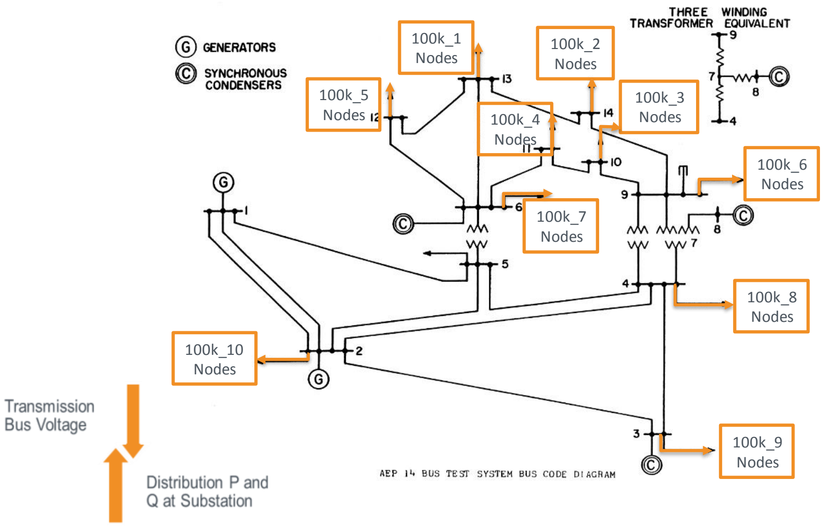
iii) 100K-node (industrial + urban/ suburban)

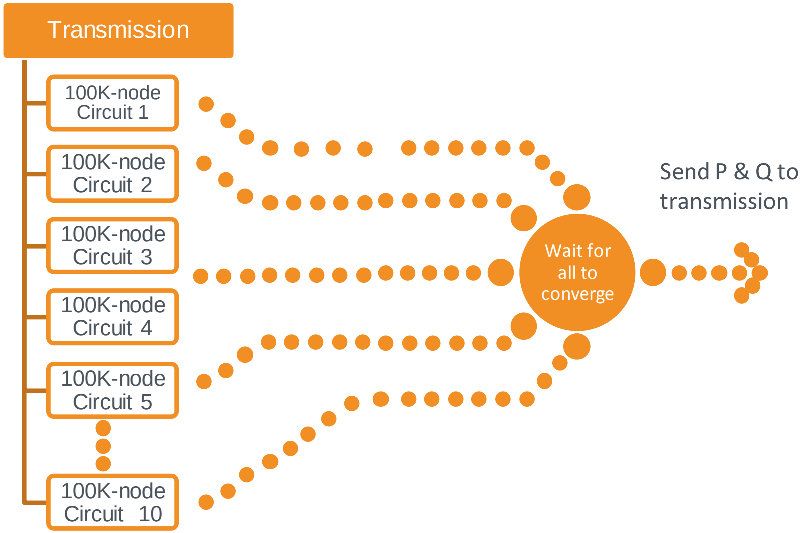


iv) 300K-node

Milestone 1 – System Architecture

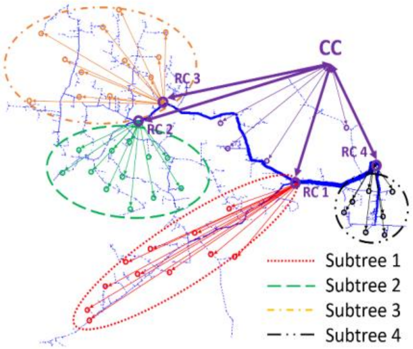
- Co-simulation of large-scale integrated T&D systems
  - Parallel implementation



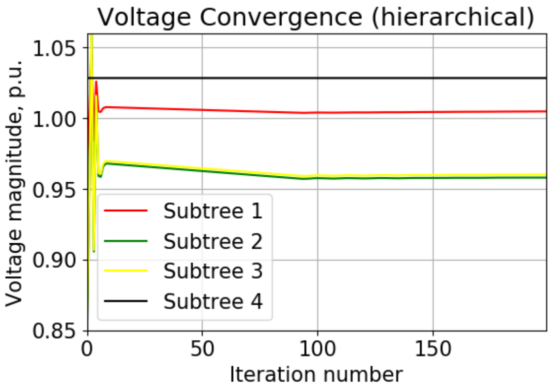


Milestone 2 – Distributed Optimal Power Flow (DOPF)

- Three-phase unbalanced ACOPF is formulated with a branch flow model, and relaxed to a convex second-order cone program, and solved by the distributed primal-dual gradient method
- Formulated a chance-constrained OPF accounting for PV uncertainties
- Success Value: <1 min for real-time operation

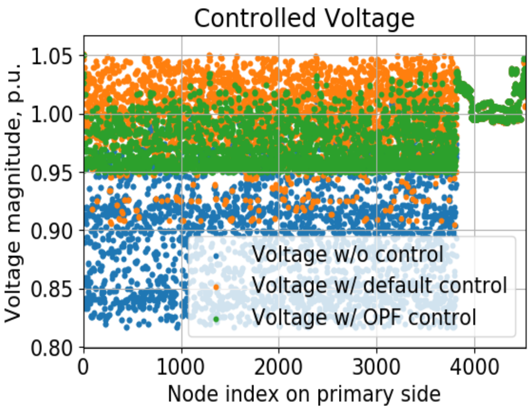


11K-node test feeder with four clusters for the hierarchical DOPF implementation.



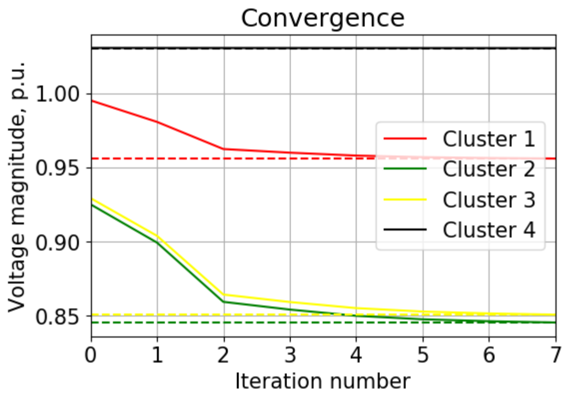
Converge: ~100 iterations for voltage regulation

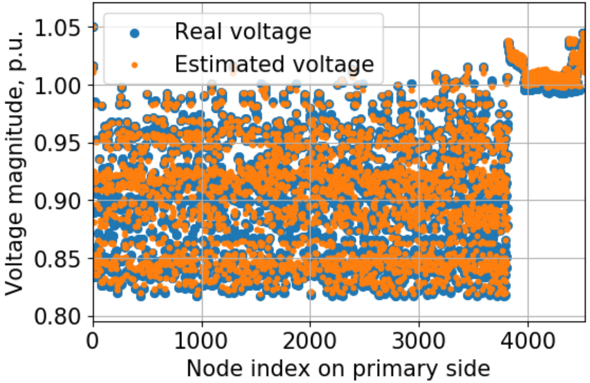
Time: ~100s on a laptop; **~40s** if parallel computation is implemented for 4 clusters.

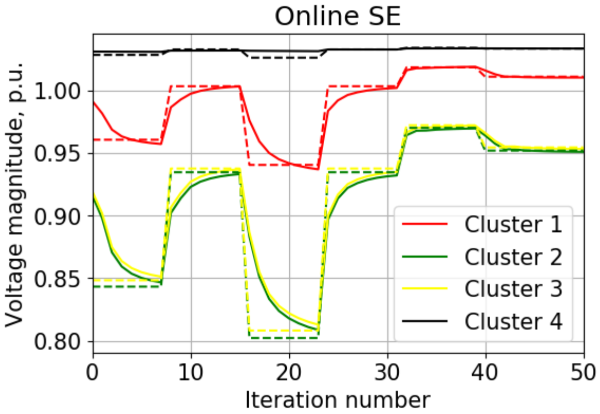


Milestone 3 – Distributed State Estimation (DDSSE)

- Online time-varying formulation and distributed online gradient algorithm for DDSSE are developed
- Success Value: accuracy <5% error, and convergence time <1-10 seconds







Converge: 7—8 iterations
Time: **9.55 seconds,** which is about **10 times faster** than centrally coordinated state estimation

% of voltage obser.	Ave. Error, %	Ave. Max. Error, %
3.6	0.45	2.3
7.2	0.45	2.2
14.5	0.42	2.0

Online DDSSE tracks the time-varying voltage magnitudes accurately

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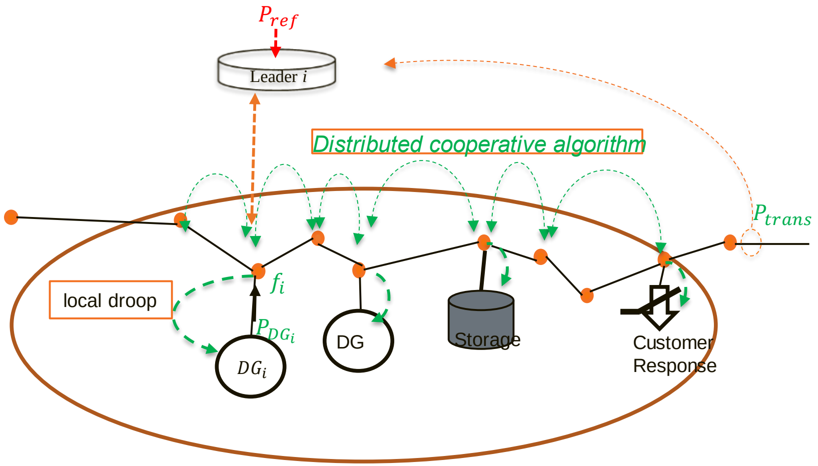
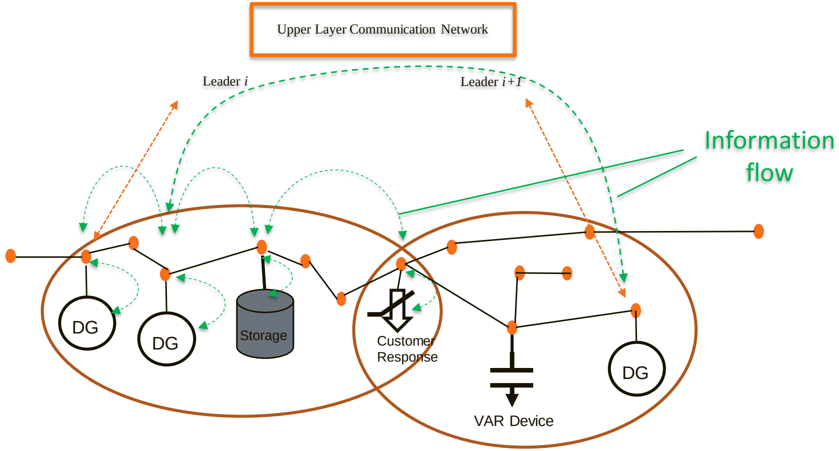
Milestone 4 – Distributed Voltage and Frequency Control

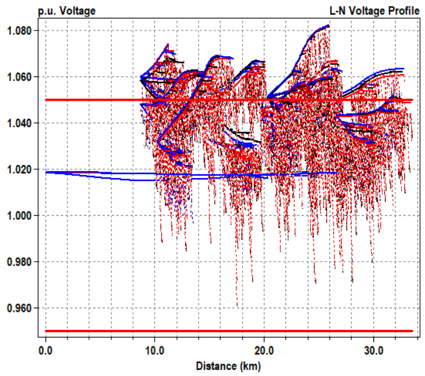
- Distributed cooperative subgradient-based algorithms for aggregate active power dispatch and autonomous reactive power control
- Cooperative voltage and frequency controls for islanded system
- Success Value: <30 seconds for the network level control



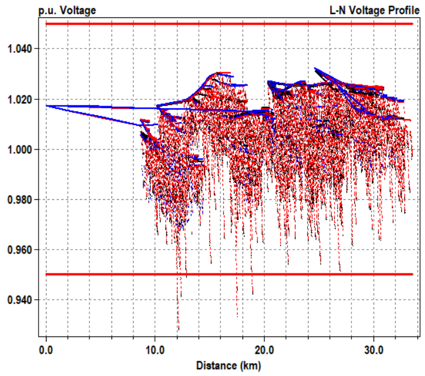


Milestone 4 – Distributed Voltage and Frequency Control

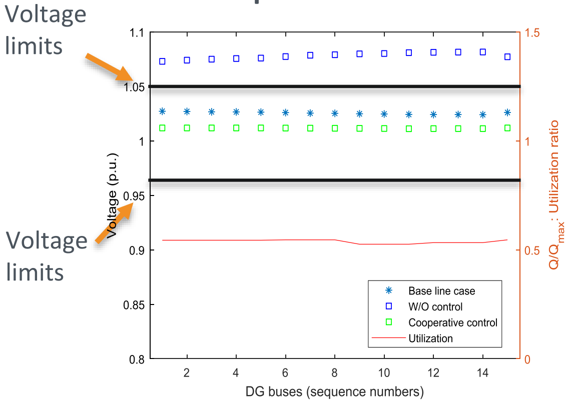
- NREL synthetic 100k system simulation with large-scale 100% PV penetration:



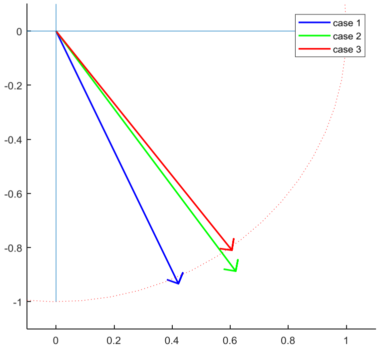
w/o control



under control



Q Utilization ratio (Feeder 12)

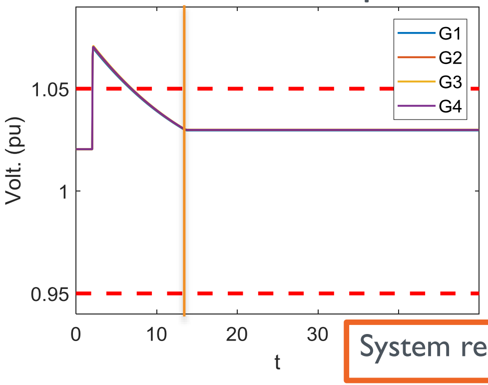


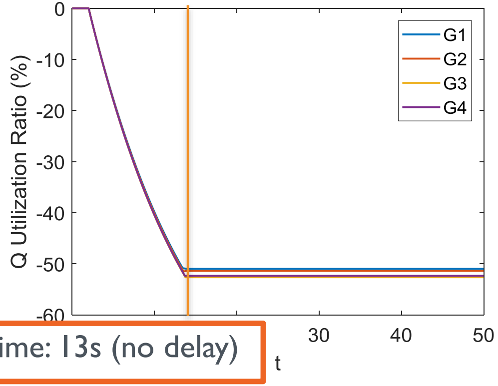
Voltage of bus ‘s_ncctt5756’ on three cases

- 104 PVs among 12 feeders, totaling 122MW (100% penetration)
- Voltage control threshold is set as 0.03
- Under distributed voltage controls, the voltage profile is within the limits
- The highest inverter capacity is 108.6%, which are PVs in Feeder 30, cluster 167.

Milestone 4 – Distributed Voltage and Frequency Control

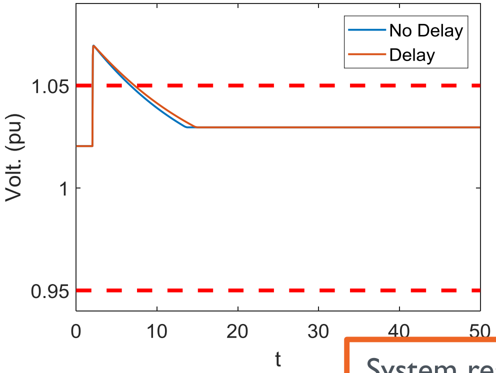
- Same 100k system simulation with 100% PV penetration:
  - At t=2s, the output of PVs increase from 0 to 100%
  - Cooperative control on, voltage threshold is 0.03 pu

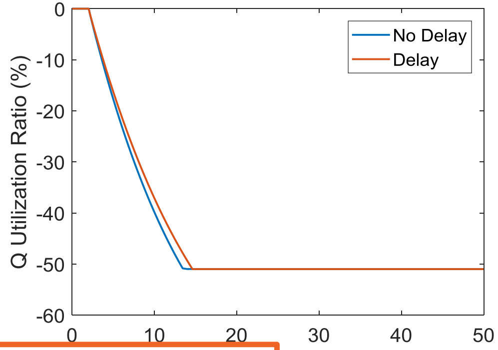




System response time: 13s (no delay)

- Delay between clusters : 1.0 s
- Delay between nodes : 0.1 s

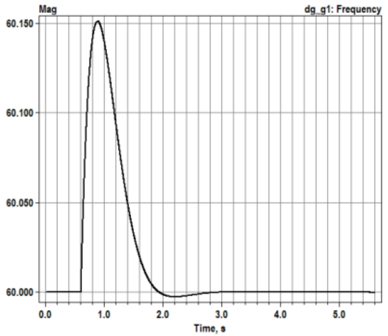




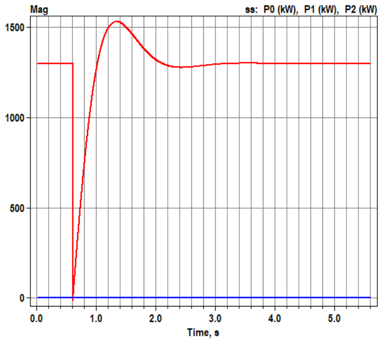
System response time: 15s (with delay)

Milestone 4 – Distributed Voltage and Frequency Control

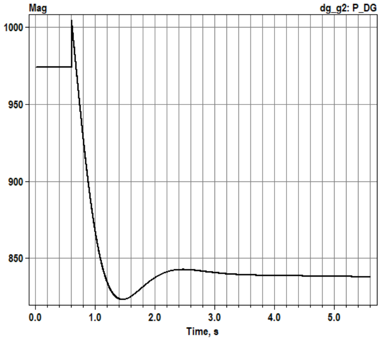
- Frequency control in the islanding mode (IEEE 8500-node system):

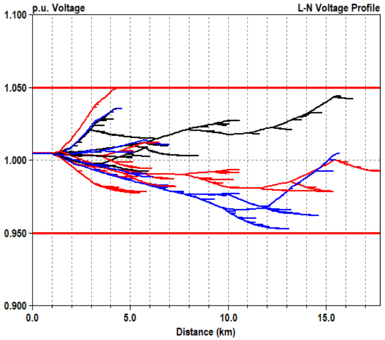


Frequency



P_{trans} (output of generator)





Scenario setup:

- Circuit breaker open at the feeder
- A generator is supplying 1300kW at slack bus
- 12 large PV farms installed
- Regulators are fixed to pos. 0

Disturbance:

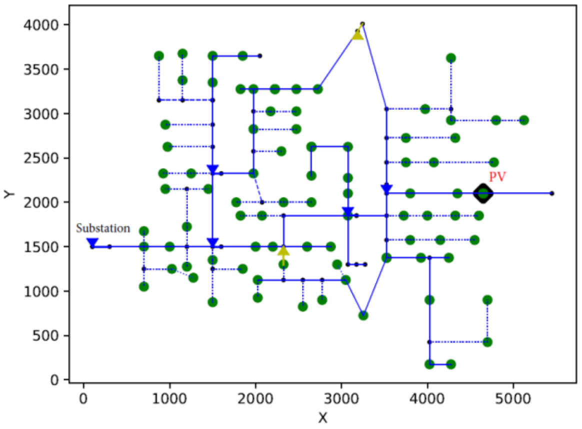
- At $t_0 = 0.6s$, a load at bus M1027043 decreases 1300kW

Frequency control:

- By cooperative control of PVs, both the frequency and power dispatch are maintained.
- The voltages are properly controlled.

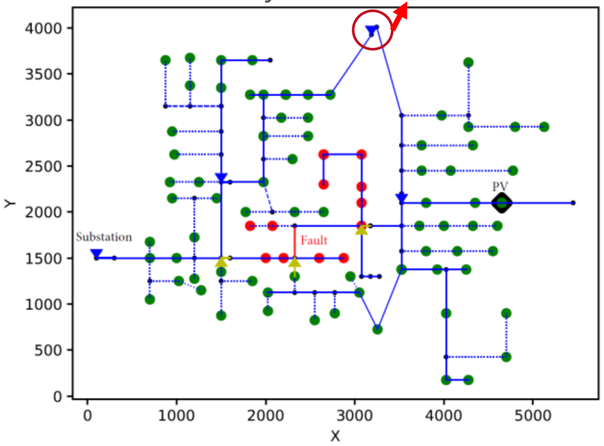
Milestone 5 – Distributed Service Restoration (DSR)

- Developed the framework of centralized service restoration and reconfiguration, and the integrated T&D restoration
  - coordinates DERs and voltage control devices for bottom-up restoration
- Success Value: converge to centralized restoration benchmark

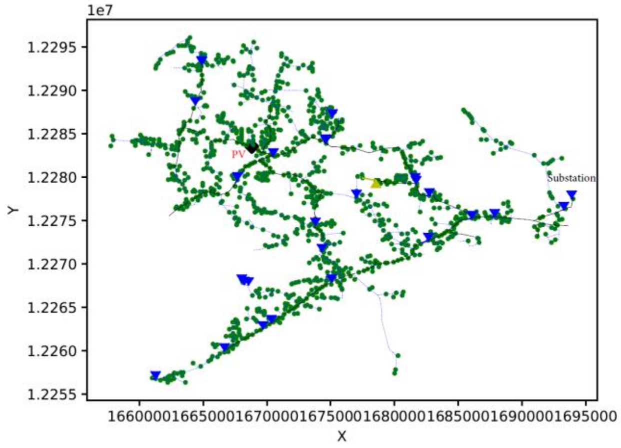


IEEE 123-Node, Normal Operation

Tie-Switch Closes to Provide power to Unfaulted area



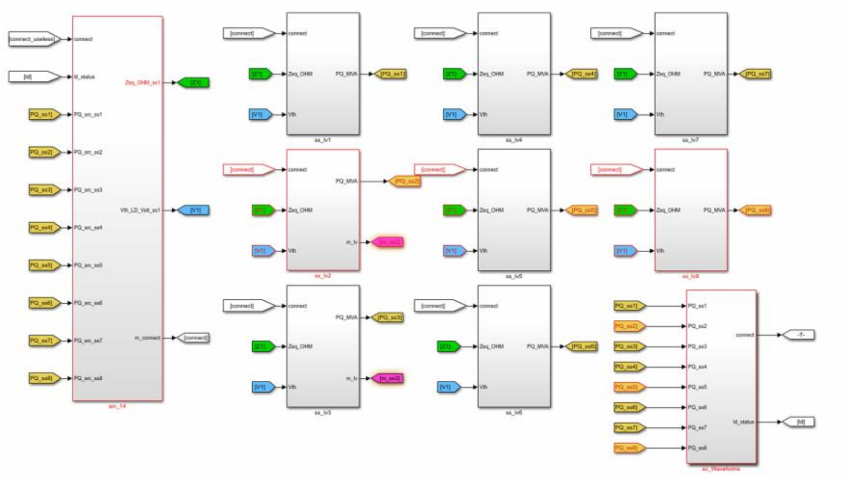
IEEE 123-Node, Faulted Element-Reconfiguration



IEEE 8500-Node, Normal Operation (One Tie switch is Open)

Milestone 6 – Real-time Simulation

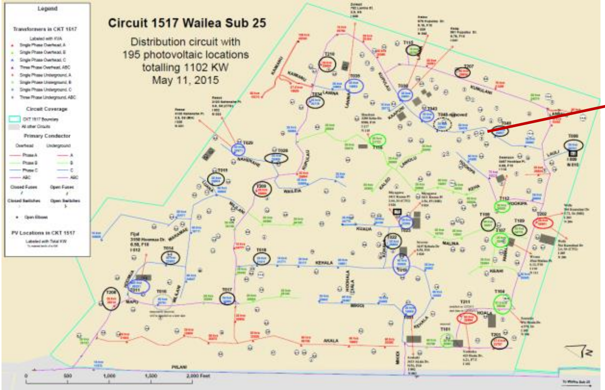
- OPAL-RT has developed the real-time testing capability of 100K-node system
  - Consisting of IEEE 118-bus system and each of 40 buses connected with one ELV test feeder system
- Results comparison using MA-OpenDSS and OPAL-RT
  - IEEE 14-bus system and 40 ELV test systems aggregated at bus 11 of transmission system
- Success Value: within 0.5% error of voltage magnitude

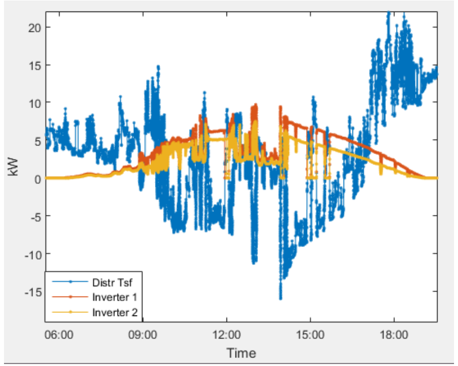


OPAL-RT			OpenDSS		
V (p.u.)	P (kW)	Q (kVar)	V (p.u.)	P (kW)	Q (kVar)
1.0569	2334	757.6	1.059	2403.57	791.54

Milestone 7 – Verification

- Maui Meadow test feeder
  - Combined measurement data and synthesized values for model conversion from DEW to OpenDSS
  - Test and evaluate the distributed voltage control algorithm



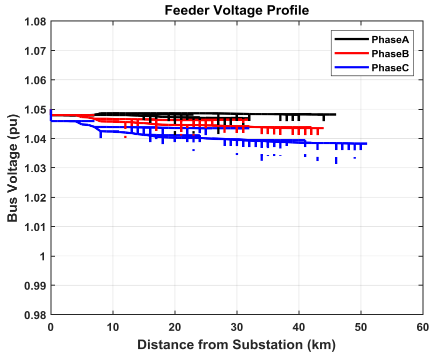


Milestone 7 – Verification

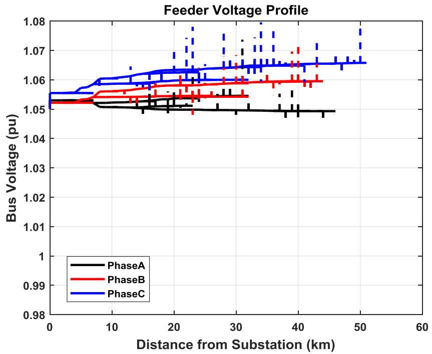
- Data: The PV and load data are from July 06, 2017, 11:15:00 AM. The total load is 1,268 kW, and the total PV output is 1,454 kW (PV penetration = 115%).

Scenarios	LTC Tap ratio	Load Level	Voltage Range [p.u.] Without PV	Voltage Range [p.u.] With PV	Voltage Range [p.u.] With Voltage Control
Base Case	1.0	1.0	[0.958, 1.000]	[0.988, 1.020]	[0.987, 1.016]
Case 1	1.05	1.0	[1.011, 1.050]	[1.038, 1.069]	[0.982, 1.049]
Case 2	1.0	0.5	[0.980, 1.000]	[0.995, 1.032]	[0.990, 1.018]
Case 3	1.05	0.5	[1.031, 1.050]	[1.046, 1.080]	[0.980, 1.049]

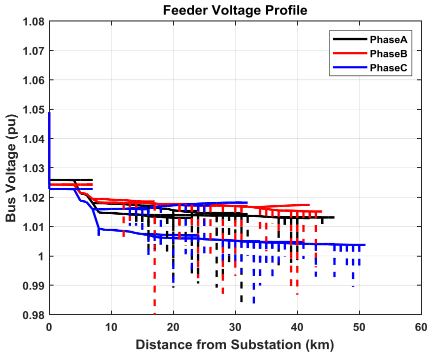
The Worst Scenario (Voltage profiles of case 3): (a) without PV generation units installed; (b) with PV penetration; (c) with the voltage control algorithm



(a)

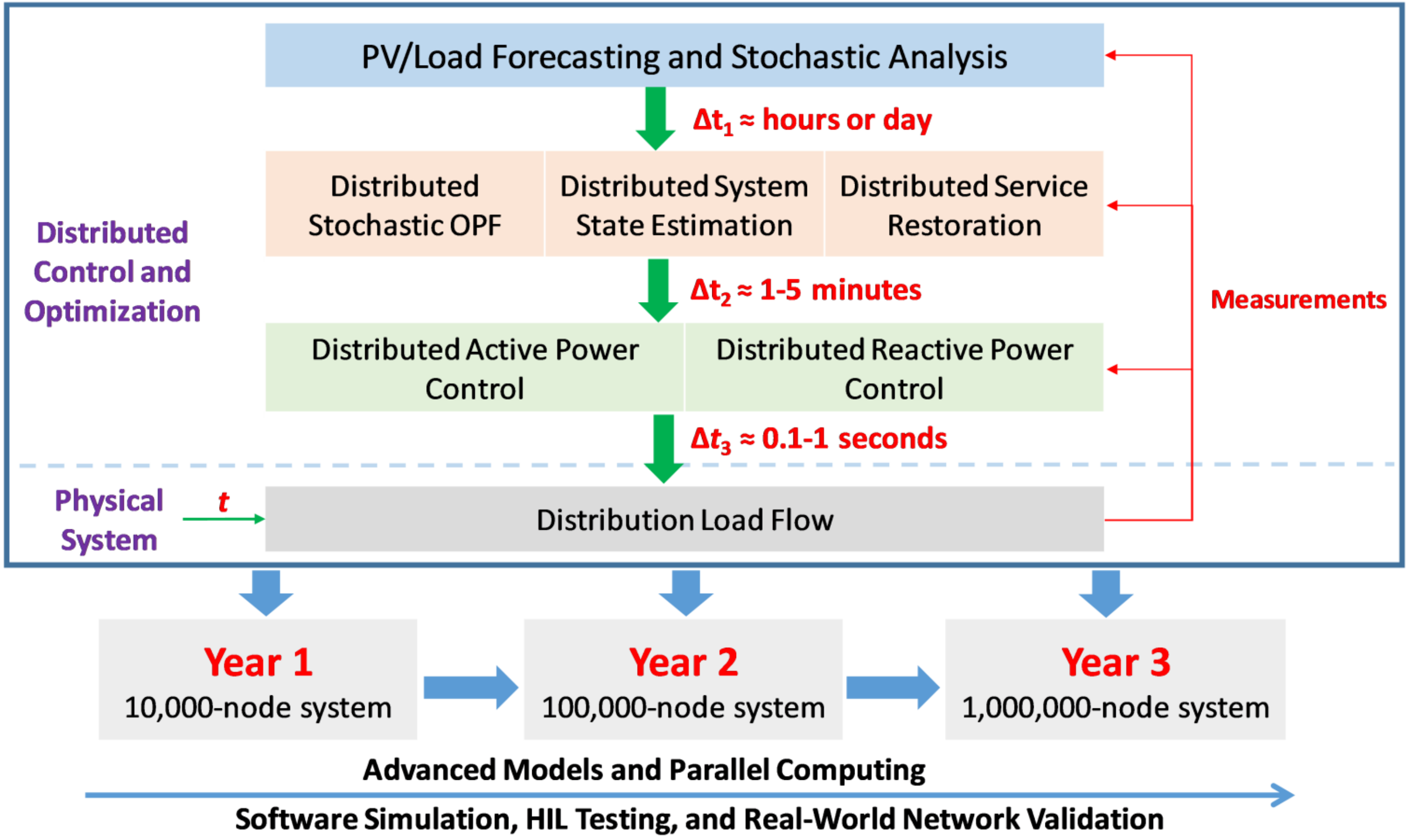


(b)



(c)

Project Performance



Project Outcomes and Products

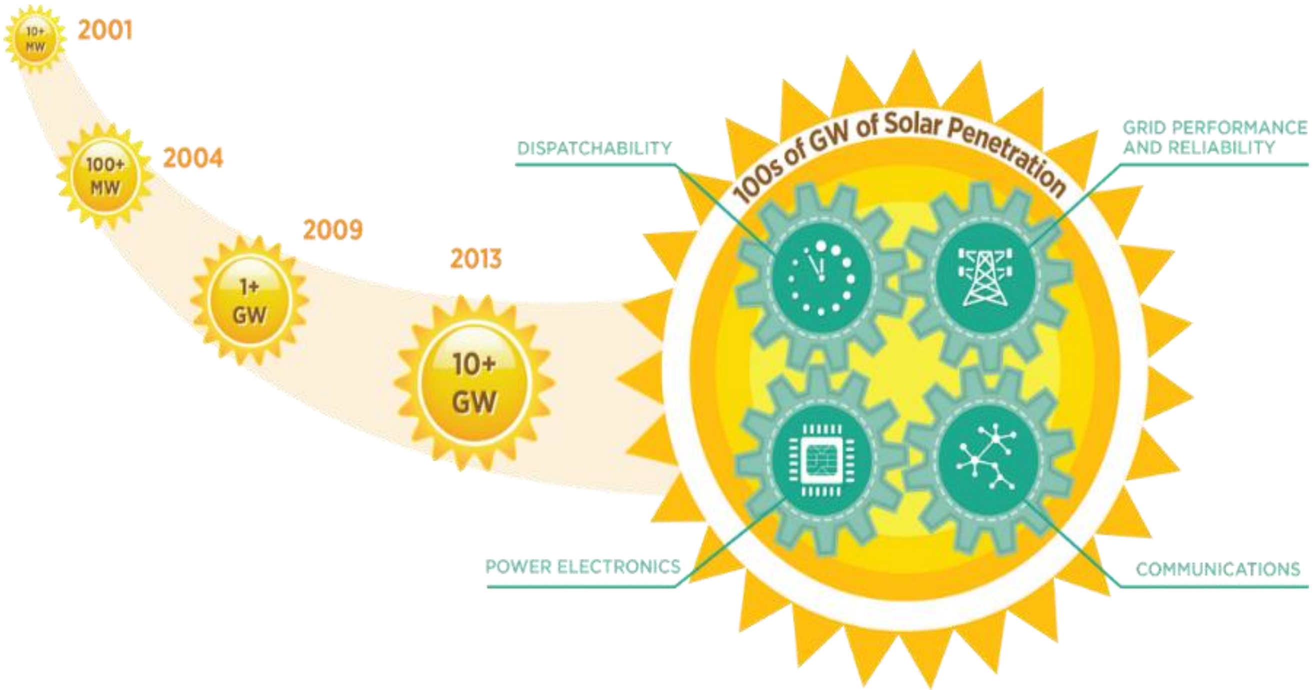
The Open-source MA-OpenDSS Platform →
- Autonomous clustering
- Cooperative controls
- T&D co-simulation
- Islanded microgrid with many PVs and one synchronous machine

Distributed Algorithms for ADMS Integration →
- On-line state estimation
- Stochastic OPF
- Cooperative P/Q controls
- Demand response
- Restoration & reconfiguration

Control-enabled Dynamic Solar Hosting Allowance (DSHA) →
- *P* and *Q* controls, hosting capacity & impact

Grid-edge Situational Awareness →
- Enhanced observability by voltage inference

Questions?



10+ MW
2001
100+ MW
2004
1+ GW
2009
10+ GW
2013
100s of GW of Solar Penetration
DISPATCHABILITY
GRID PERFORMANCE AND RELIABILITY
POWER ELECTRONICS
COMMUNICATIONS