SOLAR ENERGY
TECHNOLOGIES OFFICE
U.S. Department Of Energy

Multi-time scale Optimization Using Distributed Solar Energy for Resilience Improvement

10/1/2018 – 12/31/2019

Bo Chen
Argonne National Laboratory

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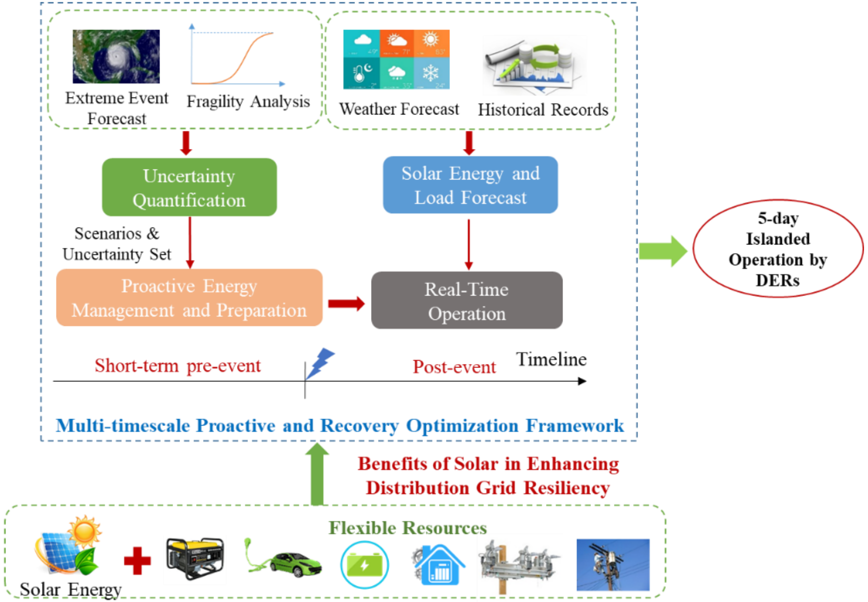
Project Objectives

- Develop an optimization framework to facilitate the benefits of distributed solar energy in resilience improvement of distribution grid against disastrous events and ensure a 5-day islanded operation supported by DERs after the events.

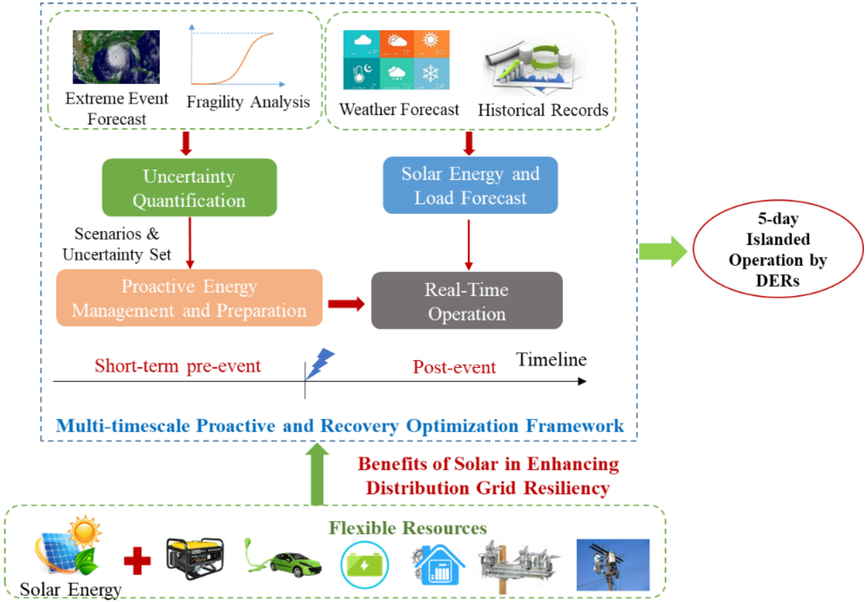
Key innovation:

- Solar energy in coordination with other flexible resources to ensure supply continuity
- Cover pre-event preparation and post-event operation
- Uncertainties caused by external factors and grid characteristics
- Verification using extensive simulation case studies: real-world and large-scale test cases



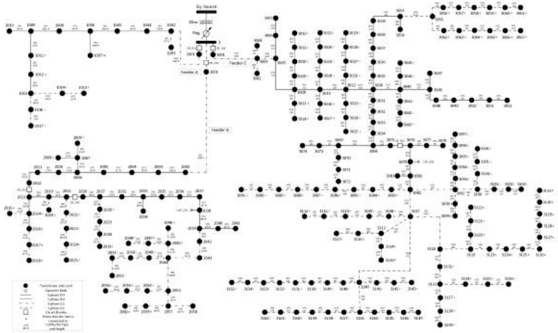
Project Scope

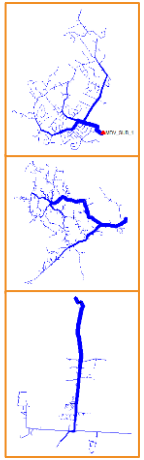
- Functional Modules
  - Damage Scenario Generation (hurricane, flooding, ice storm)
  - Pre-Event Preparation (days before the event)
  - Post-event Restoration (hours or days after the event)
  - Real-time Energy Management (days with minute-level dispatch resolution)

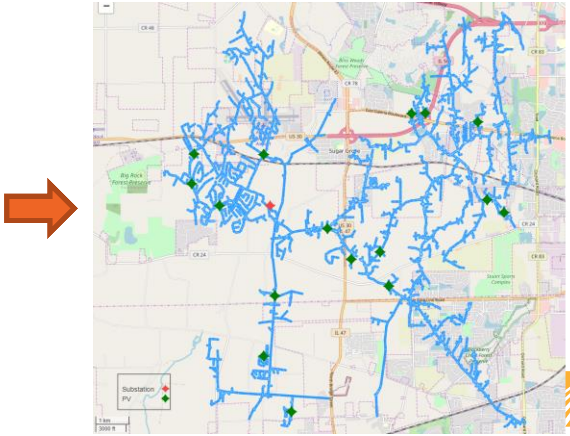


Test Systems – Large-scale System

- Large-scale test system
  - EPRI Ckt5 (48 miles)
  - EPRI Ckt7 (8 miles)
  - IEEE-8500 (10 miles)
  - 9,057 buses and 14,319 nodes
- Real-world utility test feeder located in Midwest U.S.
- 3 types of PV systems (utility-scale, midsize PV, and residential PV)
  - On-grid (grid-tied) system
  - Hybrid on/off-grid (PV with battery)
  - PV + battery with grid forming capabilities

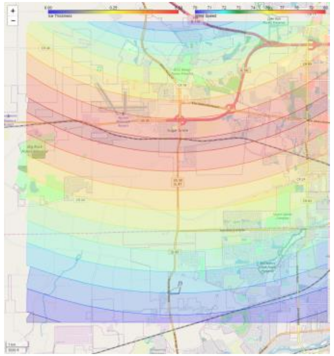




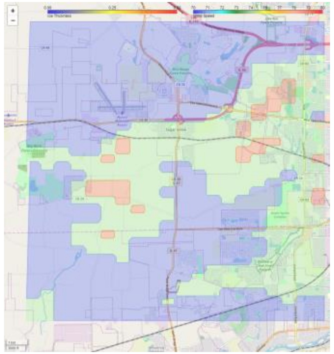


Damage Scenario Generation

- 3 types of natural disasters: Hurricane, flood, winter storm
- 3 steps following the similar standardized process in HAZUS software developed by FEMA
  - Wind speed distribution adapted from hurricane extreme weather events
  - Ice thickness distribution determined based on wind speed, elevation and icing duration
  - Flooding distribution determined based on elevation



Wind speed



Ice thickness

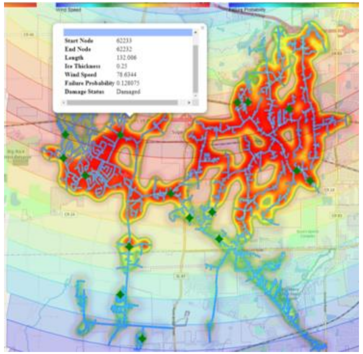
1. Generate weather metric of extreme weather events
2. Prepare fragility model of test systems which describes the behavior of electric components in test system under extreme weather events
3. Acquire damage status of components in test system subject to specific extreme weather events

Evolution

Simulation-based

Snapshot

Fragility curve-based



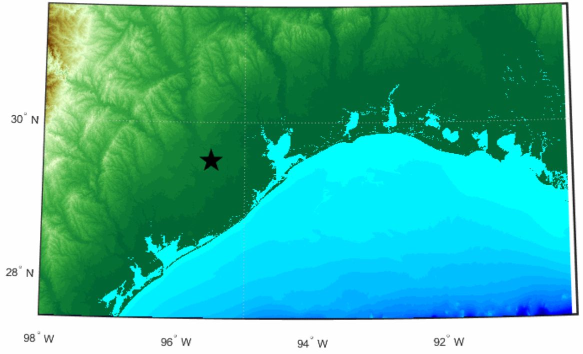
Clustered damages

Damage Scenario Generation

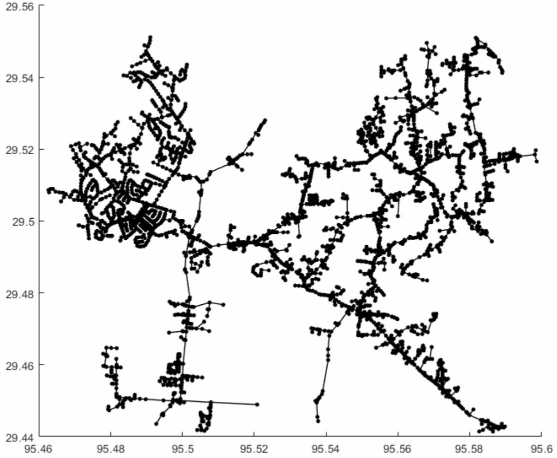
- **Large-scale** test case under **hurricane** extreme weather events

Level-2 Hurricane

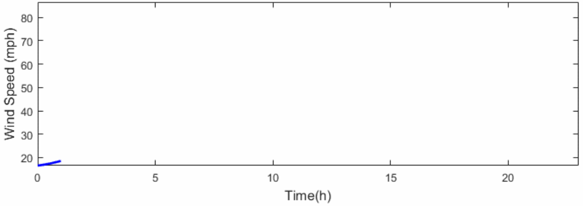
A Level-2 Hurricane Tracking Path



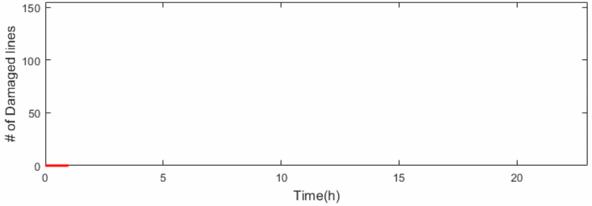
Line Damage Status on the Large-scale Test System



Wind Speed at the Central Point of the Test System

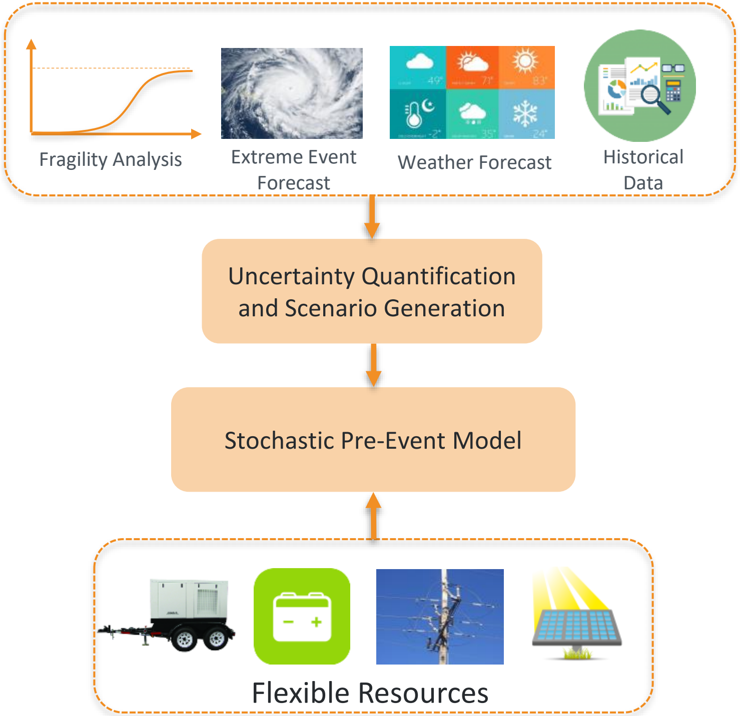


The Total Number of Damaged Lines



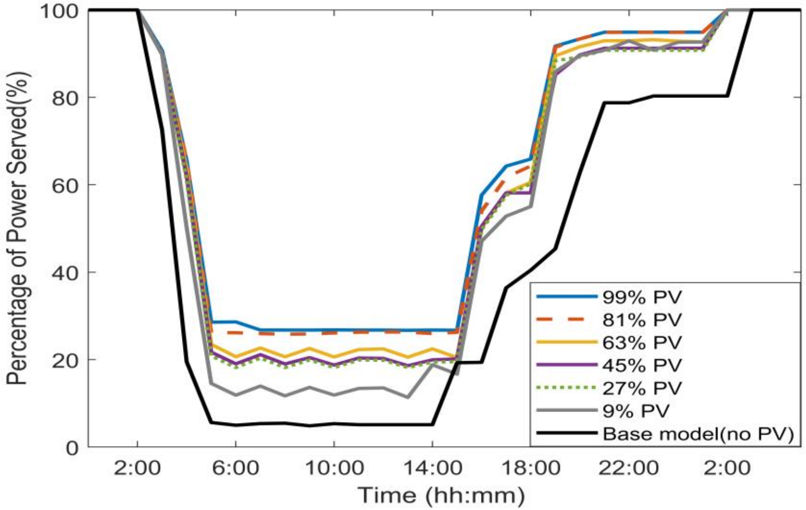
Stochastic Pre-Event Preparation

- The pre-event problem is modeled as a two-stage stochastic program
  - First stage: allocate resources
    - Pre-position mobile generators
    - Fuel allocation
    - Pre-position crews
  - Second stage: operate the distribution system
    - Generation and line flow limits
    - Unbalanced power flow
    - Fuel consumption
    - Energy Storage Charging and PV systems
    - Reconfiguration and isolation
    - Repair process
- The uncertainty is represented by generating a large number of possible scenarios
  - Damage to the grid
  - Solar irradiance



Stochastic Pre-Event Preparation

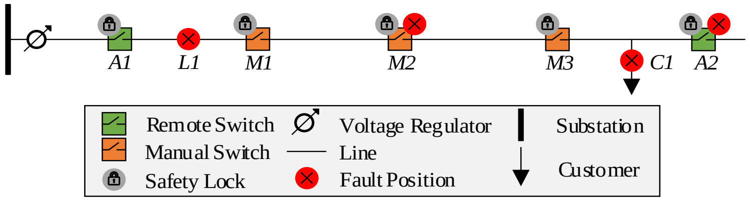
- Grid resilience improved as PV penetration increases from 0% to ~100%
  - Unserved energy reduces
  - Average outage duration reduces

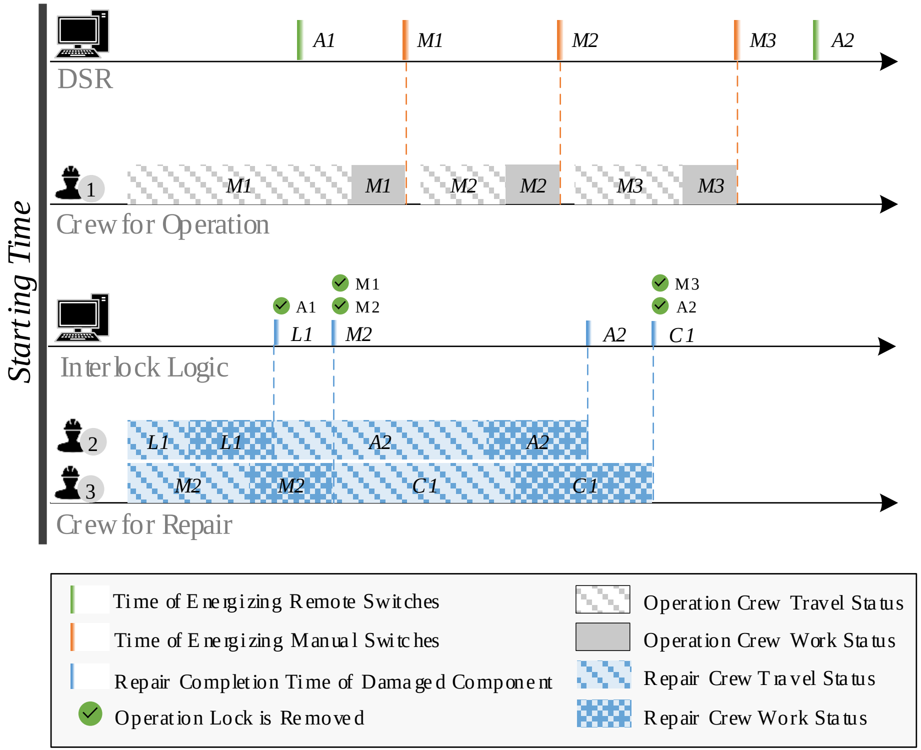


PV Level	Load Served (kWh)	Resilience Improvement Percentage(%)	Average Outage Duration (h)	Outage Decreased Percentage(%)
0	251210.72		14.69	
9%	318668.37	21.17	12.33	16.05
27%	335525.77	25.13	11.72	20.21
45%	336710.74	25.39	11.65	20.67
63%	344588.22	27.10	11.21	23.71
81%	360668.04	30.35	10.45	28.84
99%	364785.93	31.13	10.12	31.12

Post-event Restoration

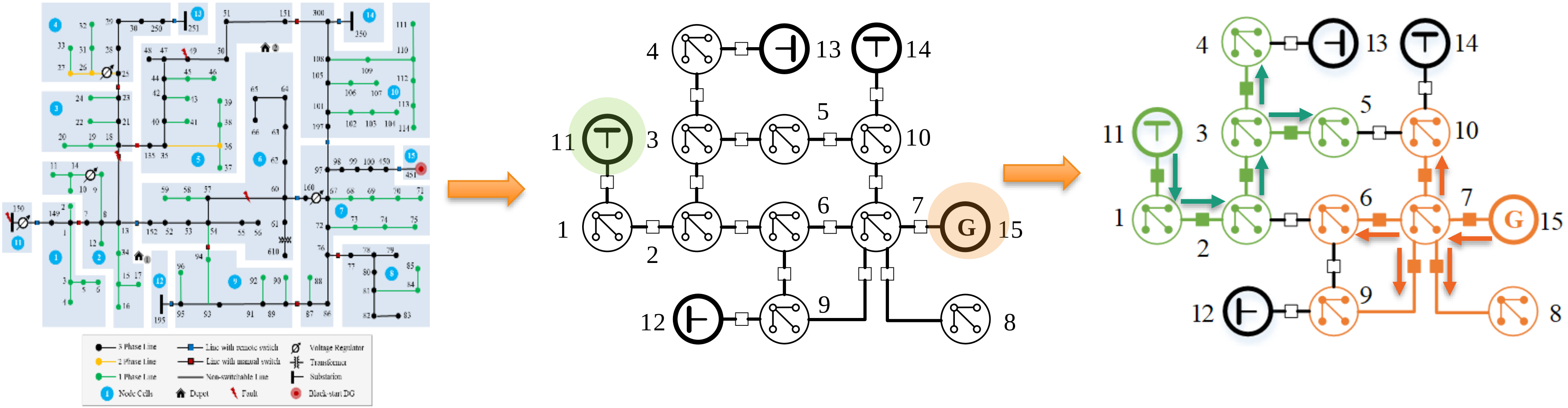
- Innovative modeling approach to address large-scale restoration problem
  - Integrate crew dispatch if needed
- Conceptual work flow:
  - Restoration (DSR)
  - Operating and Repair (Crew for Operating switches and repair)
  - Coordination (Interlock Logic)





Post-event Restoration

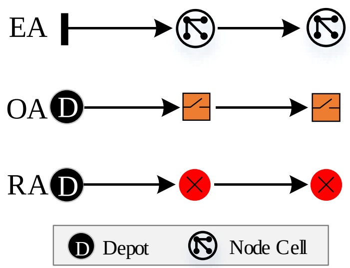
- Concept of “**cell**” and “**traveling current**”
  - System circuit can be grouped into multiple “cells” by auto and manual switches
  - A cell can contain normal/damaged DERs, line segments, and loads.
  - Restoration is a process of operating switches to **energize cells sequentially**:
  - **Energization current will travel through switches from sources to downstream cells**.

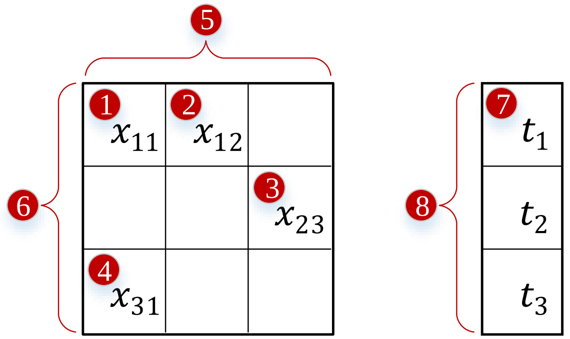


Concept of node cell. (a): Modified IEEE 123 node test feeder.
(b): Node cell representation of IEEE 123 node test feeder.

Post-event Restoration

- EA (Energization Current)
- OA (Operation Crew)
- RA (Restoration Crew)
- All have **similar variable definitions**

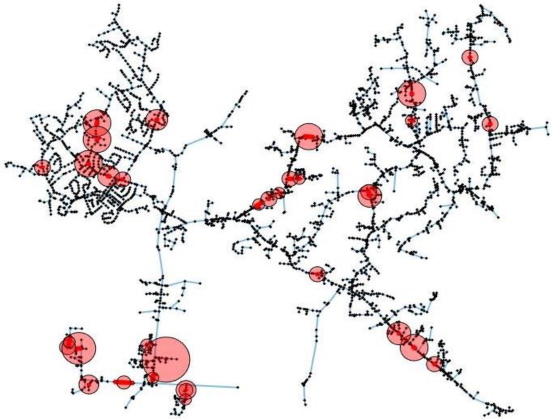




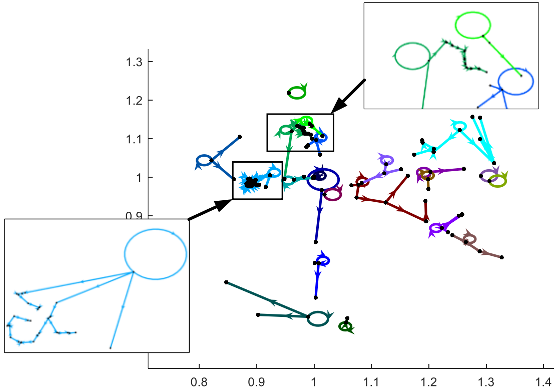
No.	Variable	Definition
①	x_{ii}	Diagonal terms of the route table. $x_{ii} = 1$, if node i is the substation for EA or the depot for OA and RA. $x_{ii} = 0$, if node i is not the “starting point.”
②③④	$x_{ij}, i \neq j$	Off-diagonal terms of the route table. $x_{ij} = 1$, if the agent travels from node i to node j. Otherwise, $x_{ij} = 0$.
⑤⑥	-	Dimension of the route table. The route table is an $n \times n$ matrix, where n is the number of node cells for EA, the number of manual switches and depots for OA, and the number of faulted components and depots for RA.
⑦	t_i	Entry of the arrival time table. t_i represents the arrival time when an agent arrives at node i.
⑧	-	Dimension of the arrival time table. The arrival time table is an $n \times 1$ matrix, where n is the same as the dimension of the route table.

Post-event Restoration

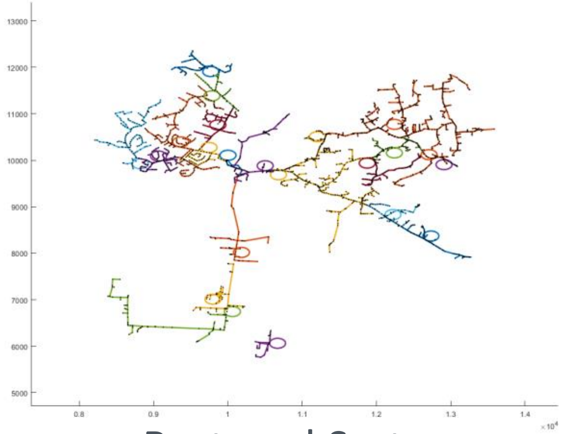
- Based on 72% penetration case
- The energization sequence for the electric power network
- Each node represents a part of distribution circuit
- Arrows represent the energization currents



Damage Distribution



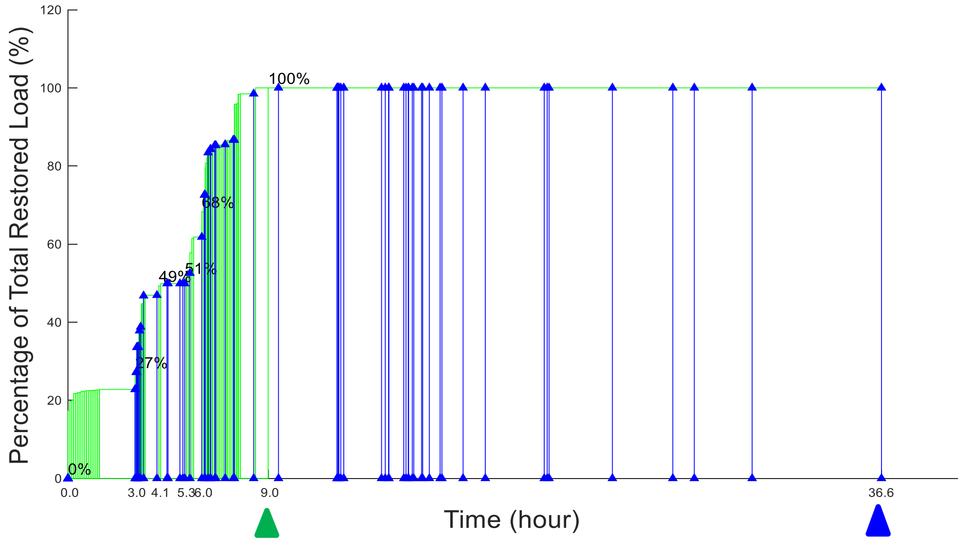
Restoration Sequence

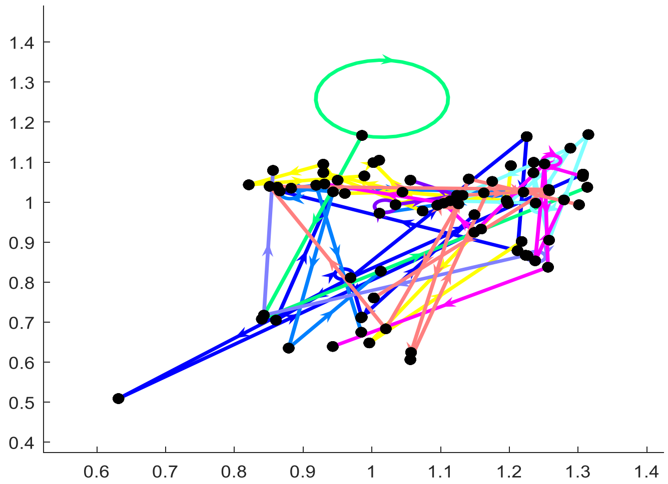


Restored System

Post-event Restoration

- Based on 90% penetration case
- Repair all damaged components (at 36 hours) after 100% load restoration (at 9 hour)
- Real-time energy management coordinates available resources through out the restoration process.





Crew Traveling Routes

Insights

- The coordination between pre-event preparation and post-event operation can improve grid resilience in response to natural disasters
- Grid resilience can be further enhanced by coordinating solar energy, energy storage, and crew dispatch through the developed framework
- Transient stability analysis, protection coordination, and inverter control need to be investigated and integrated with the planning and restoration process

Publications

- Arif, Anmar, Zhaoyu Wang, Bo Chen, and Bo Chen. "Repair and resource scheduling in unbalanced distribution systems using neighborhood search." IEEE Transactions on Smart Grid 11, no. 1 (2020): 673-685.
- Arif, Anmar, Zhaoyu Wang, Chen Chen, and Bo Chen. "A Stochastic Multi-Commodity Logistic Model for Disaster Preparation in Distribution Systems." IEEE Transactions on Smart Grid 11, no. 1 (2019): 565-576.
- Chen, Bo, Zhigang Ye, Chen Chen, and Jianhui Wang. "Toward a MILP modeling framework for distribution system restoration." IEEE Transactions on Power Systems 34, no. 3 (2018): 1749-1760.
- Chen, Bo, Zhigang Ye, Chen Chen, Jianhui Wang, Tao Ding, and Zhaohong Bie. "Toward a synthetic model for distribution system restoration and crew dispatch." IEEE Transactions on Power Systems 34, no. 3 (2018): 2228-2239.
- J. Li, M. E. Khodayar and M. R. Feizi, "Hybrid Modeling Based Co-Optimization of Crew Dispatch and Distribution System Restoration Considering Multiple Uncertainties," in IEEE Systems Journal
- J. Li et al., "Distributed Online VAR Control for Unbalanced Distribution Networks With Photovoltaic Generation," in IEEE Transactions on Smart Grid, vol. 11, no. 6, pp. 4760-4772, Nov. 2020
- Xin Liu, Bo Chen, Chen Chen, Dong Jin. "Electric power grid resilience with interdependencies between power and communication networks – a review." IET Smart Grid, Volume 3, Issue 2, 2020.
- Shanshan Ma, Nichelle'Le Carrington, Arif, Anmar, and Zhaoyu Wang. "Resilience assessment of self-healing distribution systems under extreme weather events." 2019 IEEE PES General Meeting, Atlanta, Aug. 2019. (Best Paper Award)
- Shijia Zhao, Bo Chen. "Multi-timescale Predictive, Proactive and Recovery Optimization Framework for Solar Energy Integrated Resilient Distribution Grid" ISGT NA 2020, Washington D.C. 2020

- **Project Team**
  - ANL: Bo Chen, Shijia Zhao, Chen Chen
  - ISU: Zhaoyu Wang, Qianzhi Zhang, Amar Arif, Shanshan Ma
  - SMU: Mohammad Khodayar, Jiayong Li, Jianhui Wang
  - Algona: John Bilsten
  - Bloomfield: Chris Ball
- **Industry Advisory Board**
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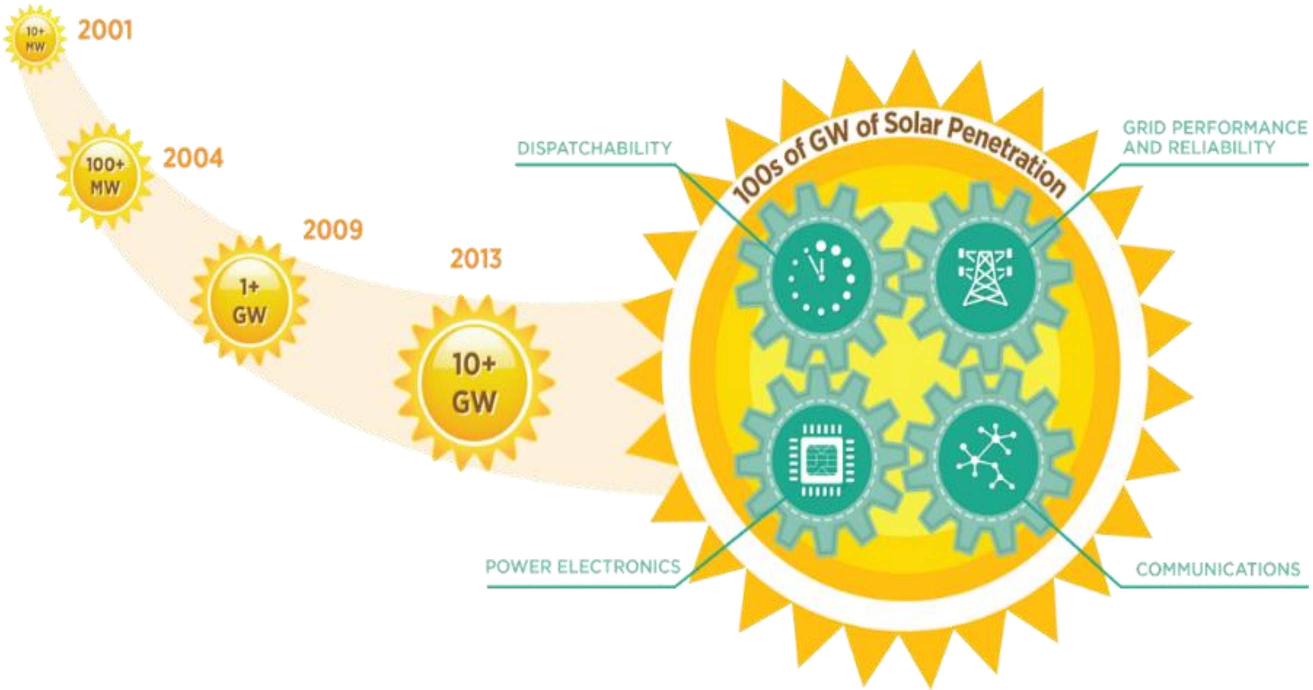
  - Maquoketa Valley Electric Cooperative
  - Aliant Energy
  - City of Bloomfield Utility
  - Algona Municipal Utilities

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