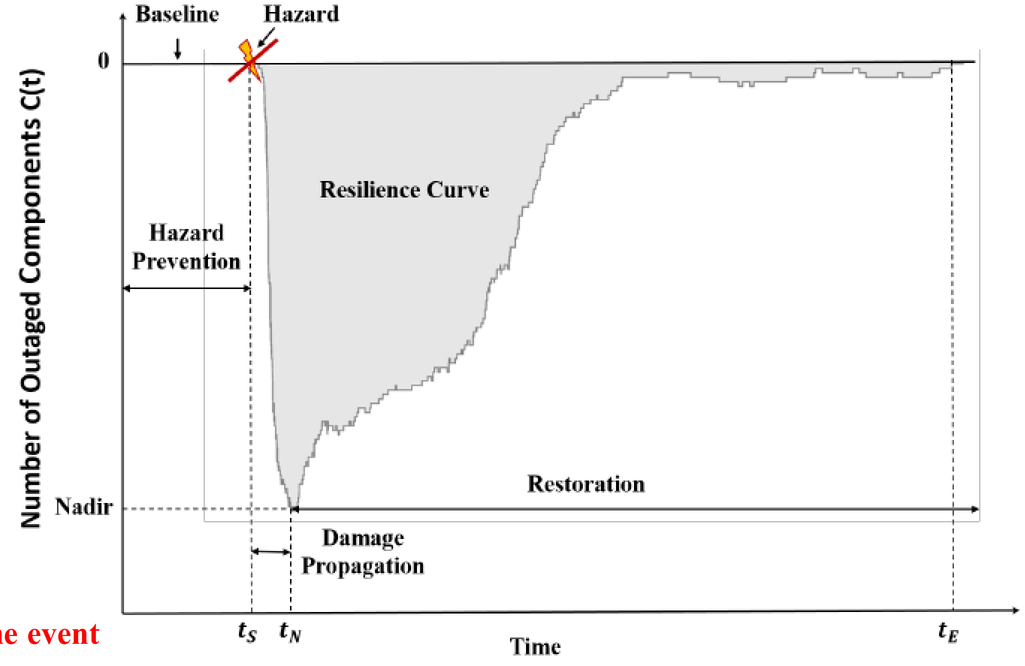
Introduction: Resilient power systems

- Resilience: the ability to ***prepare*** for and adapt to changing conditions and withstand and ***recover*** rapidly from disruptions.



Weather forecast

- Generate metrics of extreme weather events

Outage prediction

- Fragility model of test systems

Extreme event occurrence

Long-term hardening planning

Pre-event preparation

Resource allocation

- Select locations for mobile DERs and mobile energy storage systems
- Allocate available fuel to generator
- Allocate crews to different areas in the grid

Post-event restoration

Timeline

Service restoration

- Fault isolation
- MG formation
- Black-start generators
- Load pickup

N. Carrington , S. Ma , I. Dobson, and Z. Wang, "Extracting resilience statistics from utility data in distribution grids," *IEEE PES General Meeting*, Montreal, Quebec, Canada, Aug. 2020.

Resilient power systems: Pre-event preparation and resource allocation

Failure probability

- Failure probability of overhead line $Pr_{fl,ij}$ with wind speed $w(t)$:

$$Pr_{fl,ij}(w(t)) = 1 - \prod_{p=1}^{N^{pole}} \left(1 - Pr_{fp,ij,p}(w(t))\right) - \prod_{c=1}^{N^{cond}} \left(1 - Pr_{fc,ij,c}(w(t))\right)$$

- Failure probability of line pole:

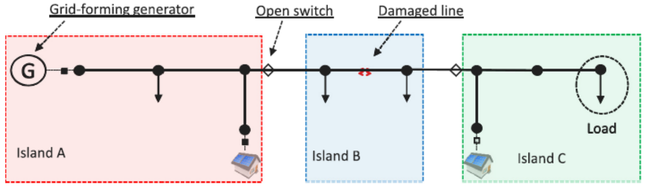
$$Pr_{fp,ij,p}(w(t)) = \Phi\left[\ln\left(\frac{w(t)/m_R}{\xi_R}\right)\right]$$

- Failure probability of line conductor:

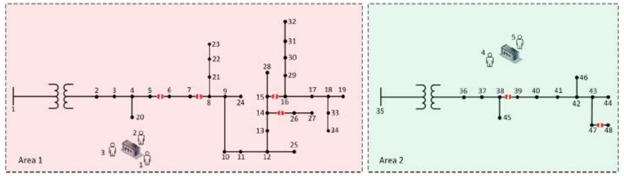
$$Pr_{fc,ij,c}(w(t)) = (1 - Pr_{u,c})\max(Pr_{fw,c}(w(t)), aPr_{ftr,c}(w(t)))$$

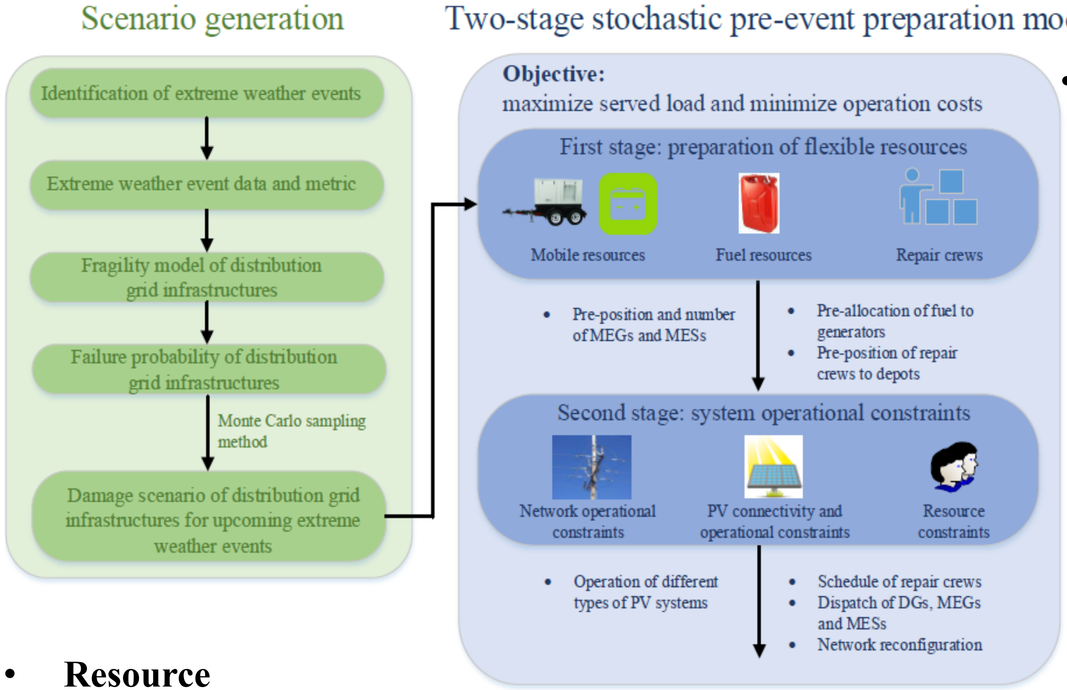
Stochastic pre-event preparation model

- Objective: maximize the served loads and minimize operating costs
- Resource allocation constraints
- Network operational constraints
- Grid-following/-forming PV generations

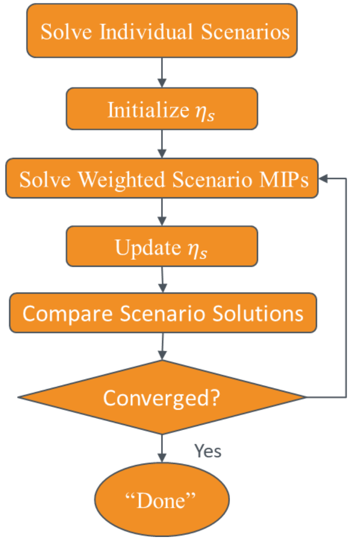


- Repair crew dispatching constraints

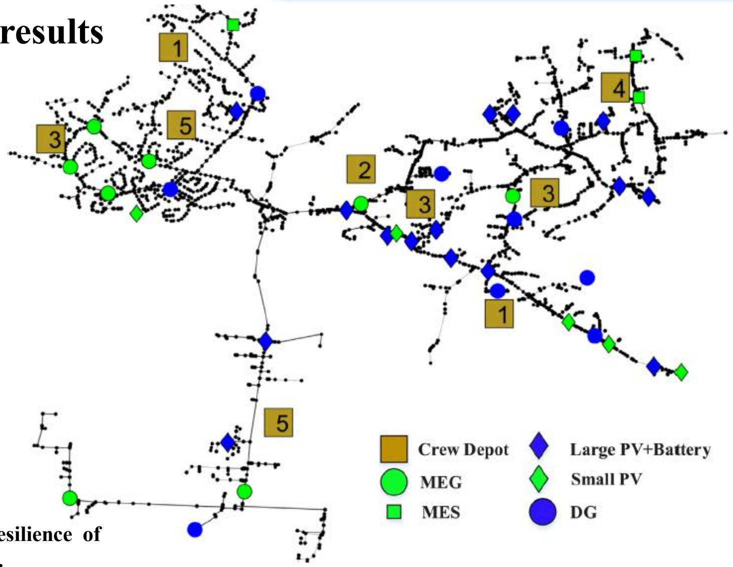




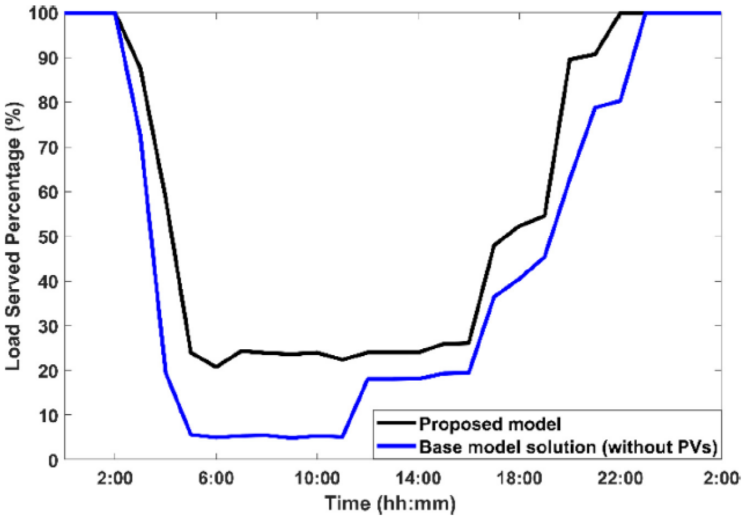
- **Progressive hedge (scenario decomposition)**



- **Resource allocation results**



- **Resilience enhancement**



- Q. Zhang, Z. Wang, S. Ma and A. Arif, "Stochastic pre-event preparation for enhancing resilience of distribution systems," Renewable and Sustainable Energy Reviews, vol.152, pp. 111636, Dec. 2021.

Resilient power systems: Post-event restoration with frequency constraints

MILP sequential service restoration:

- **Objective: maximize the total restored loads**

$$\max \sum_{t\in[t,t+T]} \sum_{i\in\Omega_L} \sum_{\phi\in\Omega_\phi} \left(w_i^{\mathrm{L}} x_{i,t}^{\mathrm{L}} P_{i,\phi,t}^{\mathrm{L}}\right)$$

- **Network operational constraints**

$$\sum_{k\in\Omega_{\mathrm{K}}(i,.)} P_{k,\phi,t}^{\mathrm{K}} - \sum_{k\in\Omega_{\mathrm{K}}(.,i)} P_{k,\phi,t}^{\mathrm{K}} = P_{i,\phi,t}^{\mathrm{G}} - x_{i,t}^{\mathrm{L}} P_{i,\phi,t}^{\mathrm{L}},$$

$$\sum_{k\in\Omega_{\mathrm{K}}(i,.)} Q_{k,\phi,t}^{\mathrm{K}} - \sum_{k\in\Omega_{\mathrm{K}}(.,i)} Q_{k,\phi,t}^{\mathrm{K}} = Q_{i,\phi,t}^{\mathrm{G}} - x_{i,t}^{\mathrm{L}} Q_{i,\phi,t}^{\mathrm{L}},$$

$$U_{i,\phi,t} - U_{j,\phi,t} \ge 2\left(\hat{R}_k P_{k,\phi,t}^{\mathrm{K}} + \hat{X}_k Q_{k,\phi,t}^{\mathrm{K}}\right) + (x_{k,t}^{\mathrm{K}} + p_{k,\phi} - 2)M, \quad \forall k, ij \in \Omega_{\mathrm{K}}, \phi, t$$

$$U_{i,\phi,t} - U_{j,\phi,t} \le 2\left(\hat{R}_k P_{k,\phi,t}^{\mathrm{K}} + \hat{X}_k Q_{k,\phi,t}^{\mathrm{K}}\right) + (2 - x_{k,t}^{\mathrm{K}} - p_{k,\phi})M, \quad \forall k, ij \in \Omega_{\mathrm{K}}, \phi, t$$

$$x_{i,t}^{\mathrm{B}} U_i^{\mathrm{m}} \le U_{i,\phi,t} \le x_{i,t}^{\mathrm{B}} U_i^{\mathrm{M}}, \forall i, \phi, t$$

- ***Grid-forming/-following inverter-based DGs***
- **Load pickup**
- **Network reconfiguration**
- ***Simulation-based frequency dynamics constraints***

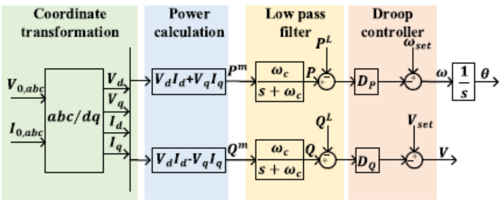
$$0 \le P_{i,t}^{\mathrm{G,MLS}} \le P_{i,t-1}^{\mathrm{G,MLS}} + \alpha\left(\Delta f^{\max} - \Delta f^{\mathrm{meas}}\right), \quad \forall i \in \Omega_{\mathrm{BS}}, t \ge 2$$

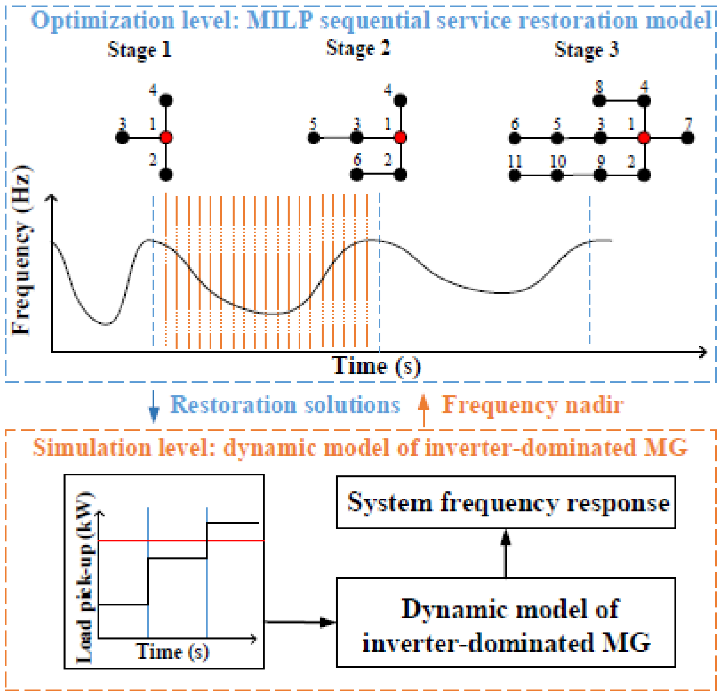
$$\alpha\left(\Delta f^{\max} - \Delta f^{\mathrm{meas}}\right) = \alpha\left(f_0 - f^{\min} - \left(f_0 - f^{\mathrm{nadir}}\right)\right) = \alpha\left(f^{\mathrm{nadir}} - f^{\min}\right) \triangleq \Delta P_{i,t-1}^{\mathrm{G,MLS}}$$

$$-x_{i,t}^{\mathrm{G}} P_{i,t}^{\mathrm{G,MLS}} \le P_{i,\phi,t}^{\mathrm{G}} - P_{i,\phi,t-1}^{\mathrm{G}} \le x_{i,t}^{\mathrm{G}} P_{i,t}^{\mathrm{G,MLS}}, \quad i \in \Omega_{\mathrm{BS}}, \phi, t \ge 2$$

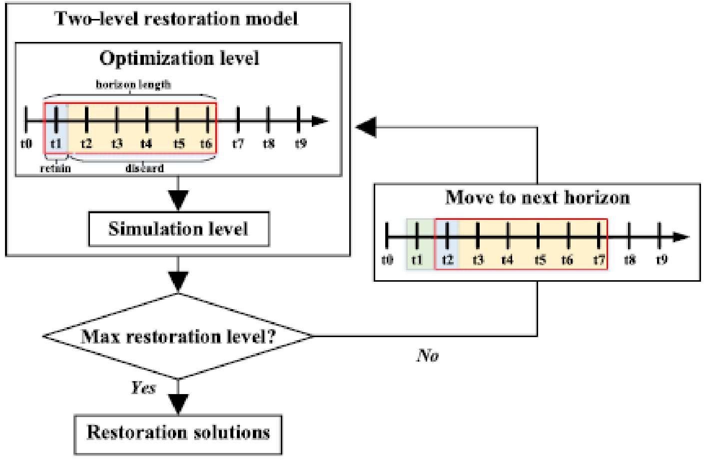
7-th order inverter-dominated MGs:

$$\begin{aligned}
\dot{P} &= \omega_{\mathrm{c}}(V\cos\theta I_{\mathrm{d}} + V\sin\theta I_{\mathrm{q}} - P),\\
\dot{Q} &= \omega_{\mathrm{c}}(V\sin\theta I_{\mathrm{d}} - V\cos\theta I_{\mathrm{q}} - Q),\\
\dot{\theta} &= \omega - \omega_0,\\
\dot{\omega} &= \omega_{\mathrm{c}}(\omega_{\mathrm{set}} - \omega + D_{\mathrm{P}}(P - P^{\mathrm{L}})),\\
\dot{V} &= \omega_{\mathrm{c}}(V_{\mathrm{set}} - V + D_{\mathrm{Q}}(Q - Q^{\mathrm{L}})),\\
\dot{I}_{\mathrm{d}} &= (V\cos\theta - V_{\mathrm{bus}} - RI_{\mathrm{d}})/L + \omega_o I_{\mathrm{q}},\\
\dot{I}_{\mathrm{q}} &= (V\sin\theta - RI_{\mathrm{q}})/L - \omega_o I_{\mathrm{d}},
\end{aligned}$$

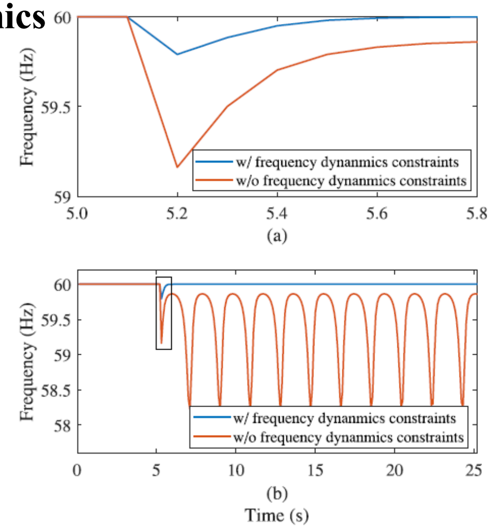




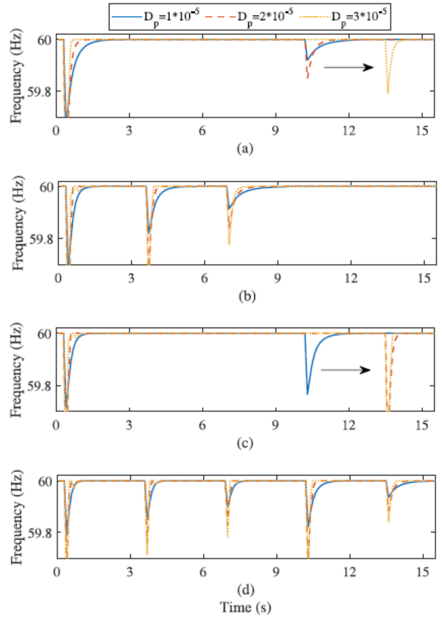
- **Implementation of rolling-horizon**



- **Frequency responses w/ and w/o frequency dynamics**



- **Impact of some hyperparameters on restoration**



- Q. Zhang, Z. Ma, Y. Zhu and Z. Wang, "A two-level simulation-assisted sequential distribution system restoration model with frequency dynamics constraints," IEEE Trans. Smart Grid, vol. 12, no. 5, pp. 3835-3846, Sept. 2021.