INFORMS Panel "Renewable Energy Planning and Operation with Decision Dependent Uncertainty”

Distributed Control and Optimization for Resilient Distribution Systems with Extremely-High PV Penetration

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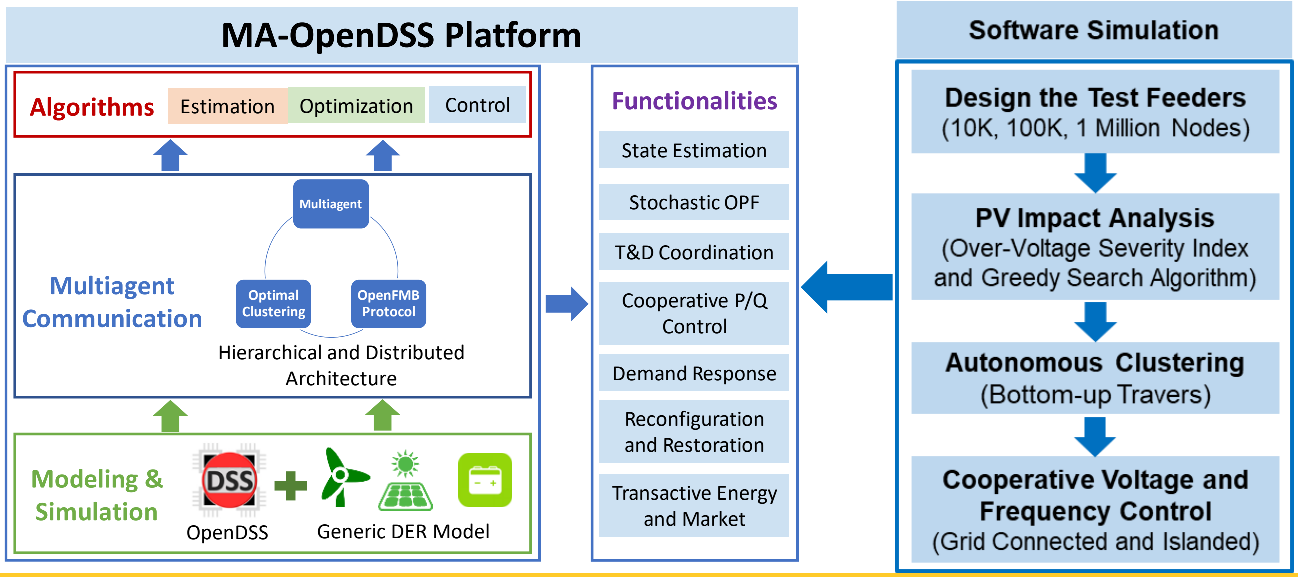
Overview

- DOE project outcomes of "**Scalable/Secure Cooperative Algorithms and Framework for Extremely-high Penetration Solar Integration (SolarExPert)**"
- A **Sustainable Grid Platform** (SGP) with scalable architecture of distributed control and optimization
  - Multi-Agent OpenDSS (MA-OpenDSS) platform
  - Distributed Stochastic OPF and Distributed System State Estimation
  - Distributed Volt/VAR Optimization and Frequency Control
  - Distributed Distribution System Restoration
  - Testing on 1 million-node system, C-HIL and P-HIL

Multi-Agent OpenDSS Platform

- 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



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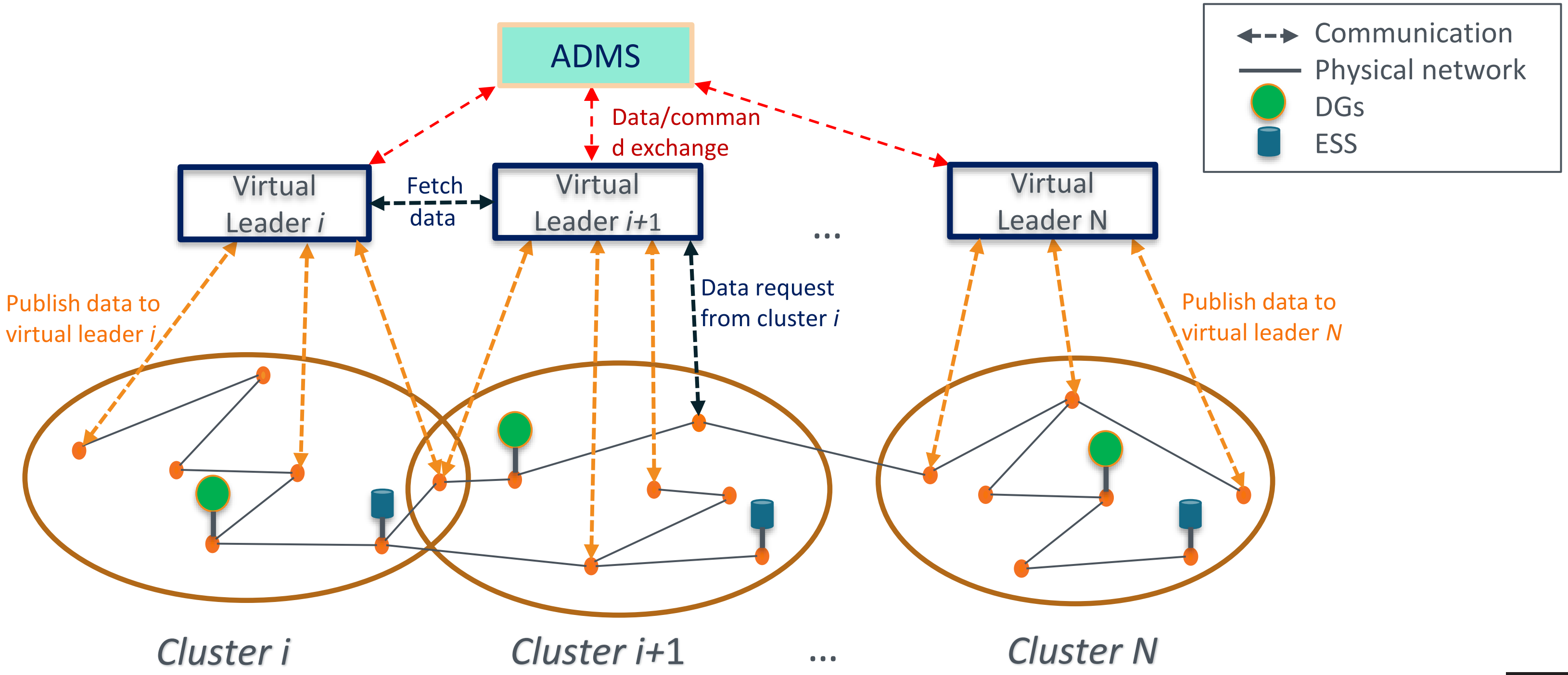
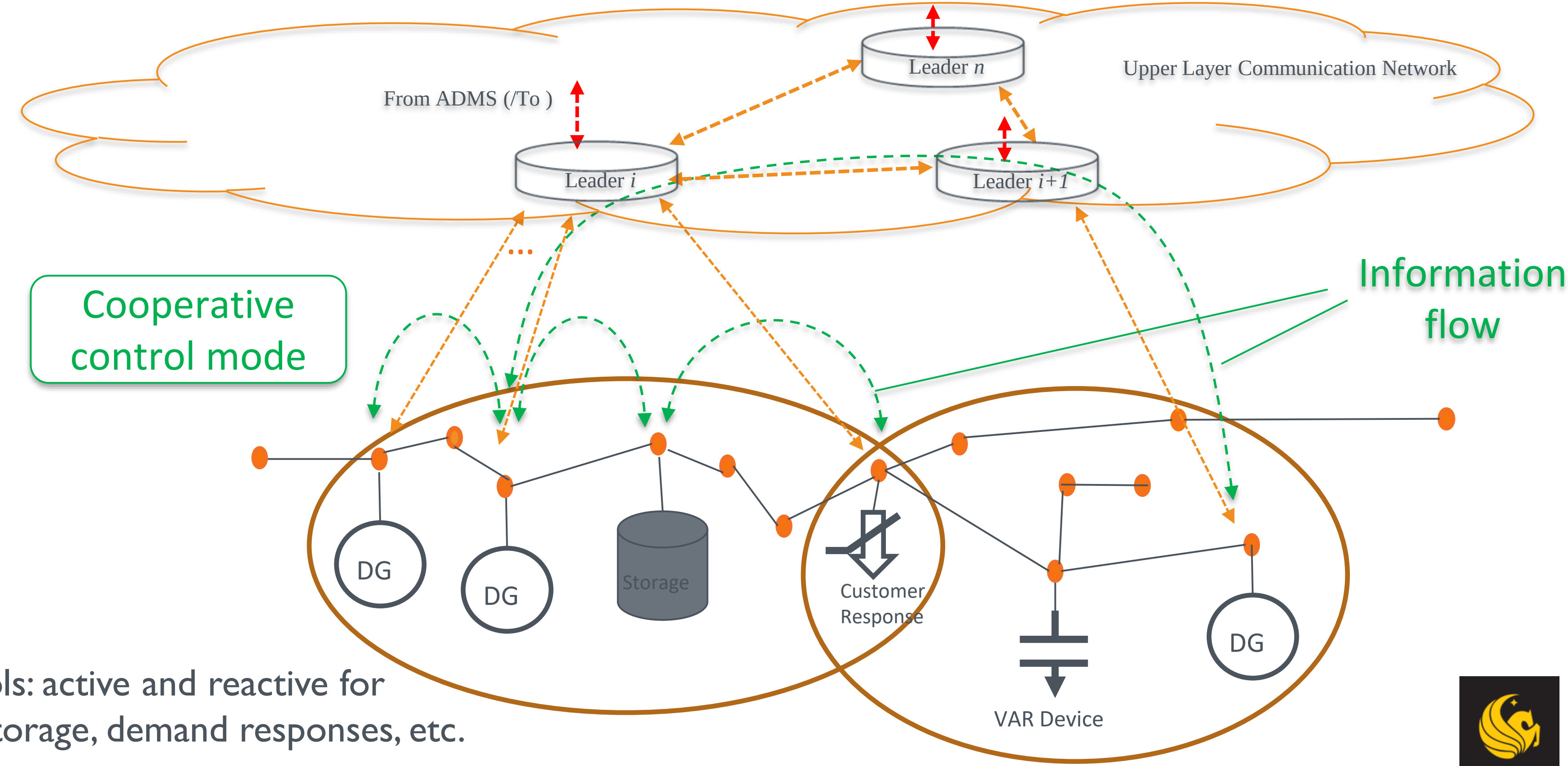
Hierarchical and Distributed Architecture



Hierarchical and distributed communication and control architecture

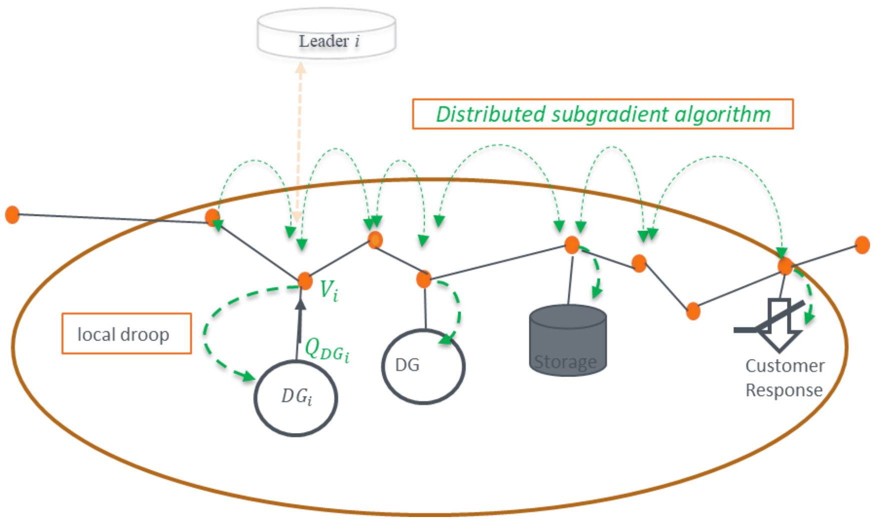
Cooperative Control Architecture

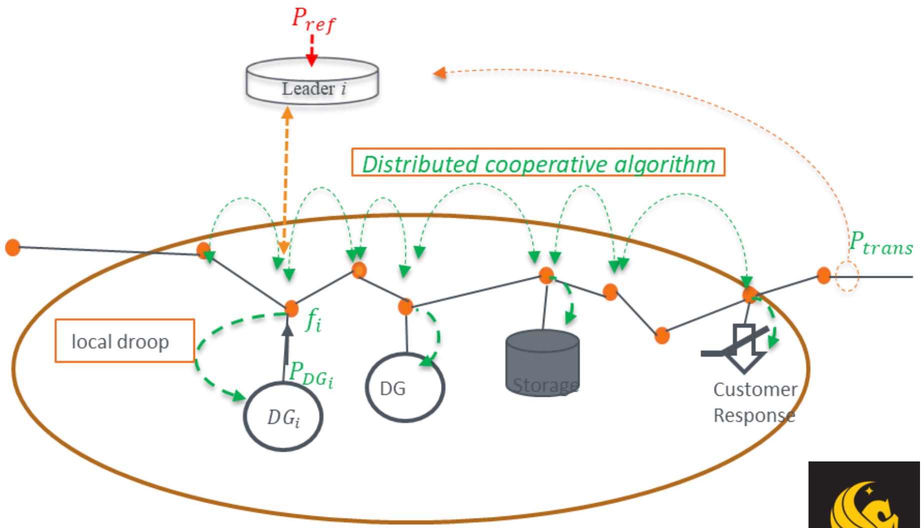


Controls: active and reactive for
DGs, storage, demand responses, etc.

Distributed Voltage and Frequency Control

- Local communication of voltage measurements and droop control
- Communication and Cooperative subgradient algorithm
- Decentralized droop control (when no communication)
- Distributed cooperative algorithm for aggregate active power dispatch





Distributed Distribution System Restoration

- The cluster-based structure improves **scalability** and **convergence speed** of the proposed DDSR.
- Define smart local agents (SLA)
- The faulted areas are detected and isolated by **sectionalizing** switches and the unfaulted areas are energized by **tie switches**.
- The proposed DDSR method can be realized through solving a small subproblem by each SLA and exchanging limited information among neighboring clusters.
- The tree topology of the entire network must be preserved which is a challenging constraint.

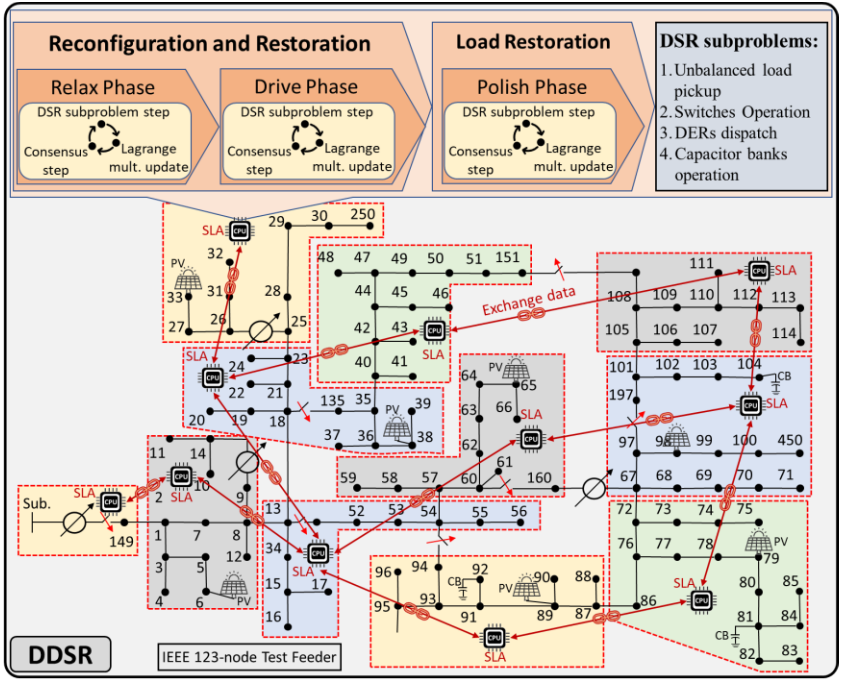


Fig. The proposed DDSR framework.

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DDSR – A Fully Distributed Solution Algorithm

- Three consecutive phases for binary variables:
  1. **Relax** binary variables,
  2. **Drive** binary variables towards Boolean values,
  3. **Polish** by fixing binding binary variables and solve MIP subproblems.
- The optimal restoration plan of DDSR:
  1. **DSR subproblem step:** The local DSR subproblems are solved by each SLA for all restoration time span.
  2. **Consensus step:** Each SLA exchanges boundary information and updates consensus variables.
  3. **Lagrange multiplier update step:** Each SLA updates based on the exchanged data.

Repeat

- Two-step restoration
  1. Reconfiguration and restoration (Relax and Drive phases)
  2. Load restoration (Polish phase)

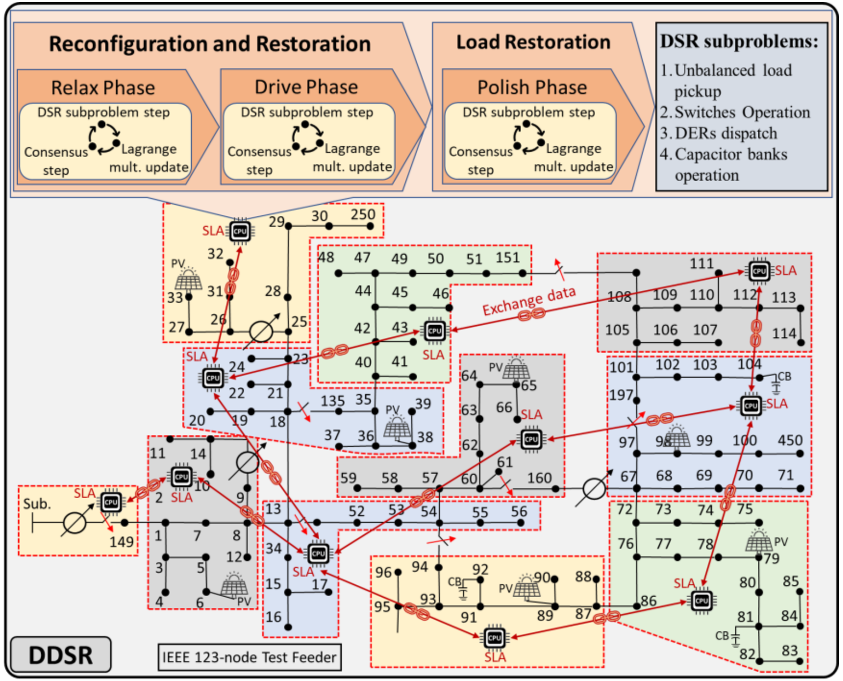
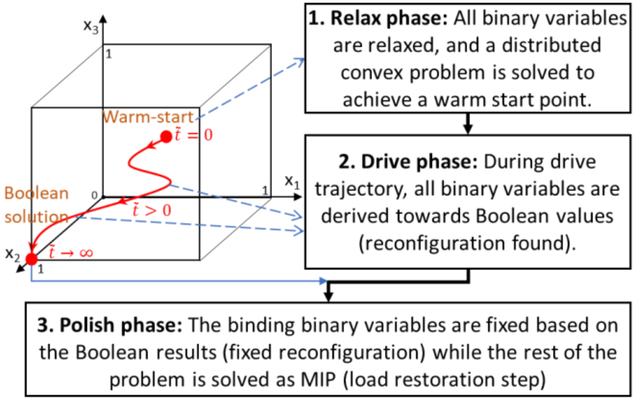
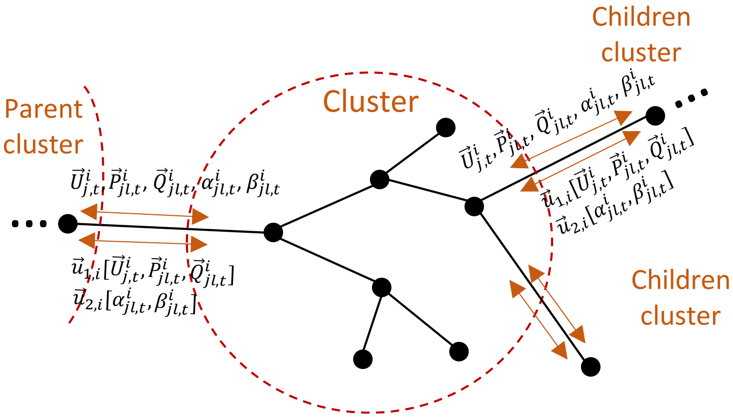


Fig. The proposed DDSR framework.

DDSR – A Fully Distributed Solution Algorithm

- Continuous variables $\vec{x}$: *active and reactive restored loads*, *voltage* of each node, *active and reactive power flow* of distribution lines, *generation of DERs*, and *capacitor banks* output.
- Continuous consensus variable $\vec{\bar{x}}$: *voltage and power flow* of the neighboring nodes and boundary lines among clusters.
- Consensus binary variables of $\vec{z}$ and its auxiliary $\vec{y}$: *picking-up loads*, *switchable lines*, and *spanning tree constraints.*





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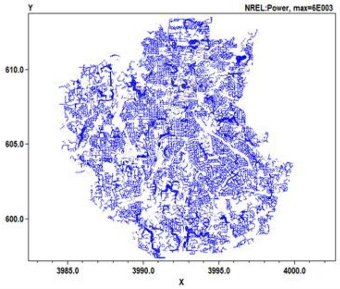
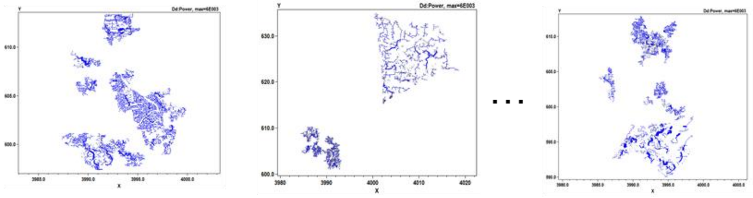
1-Million Node Test System

1 Million Node System

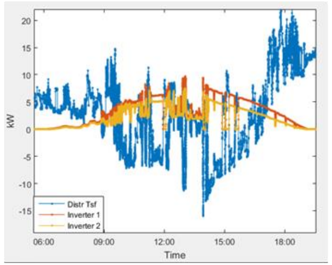




NREL Synthetic Networks:
Bay Area (7M) + Greensboro, NC (3M)

Ten 100k-node systems
(urban/suburban, industrial, rural)

100% PV Penetration



Actual System Data (Duke, Hawaii) + Different PV sizes and location (Large, Small) + Worst-Case Scenarios (OVSI)

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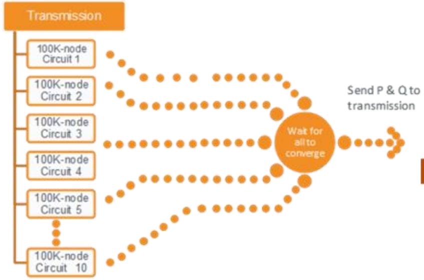
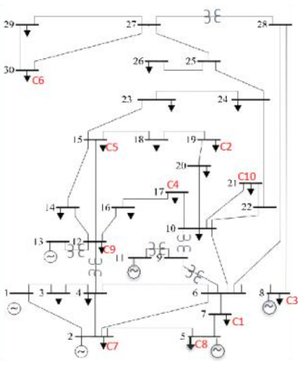
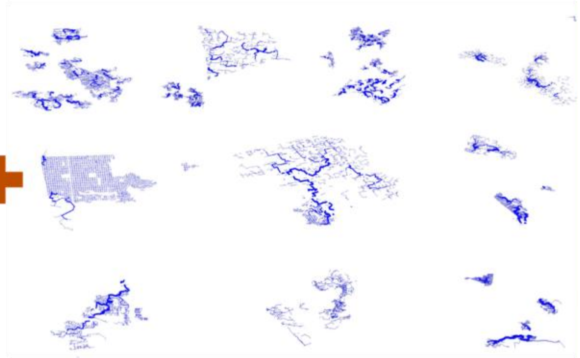
Integrated 1 Million-node T&D System

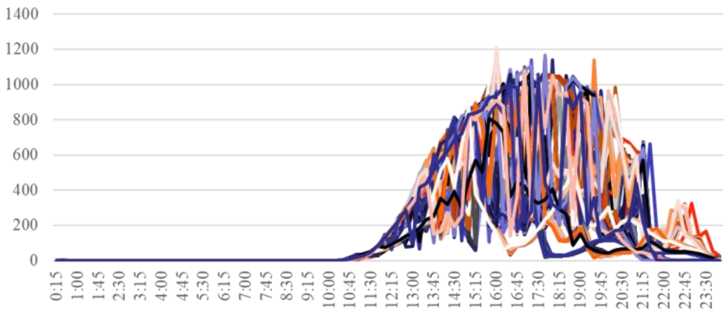


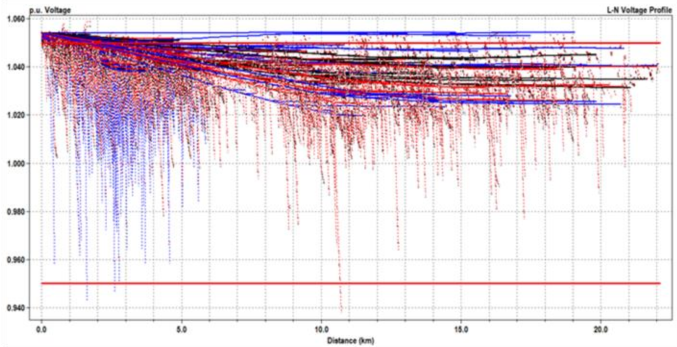


Transmission System



Ten 100k-node Distribution Circuits

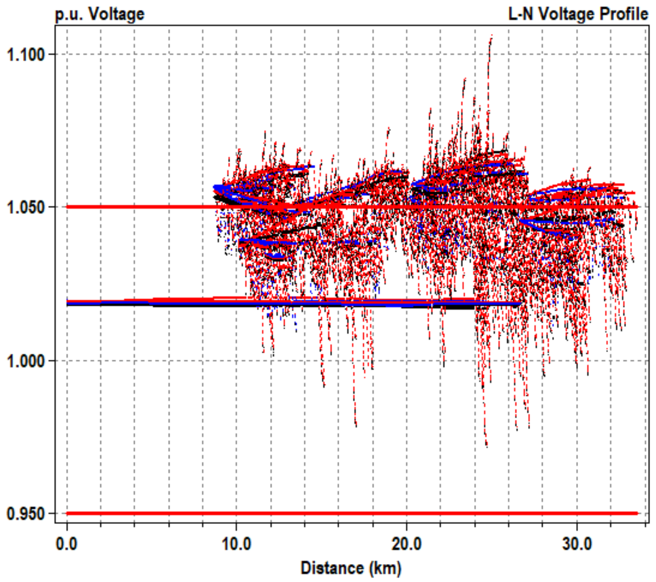


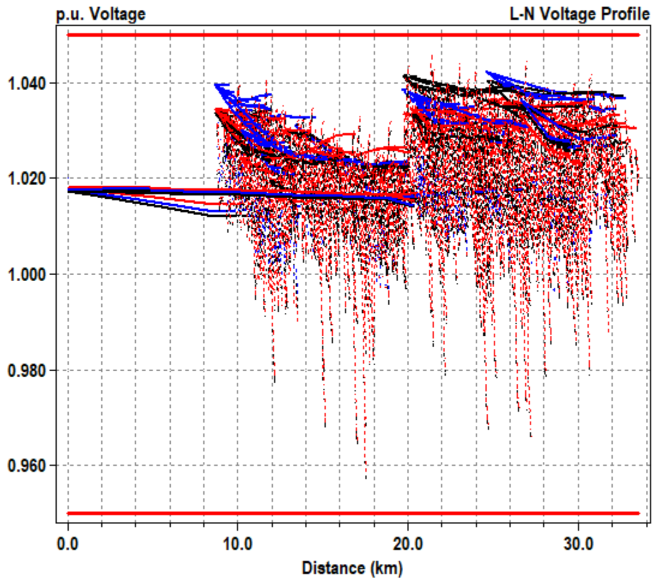


Circuit 7 Voltage Profile

Testing Performance – Volt/VAR Control

- Worst-case: 174,284 PVs among 12 feeders, 158MW total (130% penetration)
- A total 68MVar of inductive reactive power is generated by PV inverters





Testing Performance – DDSR

- This network is built from NREL test network which consists 10 feeders.
- The network is integrated with distributed PVs with 100% penetration but the irradiance is 20%.
- To implement the distributed distribution service restoration the network is divided into **10 clusters**.

Fig. Distributed small-scale PV generators shown by purple color dots.

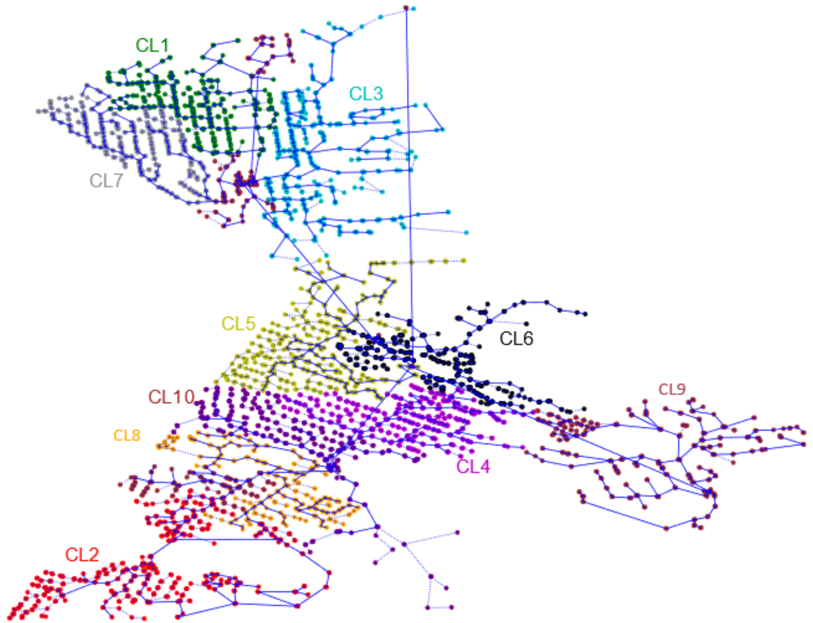


Fig. The network is divided into 10 clusters.

Testing Performance – DDSR

- There is a major outage with 3 restoration steps of [15MW, 30MW, 70MW] following transmission restoration.
- One faulted line named `Line.l(r:p1udt746-p1udt752)' occurred during restoration.
- Faulted area is being isolated by sectionalizing switches ‘S_Sw1' and ‘S_Sw2’.
- Tie-switch ‘Tie_Sw1' is being closed to energize unfaulted out-of-service area while all other tie-switches remain open to prevent any loop during operation.

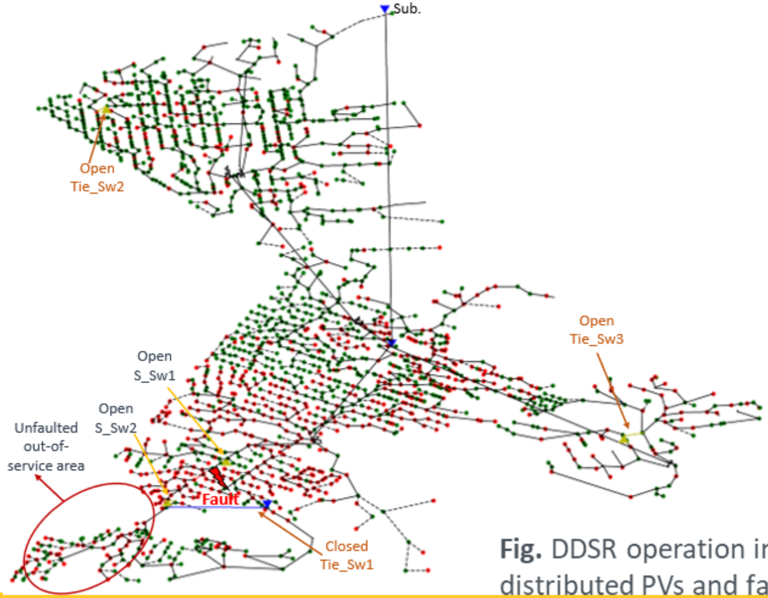


Fig. DDSR operation in first time step with distributed PVs and faulted lines.

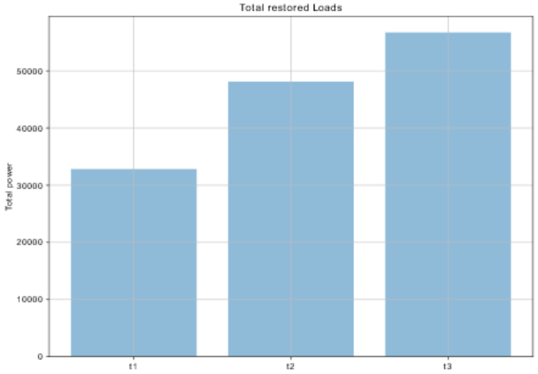


Fig. Total restored loads at each time step

Testing Performance – DDSR

- DDSR coordinates PVs with transmission capacity to retore more loads.
- Faulted area is being isolated by sectionalizing switches ‘S_Sw1' and ‘S_Sw2’.
- Tie-switch ‘Tie_Sw1' is being closed to energize unfaulted out-of-service area while all other tie-switches remain open to prevent any loop during operation.

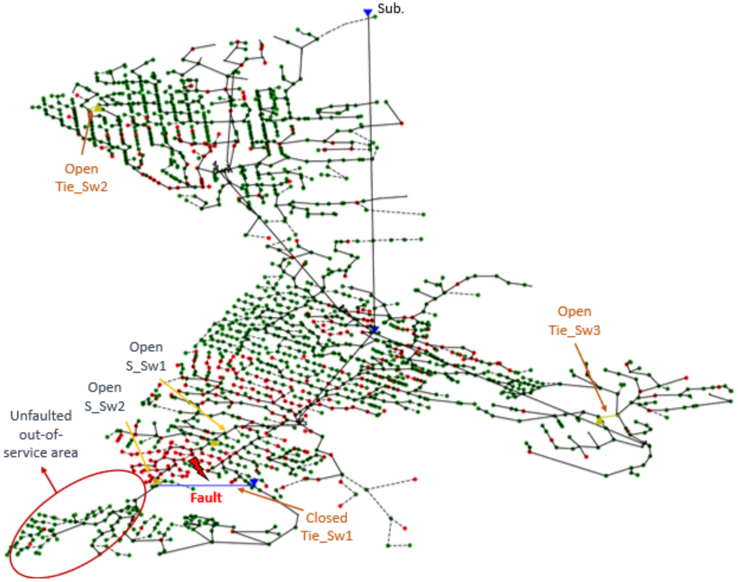


Fig. DDSR operation in second time step with distributed PVs and faulted lines.

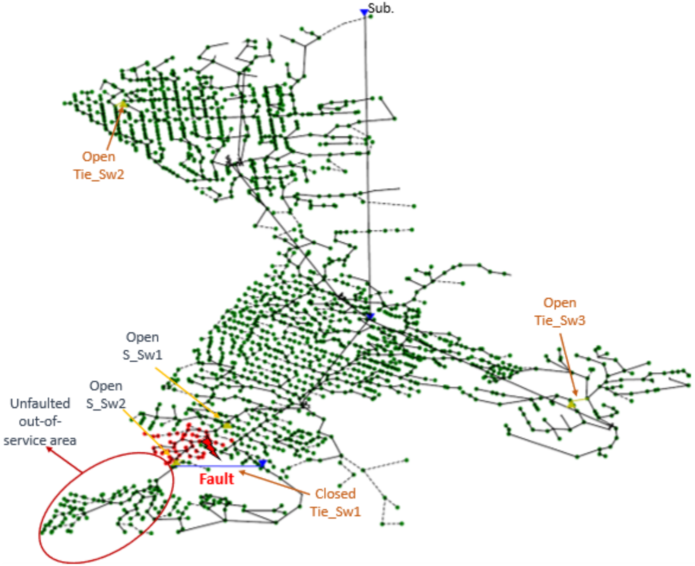
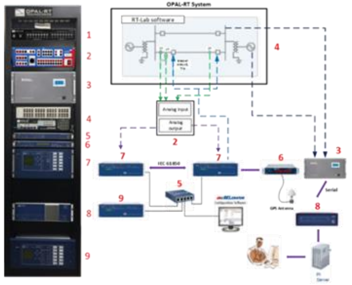


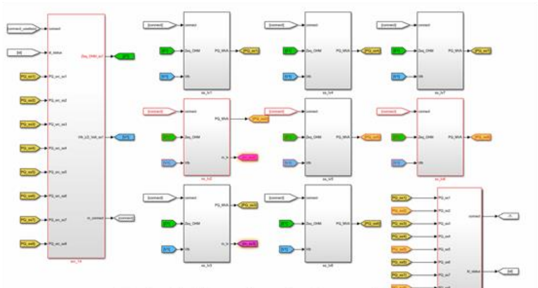
Fig. DDSR operation in third time step with distributed PVs and faulted lines.

HIL Real-Time Simulation

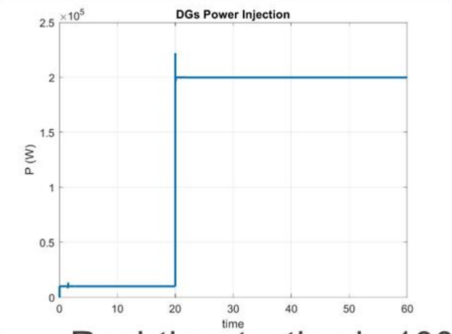


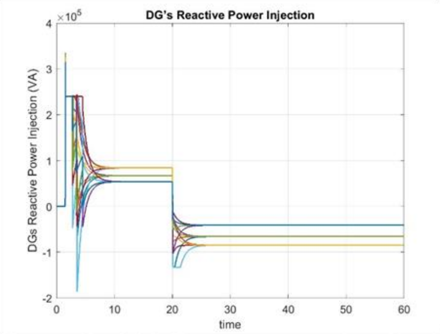
OPAL-RT Testbed at UCF

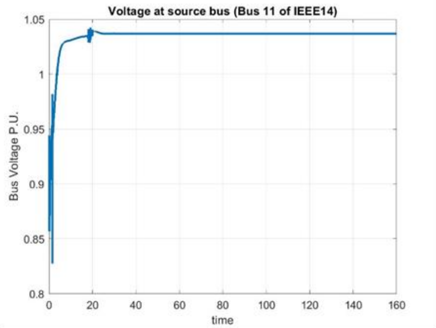
Controller-HIL and Power-HIL at NREL

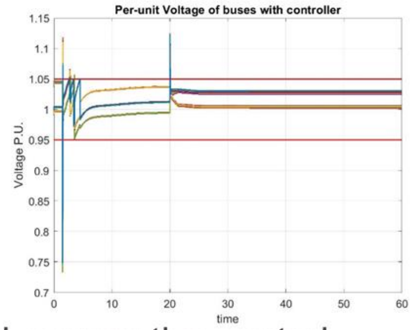


Distributed Control Implementation in OAPL-RT









- Real-time testing in 100,000-node T&D system, including 15 controls with distributed cooperative control
- Initial power injection at 10kW, second power injection at 200kW at 20 seconds

Thank you!

Acknowledgements to
DOE SETO Award DOE-EE0007998

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