Distributed Optimization for the Resilient Power Grid

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Enabling Resiliency

Needs

- Number of increasing weather and cyber events
- Need proactive and corrective optimal control
- Need scalable solutions with increasing state and control variables

Solution

- Distributed Optimization offers scalable and resilient control

Challenges

- DO with discrete variable
- Nonlinear objective functions and constraints
- Deployment challenges

What can we do about it?

Optimization Algorithms

1

Algorithms/ Tools

Distributed optimization algorithm considering continuous and discrete variables, faster convergence and accuracy to enable resilient control,

Resilience Metric

2

Metrics

Measure effectiveness of alternative solutions to enable resilience

Testbed

3

Testbed for Validation

Validate algorithms and tools for deployment

Key efforts are needed to solve the future grid problem with increasing extreme events


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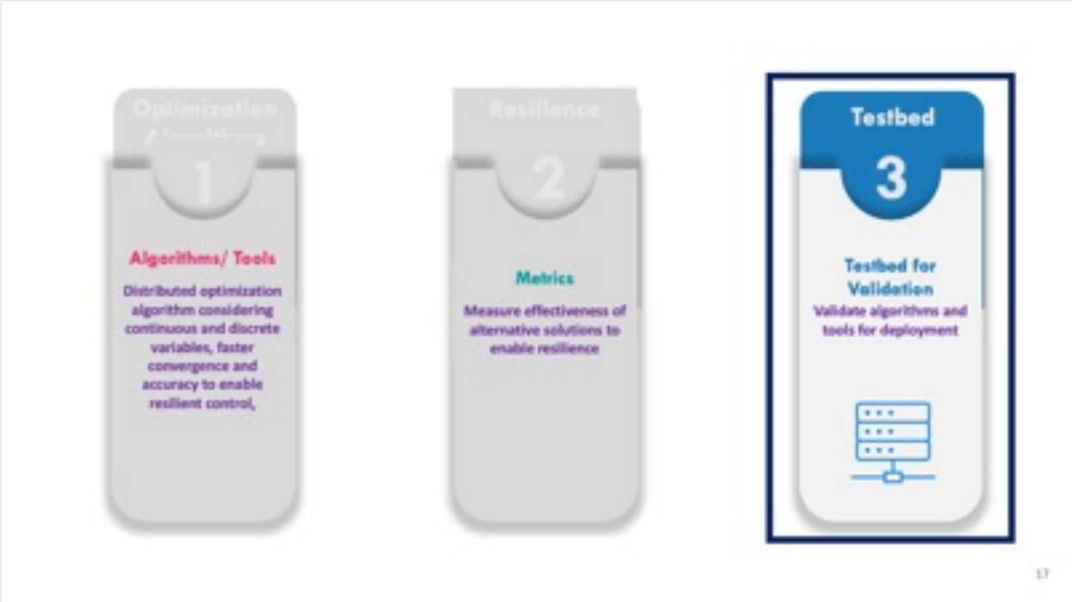
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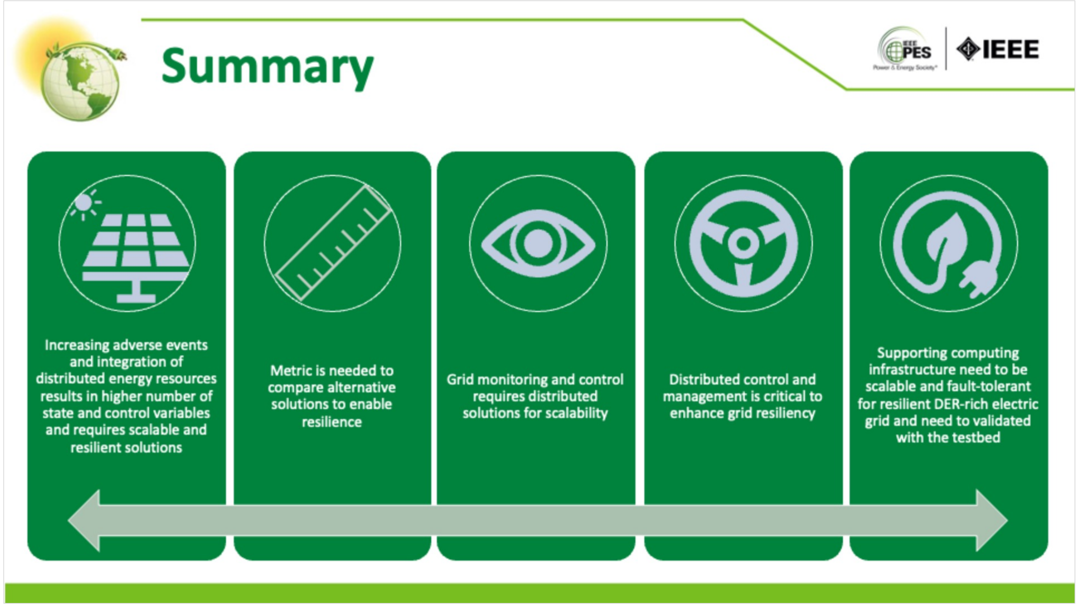
Summary
PES
IEEE
Increasing adverse events and integration of distributed energy resources results in higher number of state and control variables and requires scalable and resilient solutions
Metric is needed to compare alternative solutions to enable resilience
Grid monitoring and control requires distributed solutions for scalability
Distributed control and management is critical to enhance grid resiliency
Supporting computing infrastructure need to be scalable and fault-tolerant for resilient DER-rich electric grid and need to validated with the testbed

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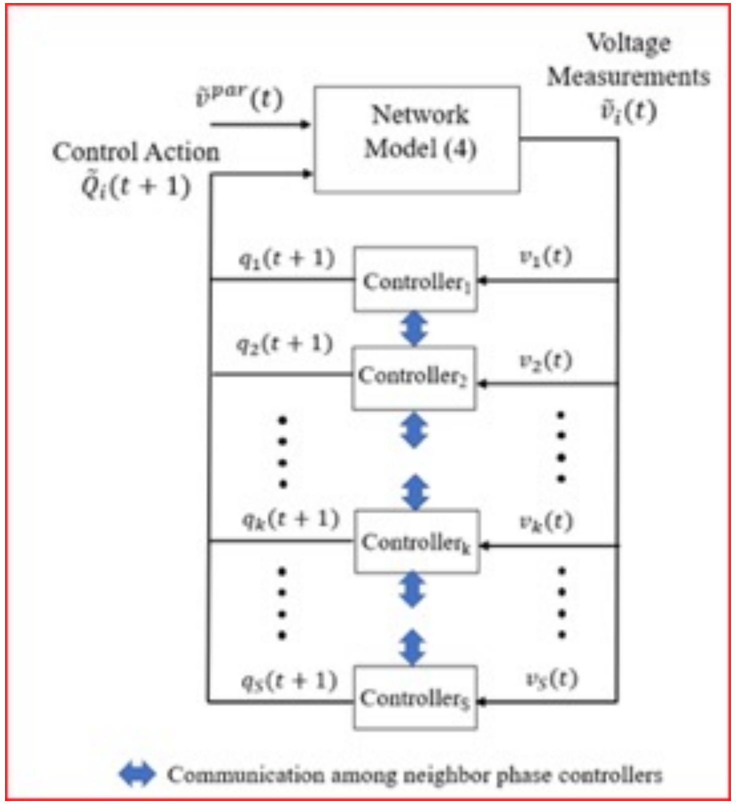
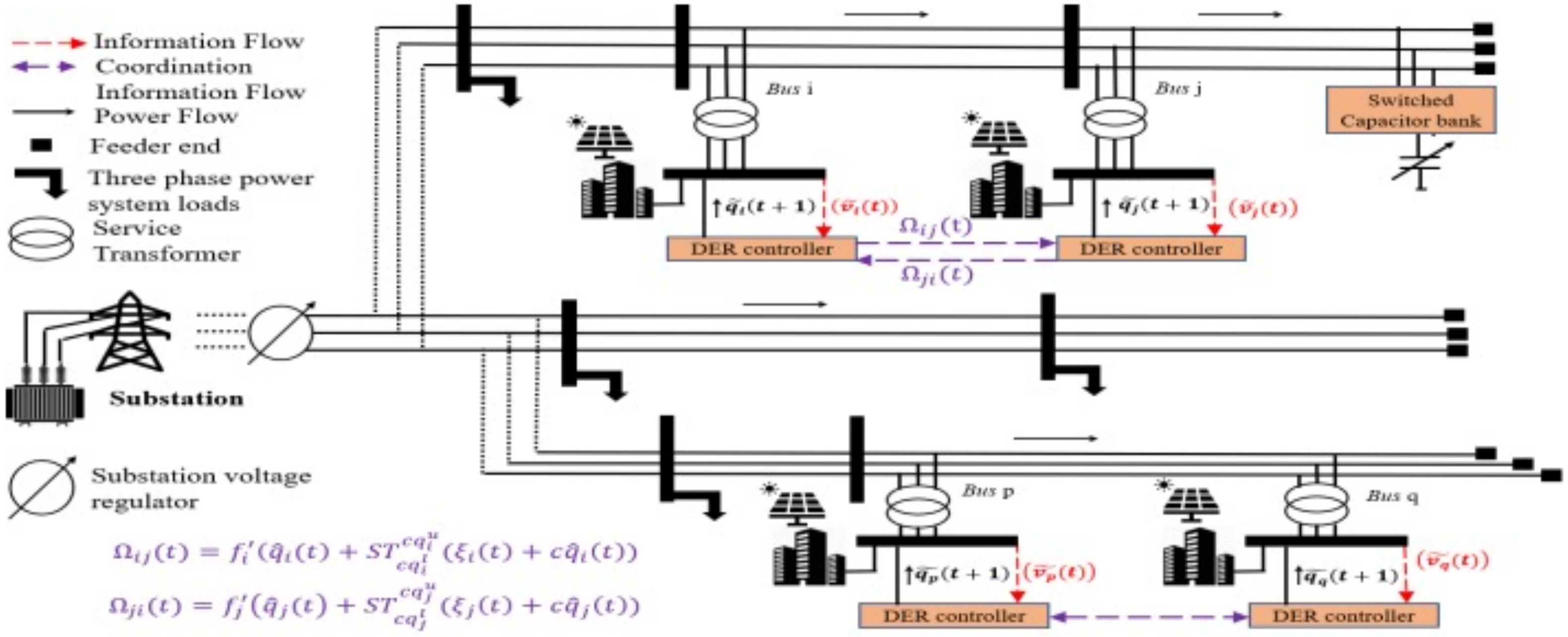
Distributed Volt-Var Control in Distribution System (OPT-DIST VC)





$$\min_{q_k}(q) \triangleq \sum_{k=1}^{S} f_k(q_k) + \frac{d}{2} q^T \bar{Z}^q q$$

$$\begin{aligned} s.t. \quad & \underline{v}_k \le v_k \le \bar{v}_k && \forall k \in \mathcal{S} \\ & \underline{q}_k \le q_k \le \bar{q}_k && \forall k \in \mathcal{S} \\ & \tilde{v} = \bar{Z}^q \tilde{Q} + \tilde{v}^{par}. \end{aligned}$$

Each kth controller performs the following steps

Step 1 (Measuring): $v_k(t)$

Step 2 (Calculating):

$$\hat{q}_k(t+1) = \hat{q}_k(t) - \alpha\Big\{\bar{\lambda}_k(t) - \underline{\lambda}_k(t) + d\hat{q}_k(t) + \sum_{j\in\mathcal{N}_k} [\bar{Z}^q]^{-1}_{kj}\Big[f'_j(\hat{q}_j(t)) + \mathrm{ST}^{c\bar{q}_j}_{c\underline{q}_j}(\xi_j(t) + c_j(t))\Big]\Big\}$$

$$\xi_k(t+1) = \xi_k(t) + \beta\frac{\mathrm{ST}^{c\bar{q}_k}_{c\underline{q}_k}(\xi_k(t) + c_k(t)) - \xi_k}{c}$$

$$\bar{\lambda}_k(t+1) = [\bar{\lambda}_k(t) + \gamma(v_k(t) - \bar{v}_k)]^+$$

$$\underline{\lambda}_k(t+1) = [\underline{\lambda}_k(t) + \gamma(\underline{v}_k - v_k(t))]^+$$

Step 3 (Injecting Reactive Power): $q_k(t+1) = [\hat{q}_k(t+1)]^{\bar{q}_k}_{\underline{q}_k}$

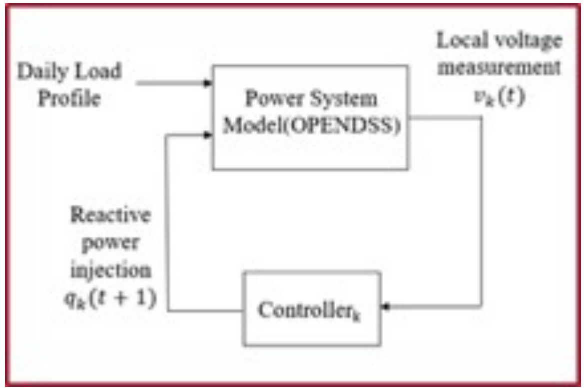
Step 4 (Communicating): Send values $f'_k(\hat{q}_k(t+1)) + \mathrm{ST}^{c\bar{q}_k}_{c\underline{q}_k}(\xi_k(t+1) + c_k(t+1))$ to neighbors $\mathcal{N}_k$.

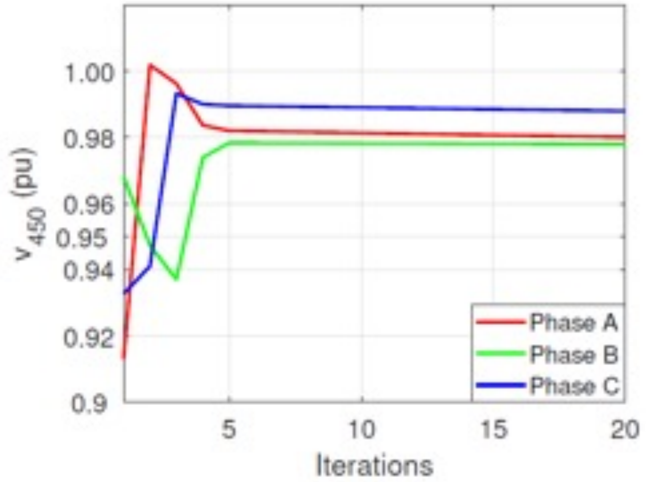
Local variables

Block sparse matrix: Elements belonging to Only neighbor phase connections are non-zero, others are zero

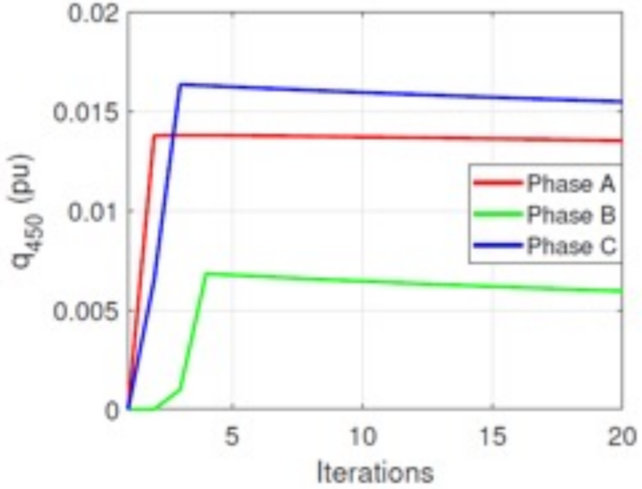
Block sparsity enables this reactive power setpoint calculation to be distributed which means we only need Ω values of neighbors

Distributed Optimal Voltage Control for Three Phase Unbalanced Distribution Systems with DERs

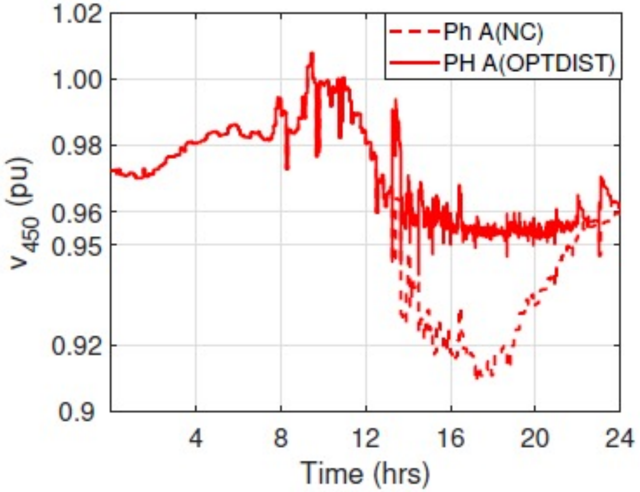




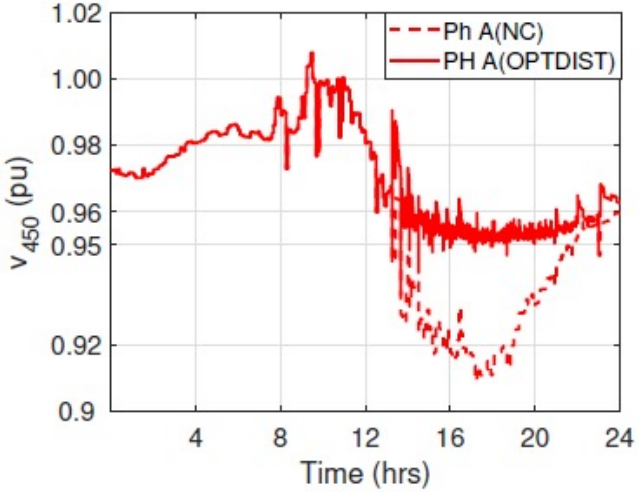
Voltage profile with distributed control



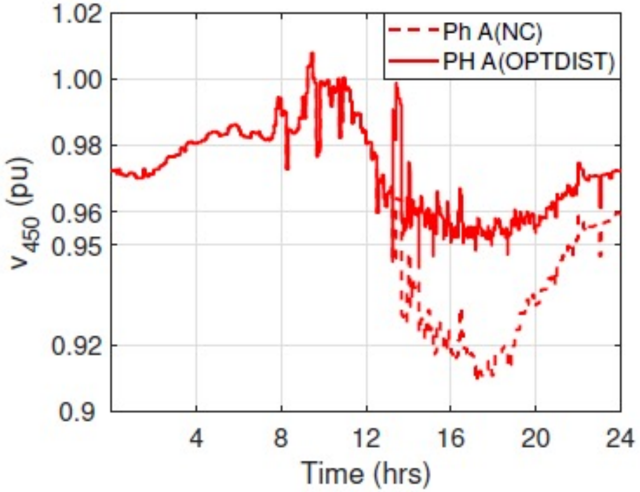
Reactive Power injection with distributed control



(a) Noisy measurements



(b) Communication Delays



(c) Modeling errors

Distributed Optimization
with Discrete Variables

- Legacy devices introducing Discrete Variables
  - Switched Voltage Regulator
    - On Load Tap Changing Transformers
    - Switched Capacitor Banks
  - Switches
    - Sectionalizer
    - Recloser
    - Tie Switches

- During overvoltage condition due to surplus in PV generation, CBs can lower the voltage preventing PV active power curtailment
- During Under-voltage, SVR can improve voltage profile thus reducing system losses

At times of power outages, the smart co-ordination of switches can ensure network restoration in optimized way and improve self healing properties of grid.

A coordinated operation of these devices leads to an efficient operation of the Power System

Distributed Optimization with Discrete Variables

Challenges

- Discrete Variables make the problem non-convex and non linear
- Mixed Integer Non linear programming problem in a distributed way is an NP-hard problem
- Implementing continuous relaxation to solve the optimization problem and rounding off later does not ensure convergence and might violate the constraints
- In most cases, feedback based approaches are not suitable due to repetitive fluctuation
- Evaluating the performance and choosing the best combination from a combinatorial analysis for the discrete variables is very difficult without a root subsystem in a completely distributed way

Distributed Optimization with Discrete Variables

Review of Key Approaches

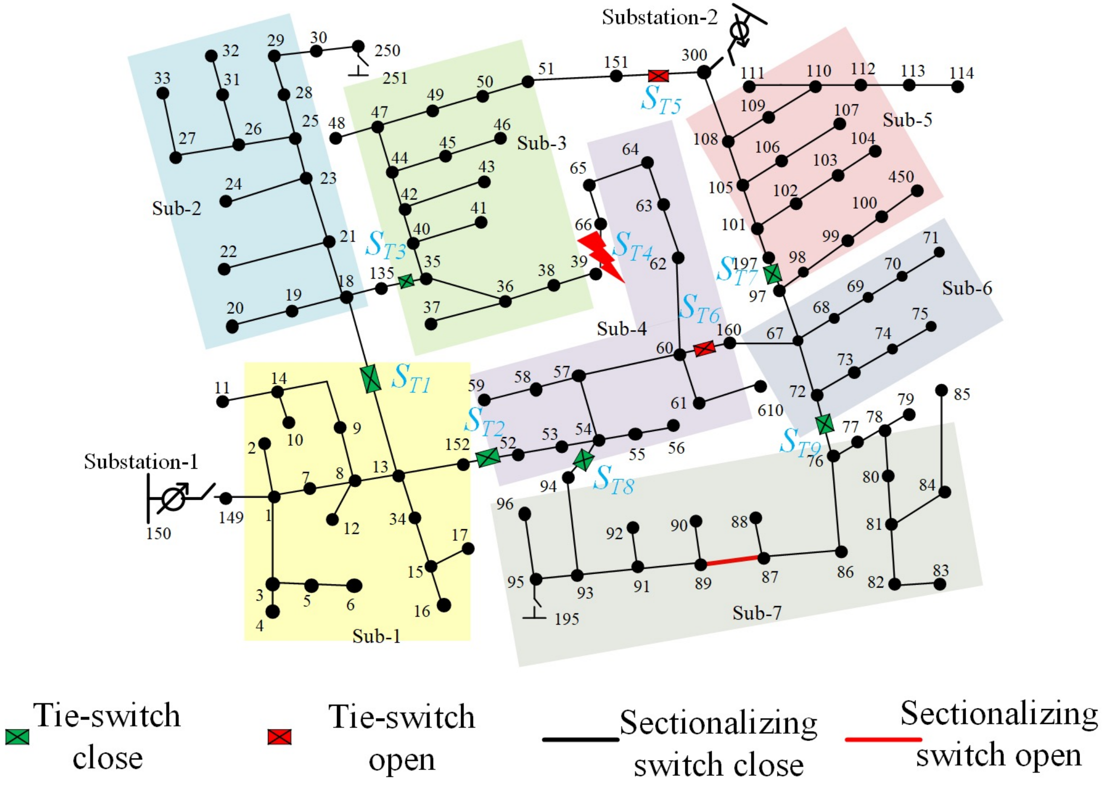
Ref.	Problem Spec	Obj. func. minimize	Discrete Algorithm	Distributed Algorithm	Boundary Variable	Communication requirements	Decision Variable	Comment
[1]	MIQP	Generation Cost & System Loss	Quadratic penalty term for non integer values	ADMM	Auxiliary variables representing the increments in real and imaginary part of voltages at boundary buses	Neighboring Areas	OLTC SCB	Guarantees convergence and optimality
[2]	MISOCP with cutting planes & Angle Relaxation	Active power curtailment Cost & system Loss	Branch & Bound	ADMM	Tie-line P and Q, primal and dual residual, boundary node voltage, objective function value of upstream and downstream region, SVR tap position	Neighboring areas	OLTC	No guarantee on convergence and optimality
[3]	MIQP	Generation Cost & System Loss	Ordinal Optimization	Dual Decomposition	Lagrange Multipliers and primal variables of boundary buses	Neighboring areas & root subsystems	OLTC SCB	Guarantees convergence to a good enough solution

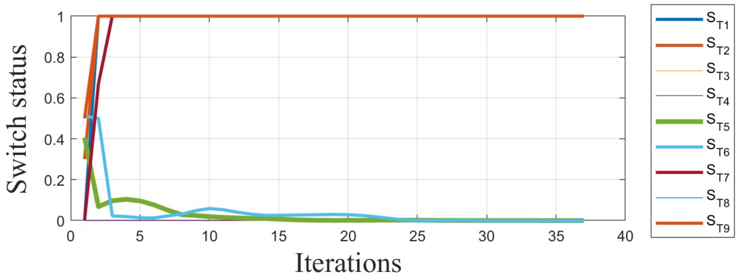
[1] W. Lu, M. Liu, S. Lin and L. Li, "Incremental-Oriented ADMM for Distributed Optimal Power Flow With Discrete Variables in Distribution Networks," in *IEEE Transactions on Smart Grid*, vol. 10, no. 6, pp. 6320-6331, Nov. 2019

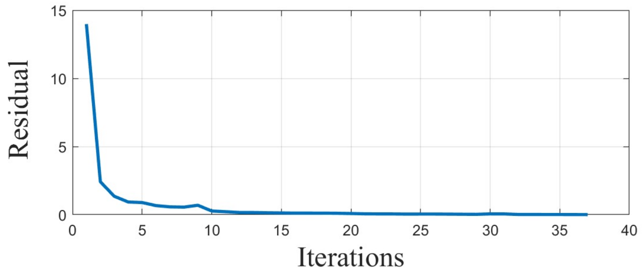
[2] Y. Liu, L. Guo, C. Lu, Y. Chai, S. Gao and B. Xu, "A Fully Distributed Voltage Optimization Method for Distribution Networks Considering Integer Constraints of Step Voltage Regulators," in *IEEE Access*, vol. 7, pp. 60055-60066, 2019

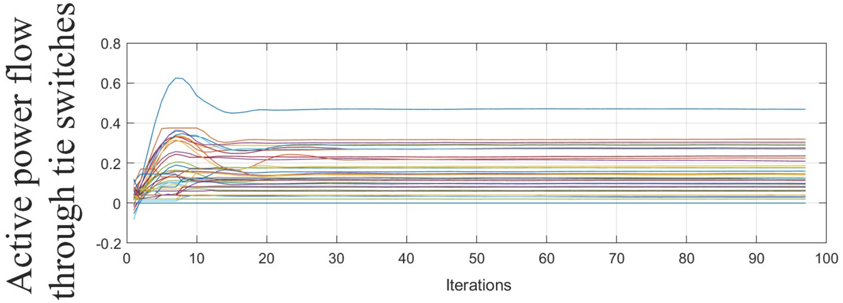
[3] C. Lin and S. Lin, "Distributed Optimal Power Flow With Discrete Control Variables of Large Distributed Power Systems," in *IEEE Transactions on Power Systems*, vol. 23, no. 3, pp. 1383-1392, Aug. 2008

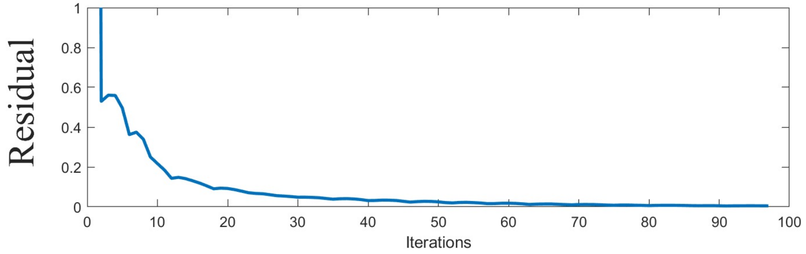
Distributed Approach for Optimal restoration: An Example











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Before Event

A.W.R.

Inspired by CDC Public Health Emergency Preparedness and Response and Weighted Sum Model (WSM).

Measuring Resilience

Anticipate

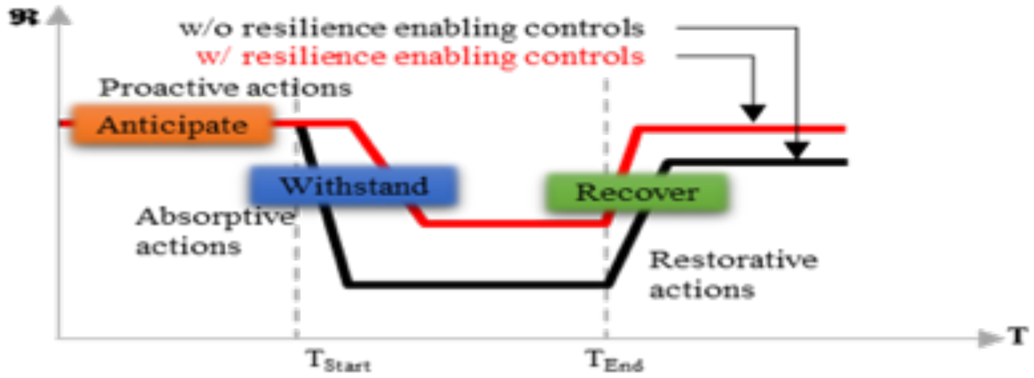
How well is the system prepared for the predicted impact of an incoming event?

Withstand

How well can system continue to supply critical loads during event?

Recover

How quickly can system recover from event and continue supply to critical loads? And at what cost?



During Event

A.W.R.

Using system characteristics-based factors, graph theory, and Multi-Criteria Decision Making (MCDM): Analytical Hierarchal Process (AHP).

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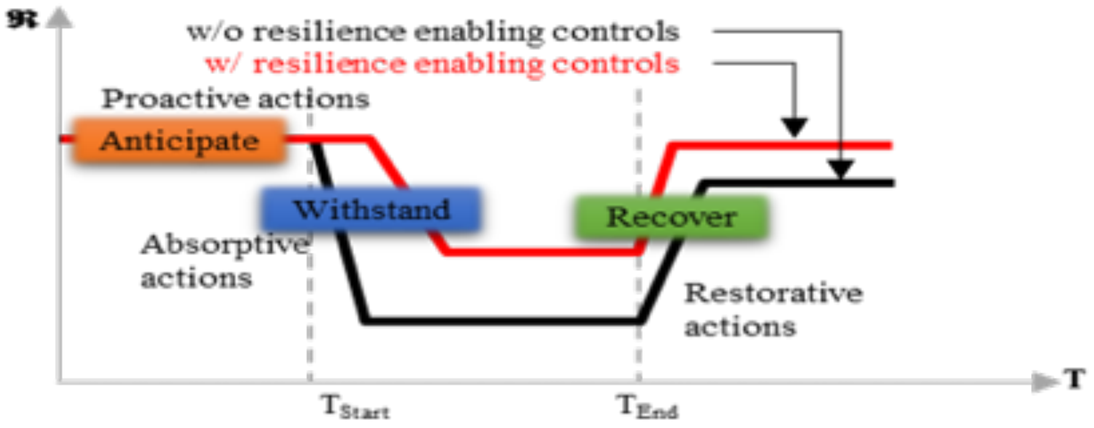

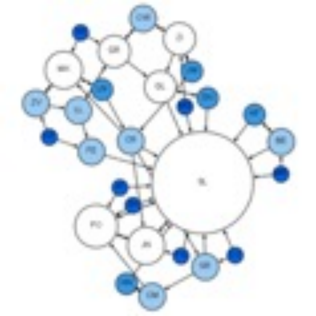

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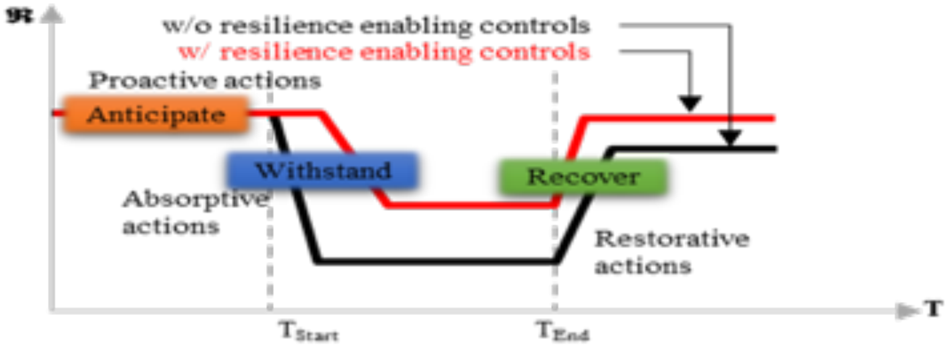

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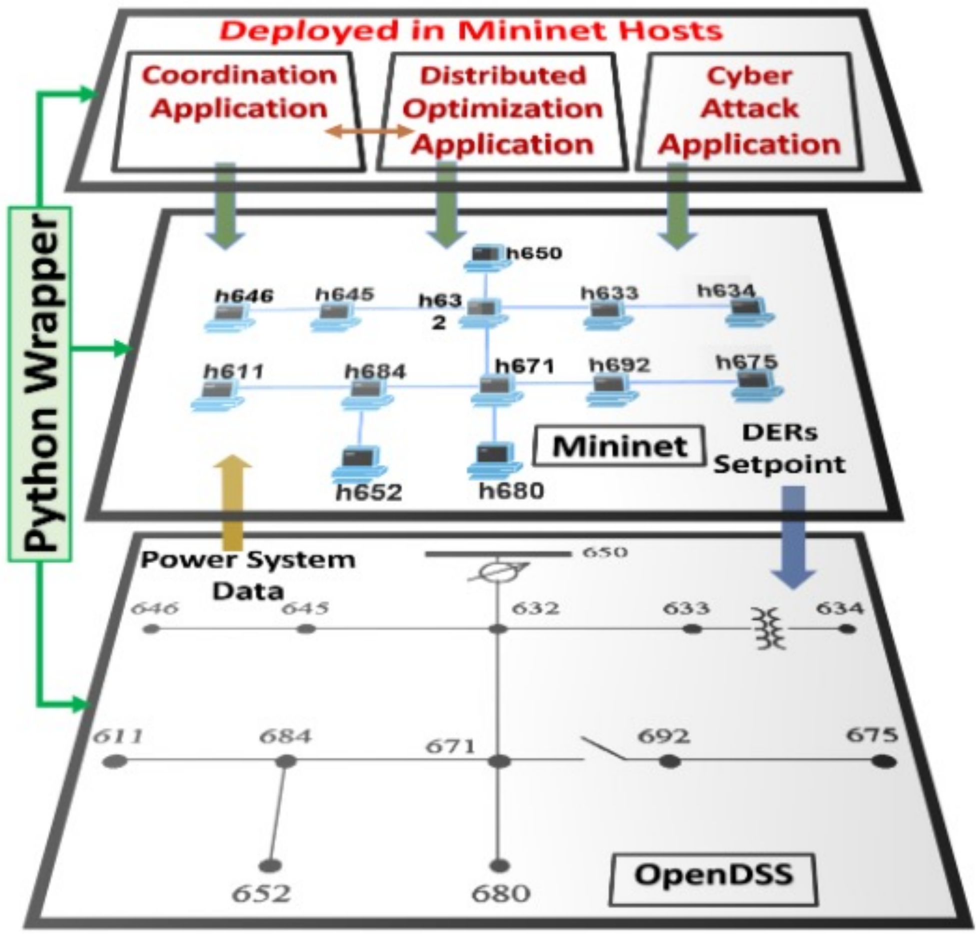
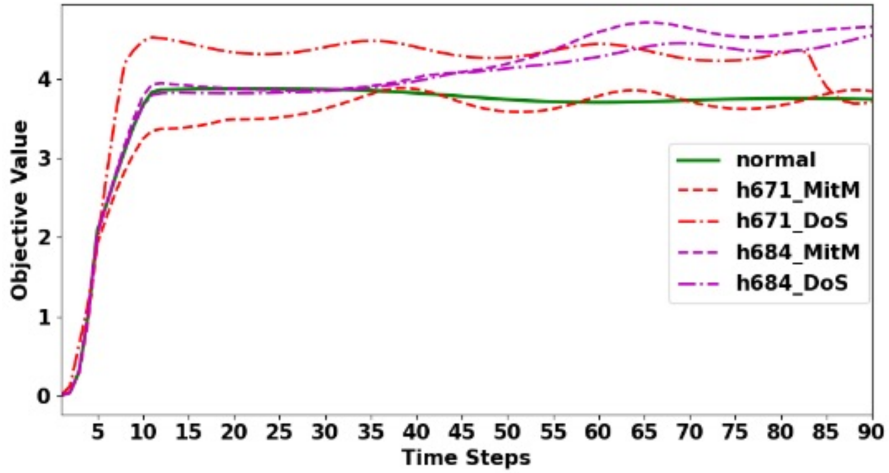
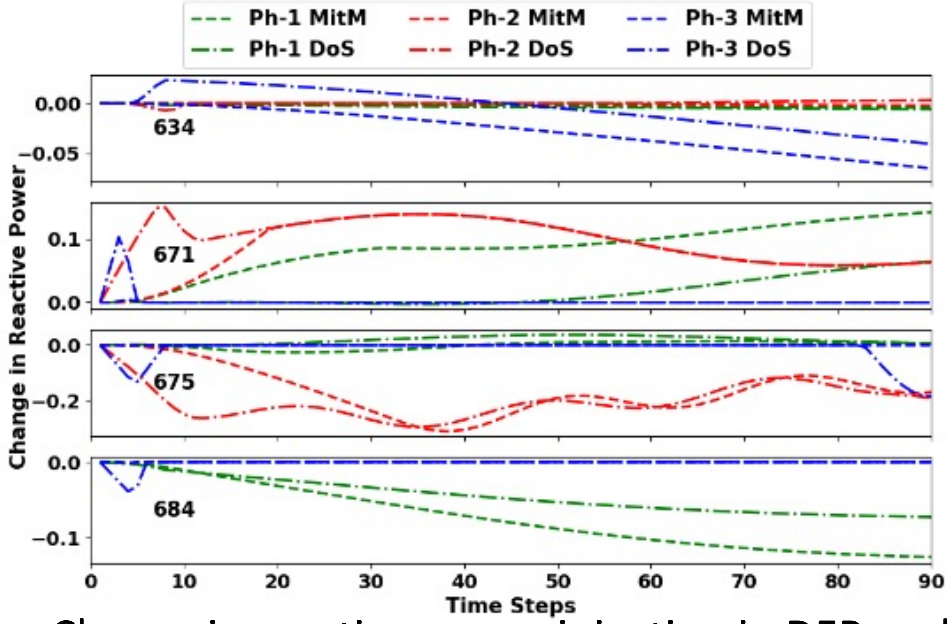
Cyber-Physical Testbed: Distributed Volt Var Control in Distribution Systems



Test-bed architecture for distributed voltage control



Objective function during different scenarios



Change in reactive power injection in DER nodes

Distributed Volt-Watt Control in Distribution Systems

OptDist-VWC: Each DER controller for a given node j ($j \in \mathcal{N}$) follows four different steps at time t:

Step 1 (Measurement): Measure local voltages at all the available phases $v_j(t)$, and active power maximum power point $p_j^{mpp}(t)$.

Step 2 (Calculating): Calculate, $\hat{p}_j(t+1), \xi_j(t+1), \overline{\lambda}_j(t+1), \underline{\lambda}_j(t+1)$, using:

$$\hat{p}_j(t+1) = \hat{p}_j(t) - \alpha\Big\{\big(\overline{\lambda}_j(t) - \underline{\lambda}_j(t)\big) + \sum_{\forall i \in \mathcal{N}_j} [\bar{Z}^P]^{-1}_{ji}\Big[f_i'(\hat{p}_i(t)) + \mathrm{ST}^0_{-cp_j^{mpp}(t)}\big(\xi_i(t) + c\hat{p}_i(t)\big)\Big]\Big\} \tag{9a}$$

$$\xi_j(t+1) = \xi_j(t) + \beta\frac{\mathrm{ST}^0_{-cp_i^{mpp}(t)}\big(\xi_j(t) + c\hat{p}_j(t)\big) - \xi_j(t)}{c} \tag{9b}$$

$$\overline{\lambda}_j(t+1) = \overline{\lambda}_j(t) + \gamma\big[(v_j^{meas}(t) - \overline{v_j})\big]^+ \tag{9c}$$

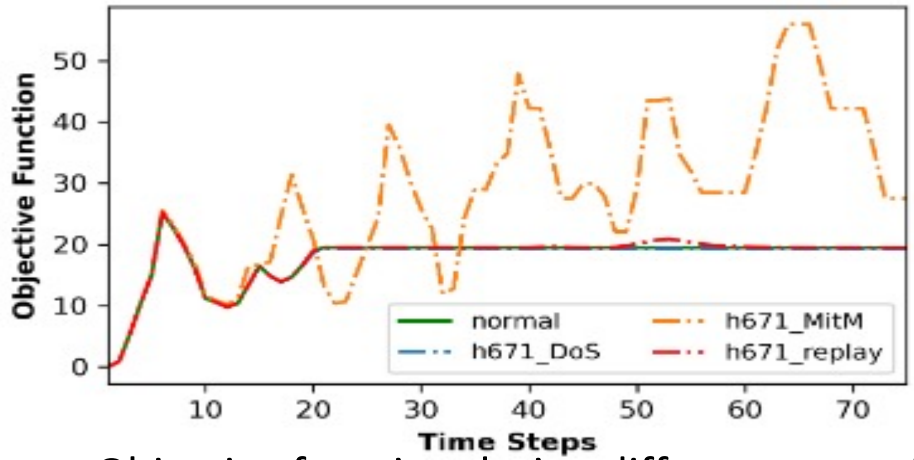
$$\underline{\lambda}_j(t+1) = \underline{\lambda}_j(t) + \gamma\Big[\Big(\underline{v_j} - v_j^{meas}(t)\Big)\Big]^+ \tag{9d}$$

here, $\mathcal{N}_j$ is the set of all neighbor nodes connected to node j ($\forall j \in \mathcal{N}$).

Step 3 (Active Power Set-Point Deployment): Active power maximum power point is calculated again, $p_j^{mpp}(t+1)$. Active power injection set-point at time $t+1$ is calculated as

$$p_j^{inj}(t+1) = \Big[p_j^{mpp}(t) + [\hat{p}_j(t+1)]^0_{-p_j^{mpp}(t)}\Big]_0^{p_j^{mpp}(t+1)} \tag{10}$$

Step 4 (Communication): Values $f_j'(\hat{p}_j(t+1)) + \mathrm{ST}^0_{-cp_j^{mpp}(t+1)}\big(\xi_j(t+1) + c\hat{p}_j(t+1)\big)$ are communicated to neighboring DER nodes. □



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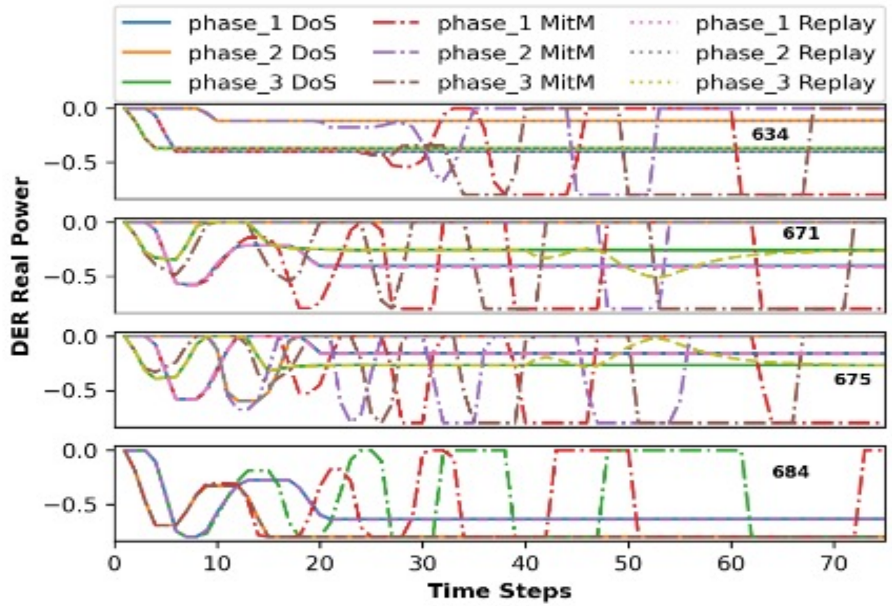

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Thanks to all the students and collaborators. We acknowledge support from the DOE UI-ASSIST and NSF CPS