SOLAR ENERGY
TECHNOLOGIES OFFICE
U.S. Department Of Energy

Final Project Presentation

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

Award # DE-EE0007998

SETO/DOE ENERGISE webinars

June 25, 2021

Team: UCF, NREL, HNEI, Duke, GE, Siemens, OPAL-RT
Principal Investigator: Dr. Zhihua Qu

Executive Summary

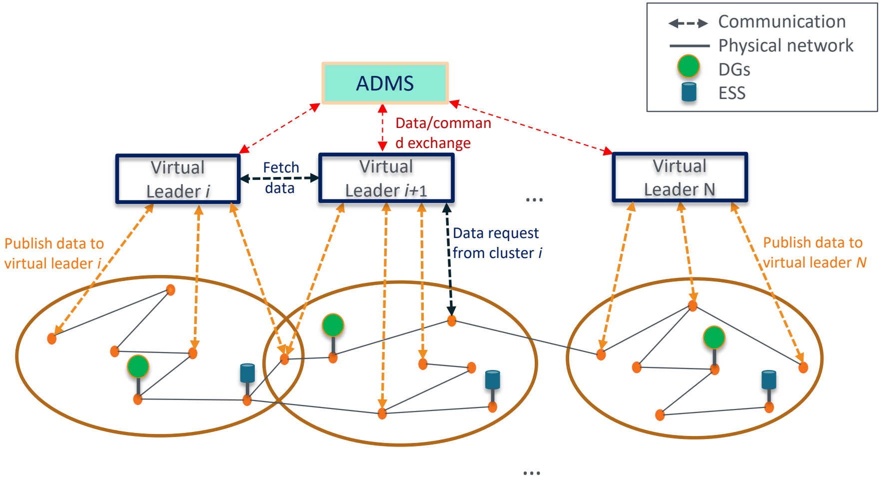
Outcomes:

- A scalable, distributed grid architecture: local communication and clustering, P/Q/f controls, stochastic OPF, state estimation, and restoration.
- Software and hardware tests: 1 million-node distribution system, 100,000-node system HIL simulation, and PHIL implementation with 100 physical devices;
- A feeder from Maui Meadows in Hawaii is studied for control-enable host capacity analysis
- **Multi-Agent OpenDSS** (MA-OpenDSS) platform
- Technology transfer with Siemens on Microgrid Management System and integration of DMS functions with MA-OpenDSS

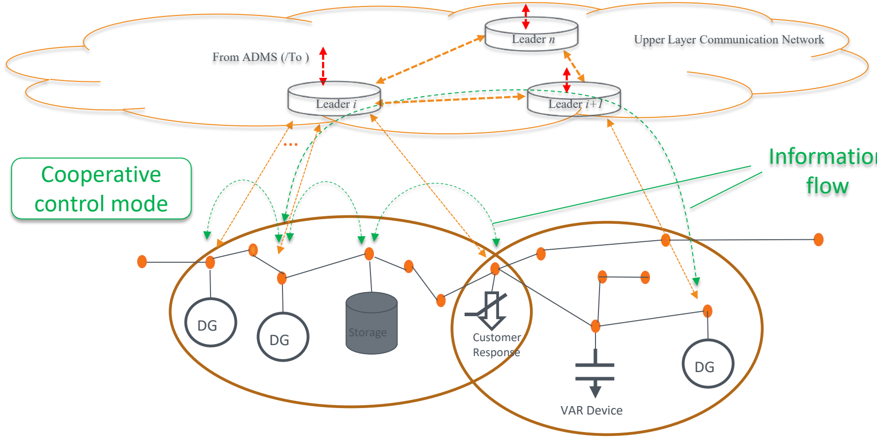
Project Innovations – 1

System Architecture of Distributed Control and Optimization

- An advanced grid architecture with hierarchical and distributed communication and control, combined with the OpenFMB standard and implemented on the Multi-Agent OpenDSS (MA-OpenDSS) platform



Hierarchical and distributed communication



Distributed architecture of optimization, estimation, and cooperative control

1-million-node Test System

- 10 different 100k-node systems: NREL' s test systems (3), and San Francisco bay area feeders (7) systems
- Two-stage greedy search for worst-case scenarios of 100% PV penetration:
  - Stage 1: primary nodes
  - Stage 2: secondary nodes

  Over-voltage-severity index (OVSI)

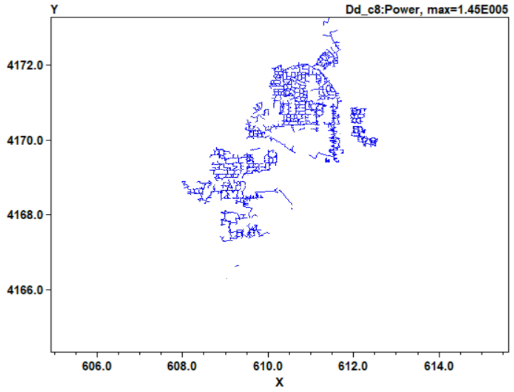
$$\text{OVSI} = \sum_{V_i \notin [0.95,\ 1.05]} |1 - V_i|$$

- PVs distributed in the secondary nodes are assumed to not exceed twice the amount of the total load in the secondary nodes

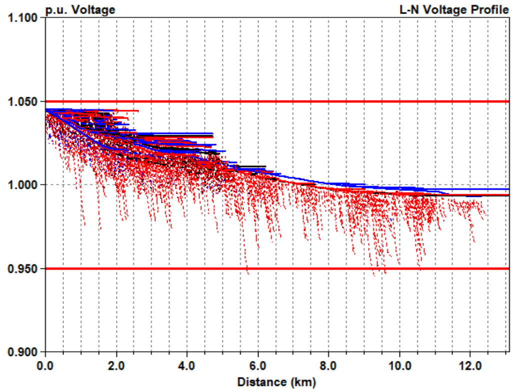
Test System	No. feeders	No. buses	Total load (MW)
1st- 100k	12	53,011	124
2nd -100k	8	47,280	105.20
3rd -100k	21	46,453	290.32
4th -100k	13	53.599	98.92
5th-100k	6	53,820	88.363
6th-100k	9	50,122	108,365
7th-100k	14	52,174	109,51
8th-100k	14	49,893	145,289
9th-100k	12	51,163	114,26
10th-100k	6	53,276	109,224

Eighth 100k-node System

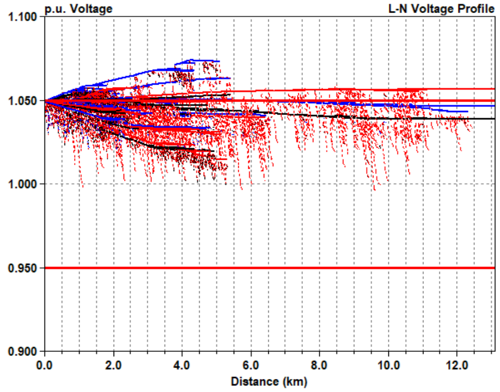
- 14 feeders, 49,893 buses, 145.29 MW total load



Circuit plot



Voltage profile: base case



Voltage profile: 100% PV

- 20682 primary, 81856 secondary for 102538 total nodes
- After greedy search, PVs are employed in 19504 primary, 59898 secondary, totaling 79402

OVSI		
Base Case	100% PV	Control
2.880	813.428	0.1522

Summary – All Systems

100k No.	No. Primary Nodes		No. Secondary Nodes		No. Nodes		OVSI		
	Total Nodes	PV Nodes	Total Nodes	PV Nodes	Total Nodes	PV Nodes	Base Case	100% PV	Control
1st	13074	12572	95572	84504	108648	97076	0	15.316	2.4076
2nd	17818	16961	79866	55901	97684	72862	3.042	96.097	1.1835
3rd	19740	19031	80248	52624	99988	71655	4.132	919.109	1.6377
4th	15194	14910	91385	77170	106579	92080	0	96.845	0
5th	17160	16857	90077	75551	107237	92408	0	0.418	0
6th	13439	13073	86482	68369	99921	81442	0.503	262.819	0
7th	12280	11502	91015	65921	103295	77423	2.552	1634.99	3.6332
8th	20682	19504	81856	59898	102538	79402	2.880	813.428	0.1522
9th	12976	12391	89061	72533	102037	84924	0	8.416	0
10th	12582	12429	93412	77124	105994	89616	0	0	0

Project Innovations – 2

Distributed Optimal Power Flow (DOPF)

- An online distributed stochastic OPF based on a reverse-forward engineering procedure and dynamic, real-time, distributed feedback control;
- The multi-level implementation further improves the convergence speed without losing any information or compromising any accuracy

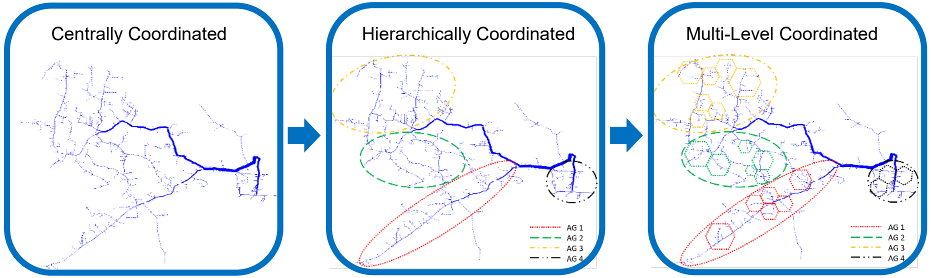
A chance-constrained OPF formulation:

$$\min_{p,q} \sum_{i \in N} C_i(p_i, q_i) + C_0(p, q),$$

$$s.t.\ \text{Power flow equations},$$

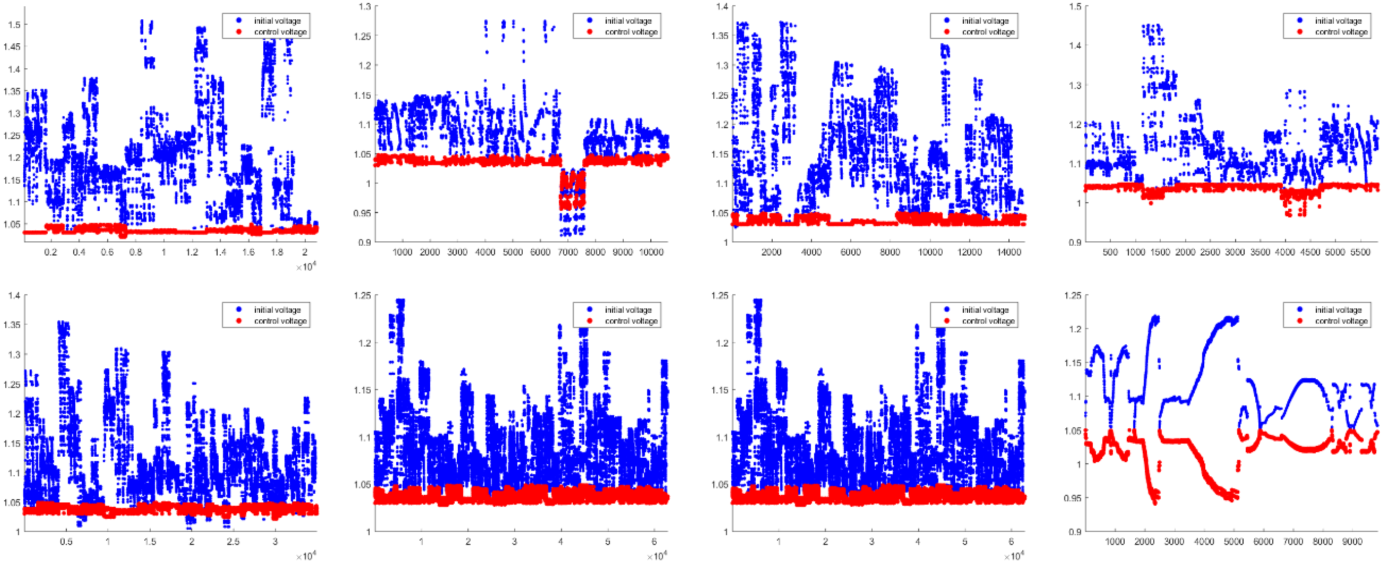
$$\text{Prob}(0.95\ \text{p.u.} \leq \text{v} \leq 1.05\ \text{p.u.}) \geq 99\%,$$

$$(p_i, q_i) \in \Omega_i, \text{for all } i \in N.$$



Performance of DOPF

- 1,000,000 nodes system with 100% renewable energy penetration
- All voltages are strictly within the bounds of 0.95-1.05 p.u., running time is less than 5 min, and 100% optimality is same as the centralized solver.
- (The designed OPF solver is applicable to general situation; the following example is to illustrate that OPF works even under extreme situations.)



Project Innovations – 3

Distributed Distribution System State Estimation (DDSSE)

- An online distributed system state estimation algorithm based on prediction-correction methods for time-varying convex optimization
- The joint real-time SE-OPF solver to calculate OPF based on the estimated voltage for more practical implementation

DSSE is formulated as overdetermined systems of non-linear equations and solved as weighted least-squares problems

1. Observability
   - pseudo-measurements
2. Accuracy
   - Gauss-Newton vs. Gradient-based
3. Efficiency

Standard OPF:

Update OPF iterations based on real voltage values is **unrealistic: lack of network-wide monitoring devices**

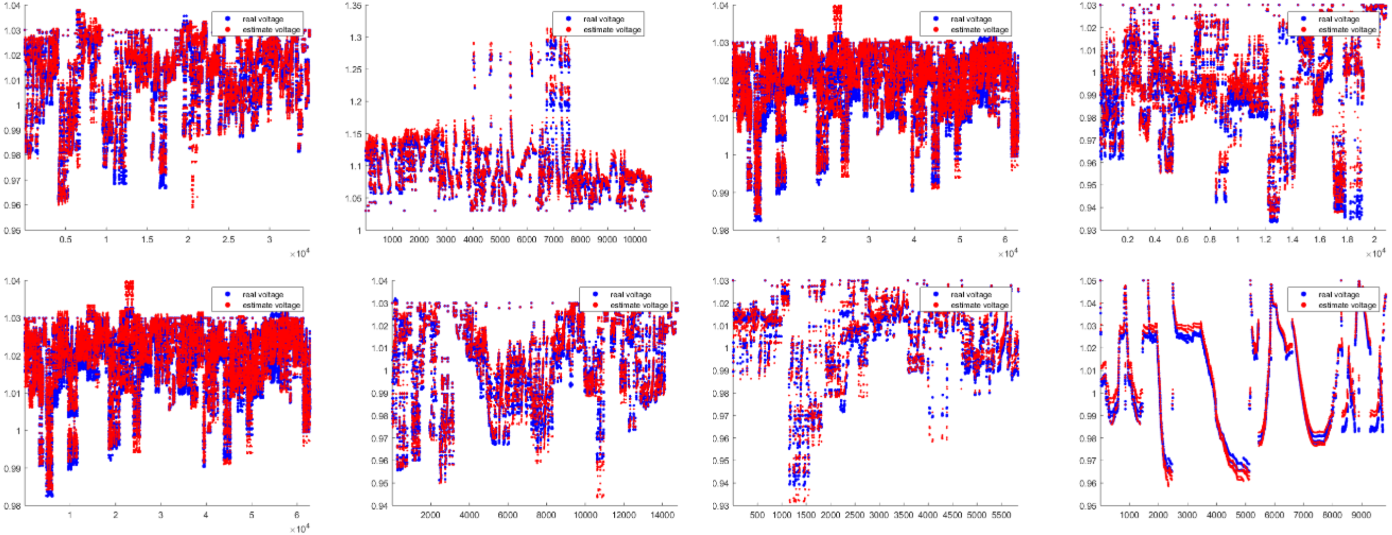
Joint SE-OPF:

Update OPF iterations based on estimated voltage values is **Realistic with verified performance.**

Performance of DDSSE

- 1,000,000 nodes system
- 10% of nodes with voltage measurement
- 1% standard deviation for voltage measurement error
- 50% standard deviation for pseudo measurement error

Area	Average Error	Maximum Error
8th 100k System of UCF (P1U + 4 feeders)	0.39%	2.21%
P2U	0.16%	0.90%
P3U	0.23%	1.29%
P6U	0.24%	3.45%
P27U	0.31%	1.42%
P29U	0.23%	2.83%
P34U	0.37%	2.02%
All Areas	0.24%	3.45%



√ Node number: > 1,000,000
√ Maximum error of all nodes: 3.45%
√ Average error per node: 0.24%
√ Running time for each feeder: <10s

Project Innovations – 4

Distributed Cooperative Control (DCC) of Voltage and Frequency

- Distributed and coordinated Volt/VAR, Watt, frequency controls are designed using the subgradient-based cooperative control/optimization framework, and they optimally dispatch the real and reactive power of multiple DERs and minimize curtailment, with the robust performance.

DCC is formulated as distributed optimization:

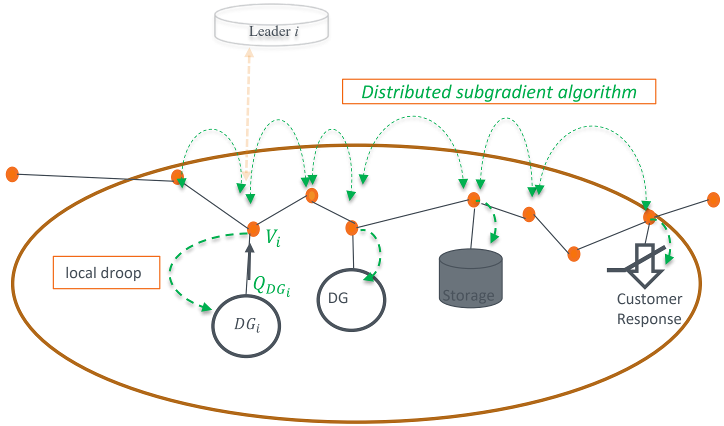
(1) Minimizing local voltage deviations:

$$\min_{Q_i \in [\underline{Q}_i, \overline{Q}_i]} \sum_{j \in \mathcal{N}_i} (V_i - V_j)^2$$

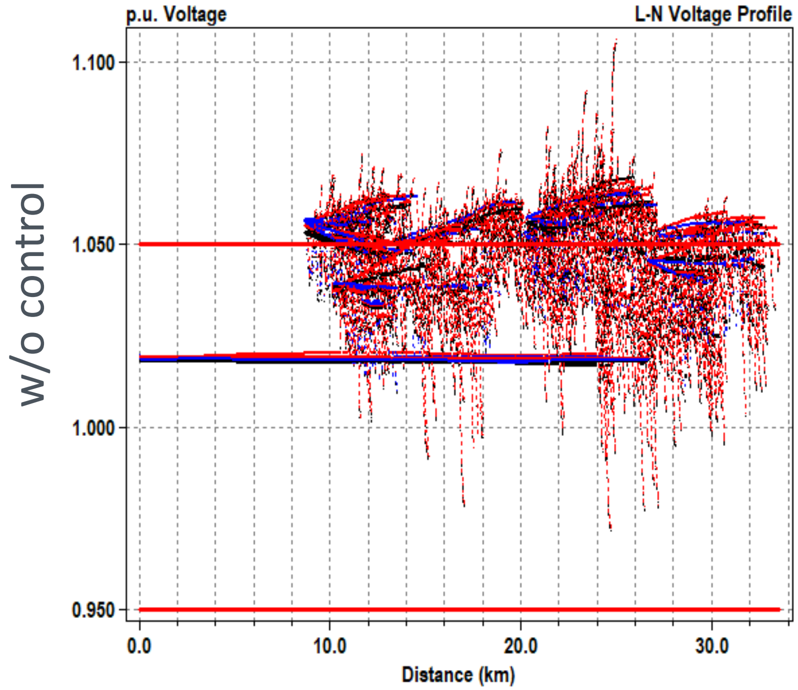
(2) Minimizing curtailment, frequency drift, and overall voltage profile

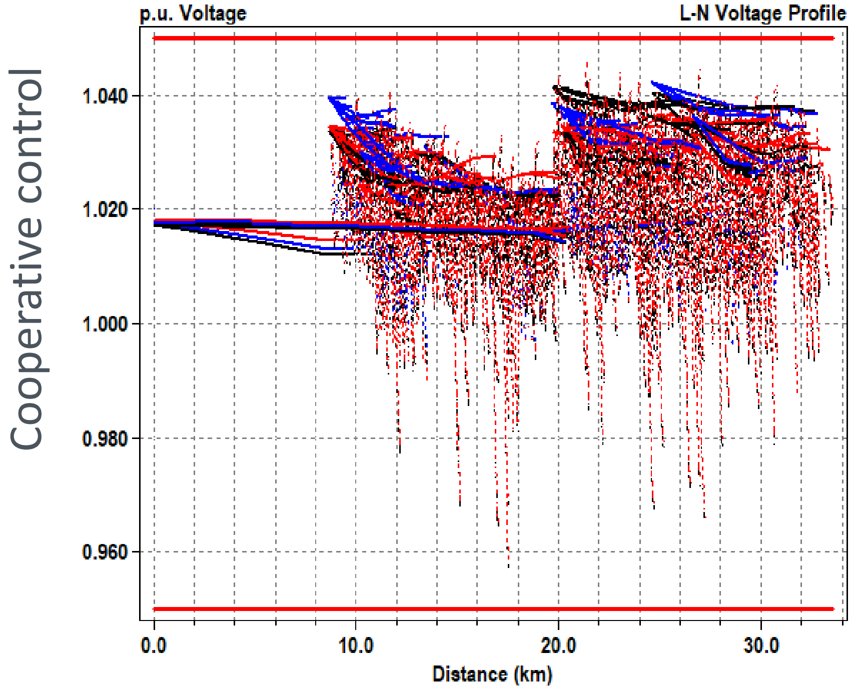
$$\min_{P_i \in [\underline{P}_i, \overline{P}_i]} \left[\beta_1 \left(P_i - P_i^{ref} \right)^2 + \beta_2 (\omega_i - \omega_0)^2 + \beta_3 (V_{max} - V_{min}) \right]$$

Also, robust w.r.t. topology change, time delay, etc.



Performance of Distributed Voltage and Frequency Control



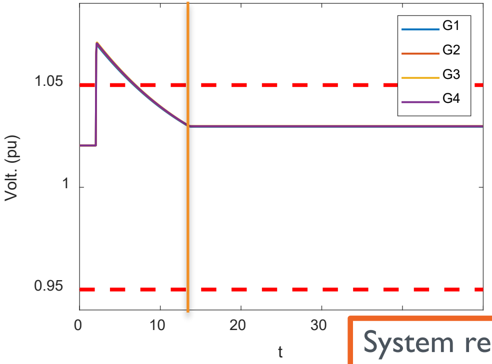


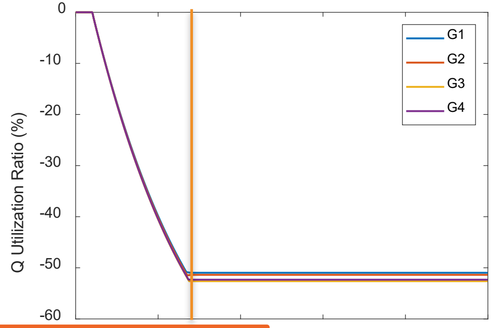
- Worst-case from the Greedy Search: 174,284 PVs among 12 feeders, 158MW total (130% penetration)
- A total 68MVar of inductive reactive power is generated by PV inverters
- The capacity of inverters are set to be 120%, voltage threshold is 0.045%.

Performance of Distributed Voltage and Frequency Control

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

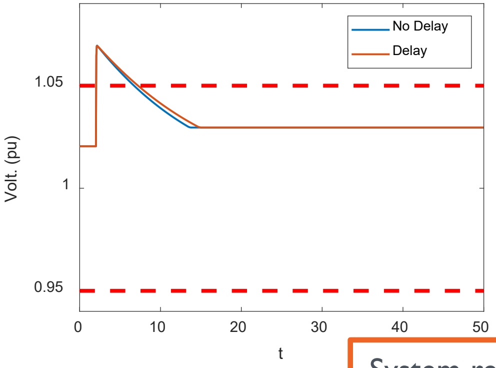
  - At t=2s, the output of PVs increase from 0 to 100%
  - Cooperative control on, voltage threshold is 0.03 pu

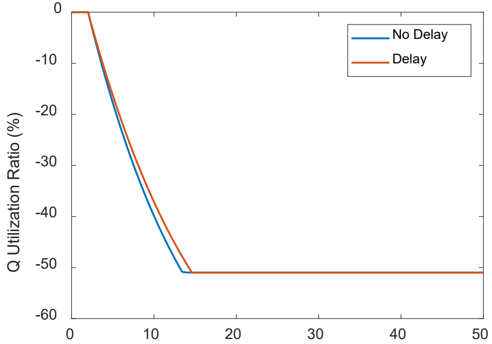




System response time: 13s (no delay)

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





System response time: 15s (with delay)

Project Innovations – 5

Distributed Distribution System Restoration (DDSR)

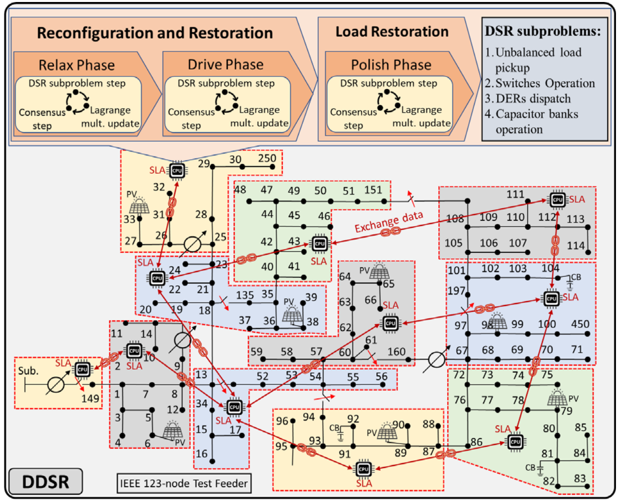
- The DDSR strategy to optimally determine the PV generation, network configuration, switching status, and load pickup, in order to restore the entire system or energize unfaulted out-of-service areas, as well as to coordinate the restorative actions between T&D networks

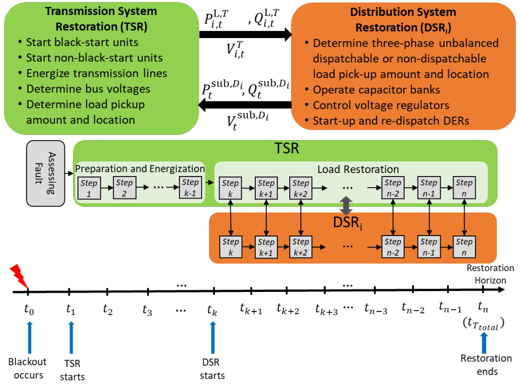
DSR is formulated as a multi-objective mixed-integer convex optimization problem

Max. Total restored loads and
optimal operation of switches

s.t.

- Security constraints
- Power flow constraints
- Connectivity & radiality constraints





Performance of DDSR

- There is a major outage with 3 restoration steps following transmission restoration
- One faulted line occurred during restoration, and faulted area is being isolated by sectionalizing switches
- Tie-switch is closed to energize unfaulted out-of-service area while all other tie-switches remain open to prevent any loop during operation
- DDSR coordinates PVs with transmission capacity to restore more loads

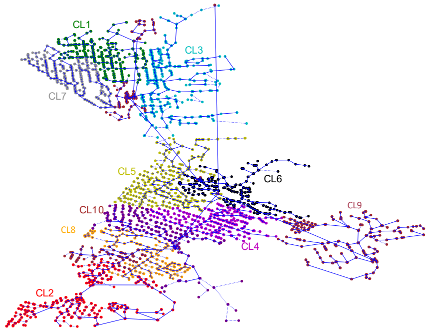


Fig. The network is divided into 10 clusters.

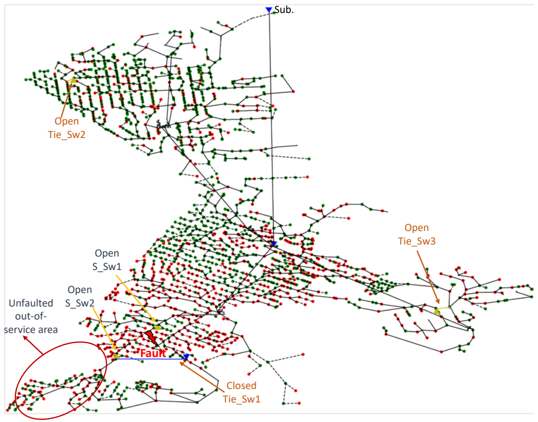


Fig. DDSR operation in first time step with distributed PVs and faulted lines.

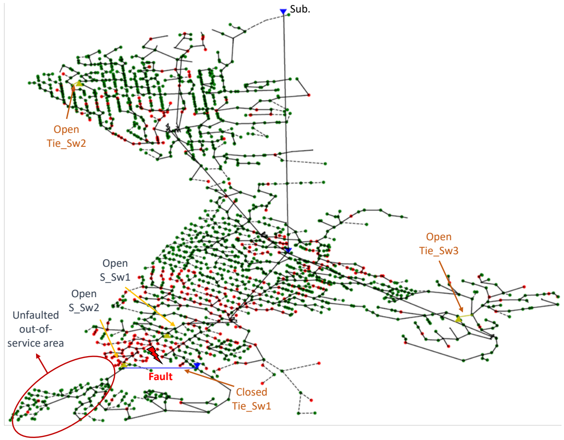


Fig. DDSR operation in second time step with distributed PVs and faulted lines.

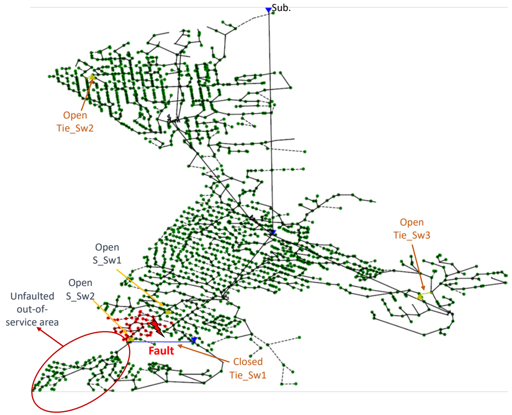
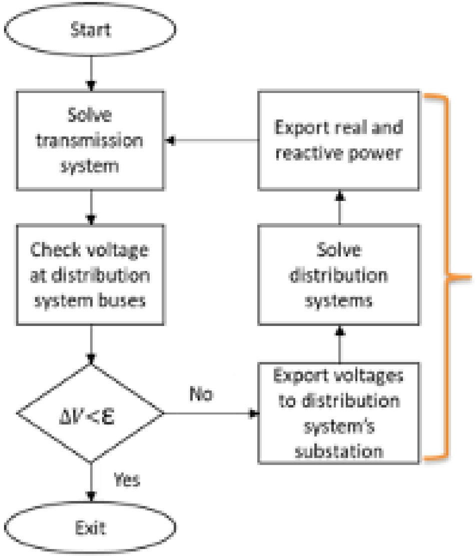
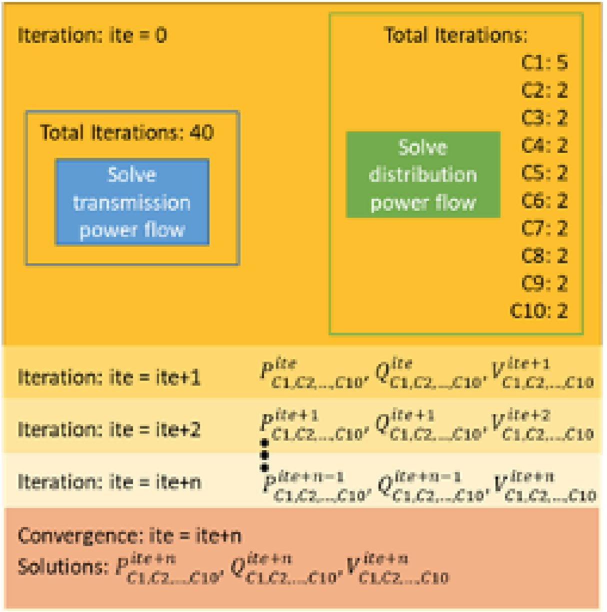


Fig. DDSR operation in third time step with distributed PVs and faulted lines.

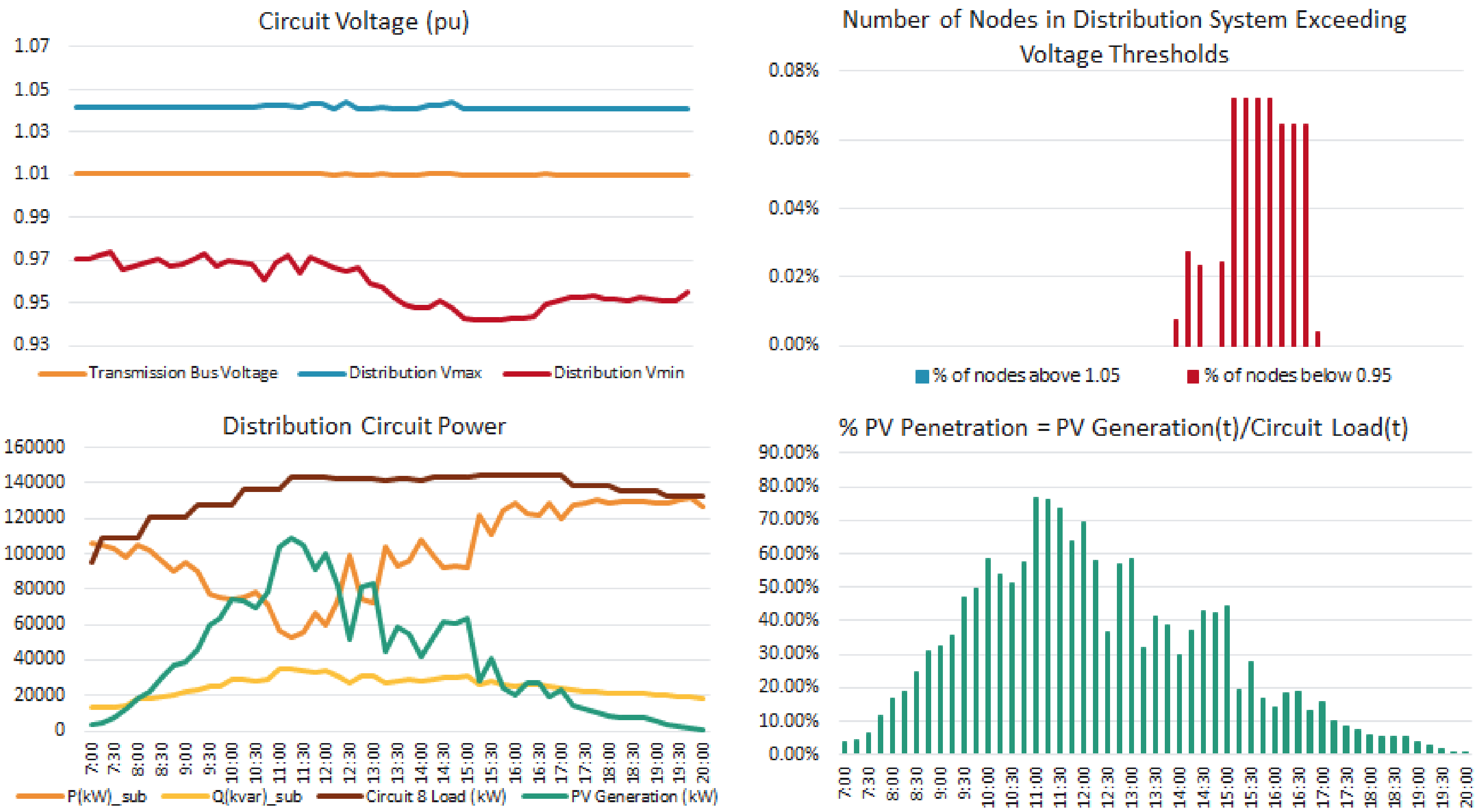
Project Innovations – 6: 1M-node T&D Co-Simulation

- 1M Node Test System:
  - Transmission System: modified IEEE 30-Bus System
  - Distribution Systems: 10 synthetic systems of 100k nodes with large PV penetration
- Time series full day simulation: 7am-8pm with 15min time step.
- Load profile and solar irradiance fluctuates with each time step
- All distribution systems utilize cooperative control to minimize voltage violations

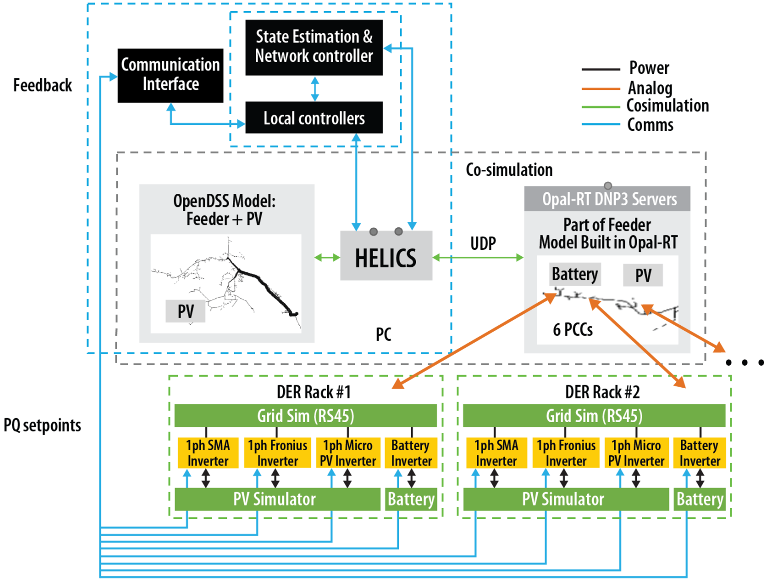


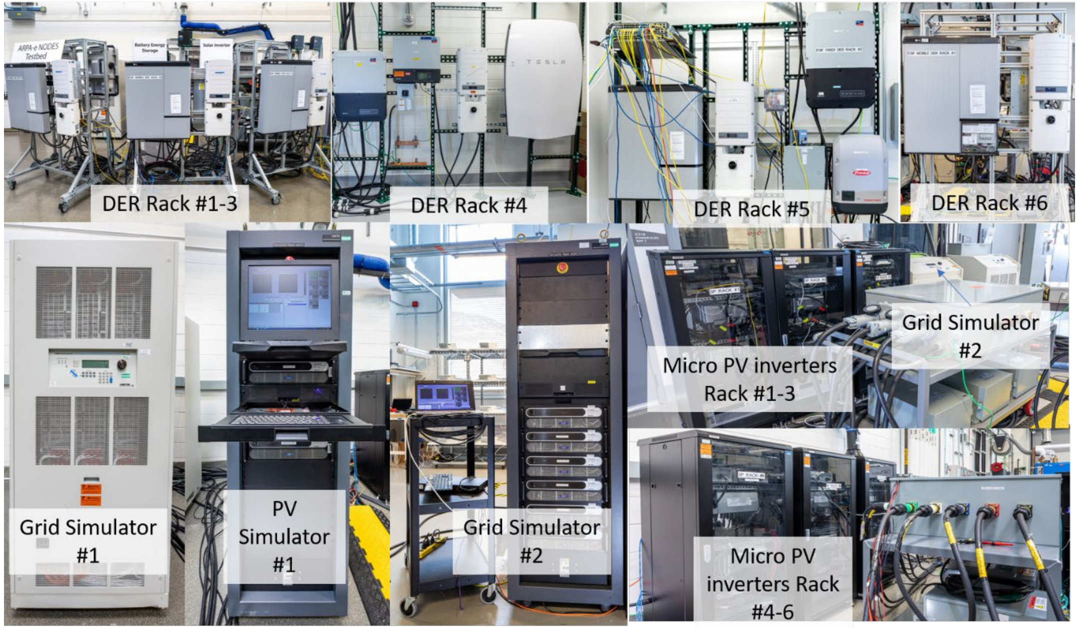


T&D Co-Simulation Results

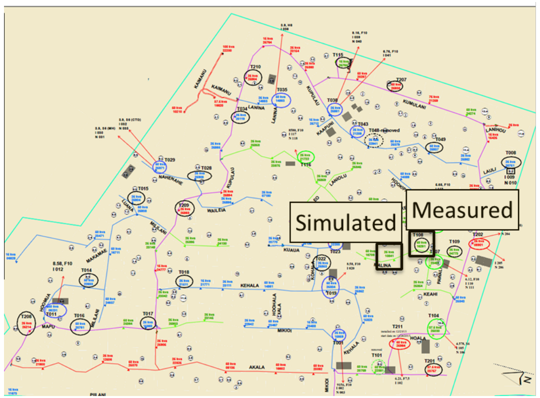


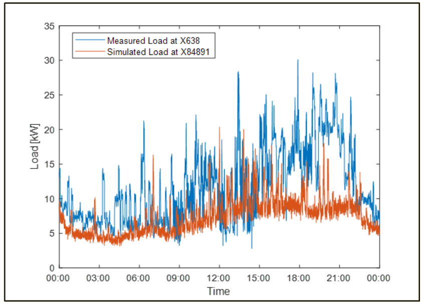
Project Innovations – 6: PHIL Implementation (100 Devices)





Project Innovations – 6: Hosting Capacity of Maui Meadows Feeder

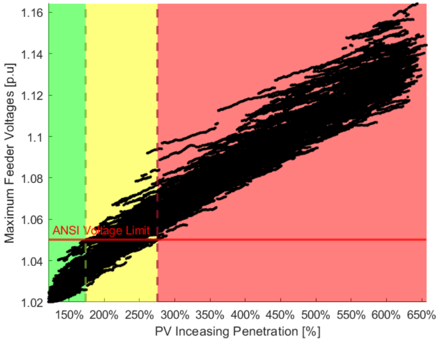




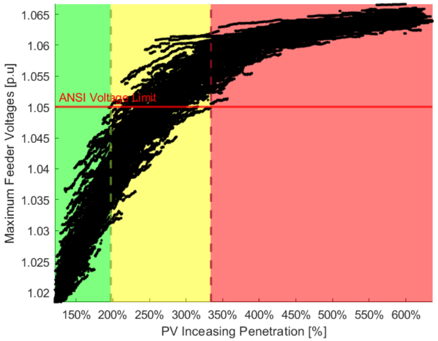
A1: Regardless of PV location, all penetrations in this region are acceptable.

A2: Depending on PV deployment, some penetrations in this region are acceptable.

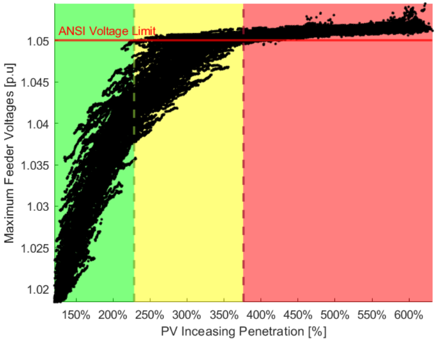
A3: Regardless of PV location, no penetrations in this region are acceptable.



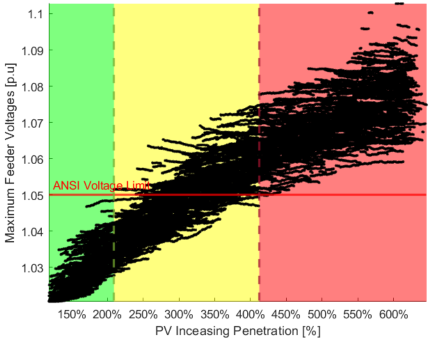
Without Control



With Moderate VVWC



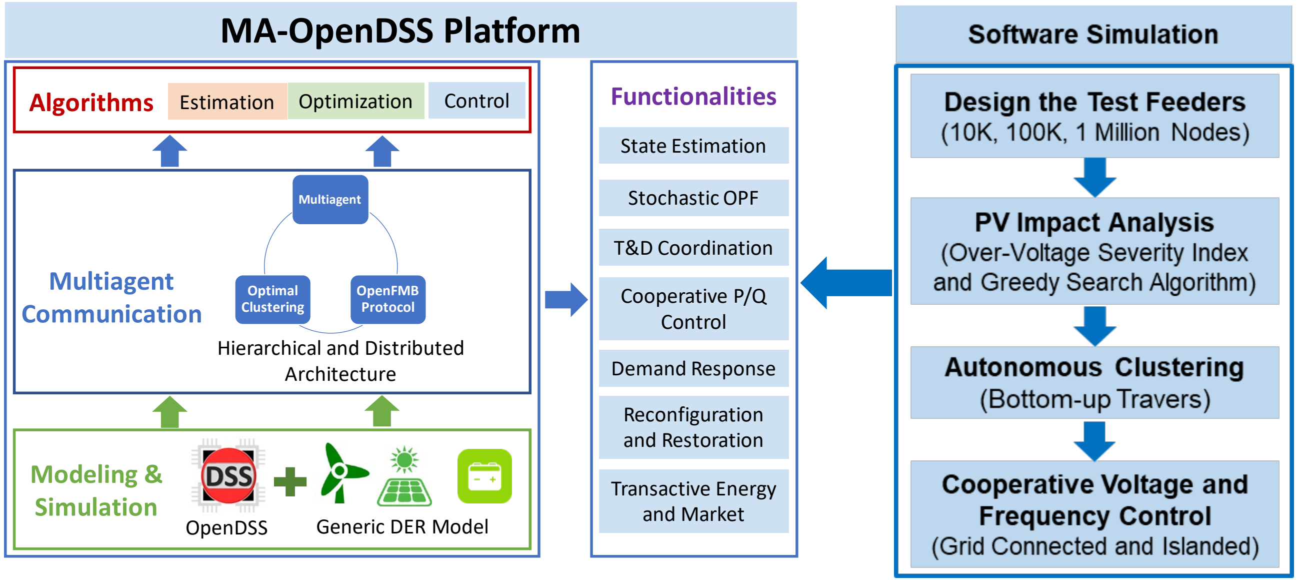
With Aggressive VVWC



With Cooperative VVC

The Design of MA-OpenDSS

- The developed system architecture includes dynamic grouping of both physical and communication topology, distributed control and optimization based cooperative principles, self-organizing according to feeder capacity and local communication options, which provide the theoretical foundation for this project.

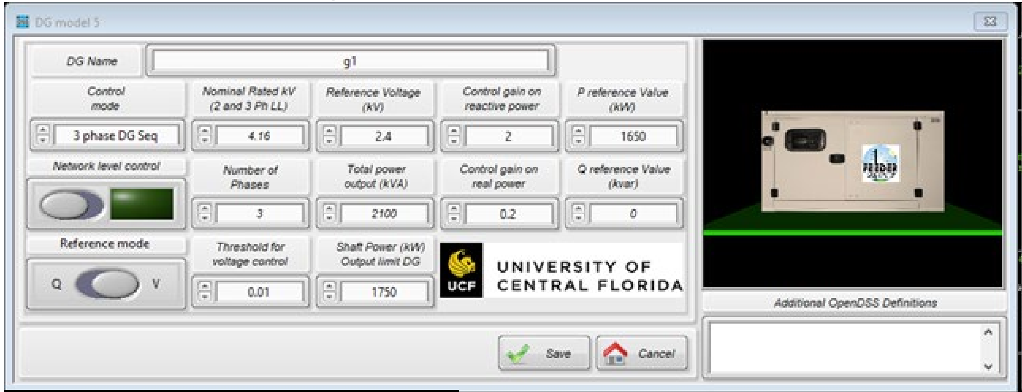


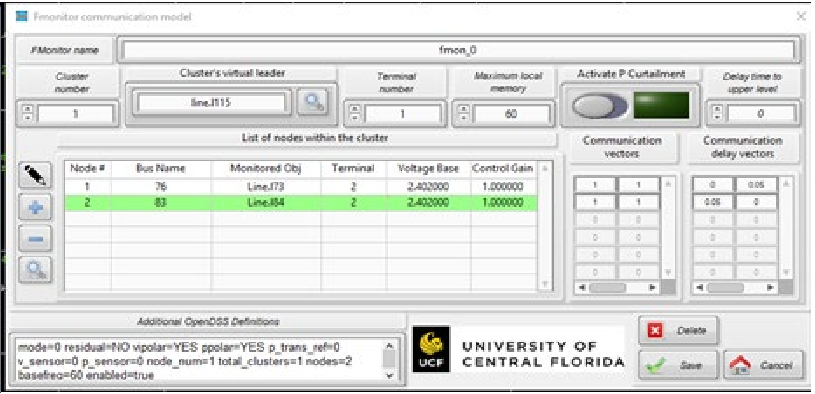
Multi-Agent OpenDSS Platform

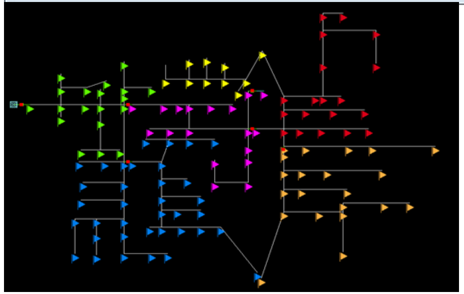
- Basic version through EPRI OpenDSS: https://sourceforge.net/projects/electricdss/
- Latest version: https://www.cs.ucf.edu/~qu/MA-OpenDSS.php

MA-OpenDSS-G

- OpenDSS-G: OpenDSS Graphic Interface.
  - Generic5 and distributed control modules were added to the platform







- Distribution circuit's clusters defined for the cooperative control

Project Outcomes and Products

- Project website: https://www.ece.ucf.edu/~qu/doe-energise-project/
  - Summary, publications, etc.

- Software: https://www.ece.ucf.edu/~qu/ma-opendss/
  - Documents with descriptions and open-source code files
  - Data files with test systems definitions
  - Simulation results with input files
  - HIL testing procedures and results

Project Outcomes and Products

The Open-source MA-OpenDSS Platform →
- Autonomous clustering
- Cooperative control
- 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 control
- Demand response
- Restoration & reconfiguration

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

Grid-edge Situational Awareness → Enhanced observability by voltage inference

Dynamic Defense and Attack-Resilient Control → Dynamic encoding & virtual anchors

Autonomous Inverter Control → Vector control design for grid forming

Thanks to DOE SETO

Questions?