



西安交通大学
XI'AN JIAOTONG UNIVERSITY

Power System Resilience

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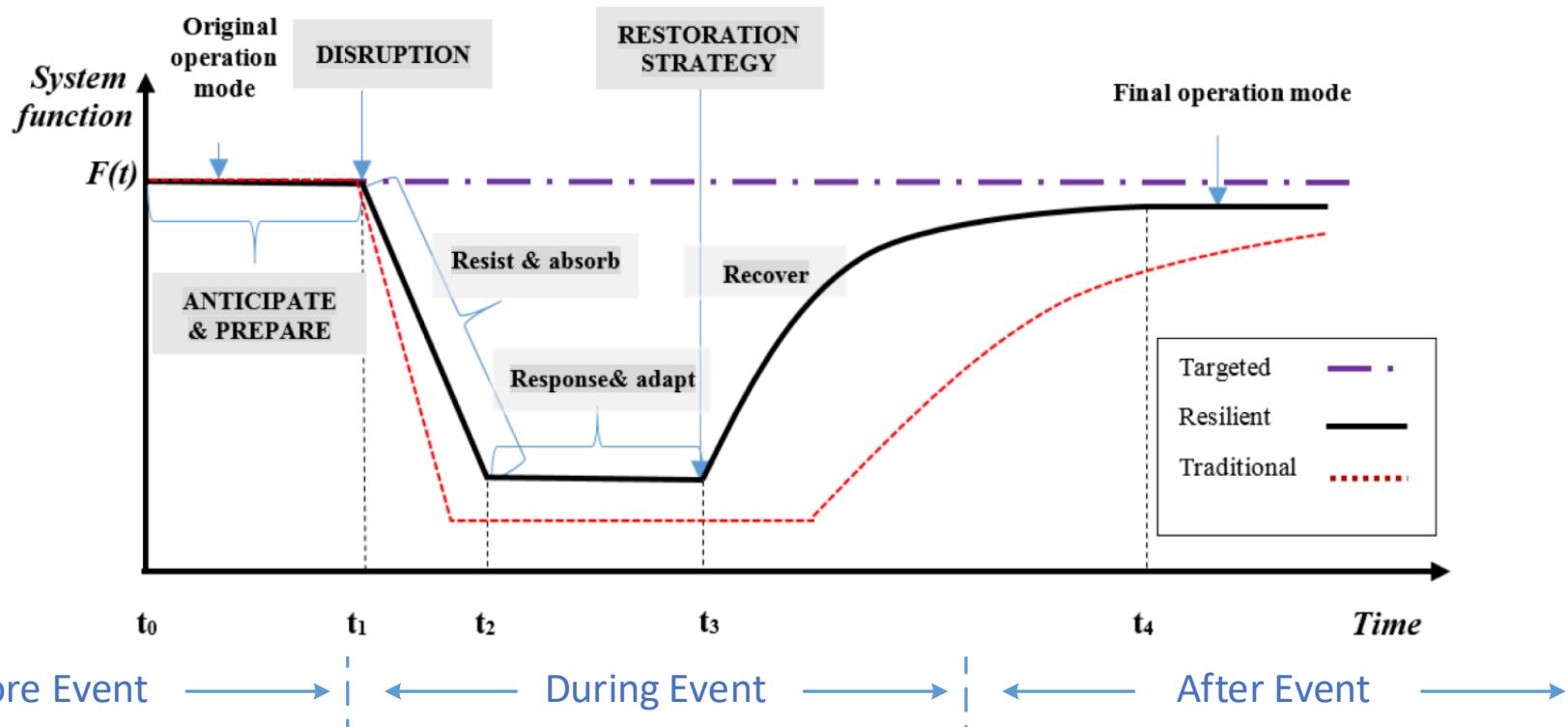
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What is resilience?



Proactive Operation

- Proactive Reconfiguration^[1]
- Pre-disturbance Resources scheduling^[2]
- Microgrids DG Allocation^[3]

Emergency Response

- Distribution Systems Defensive Sectionalization and Microgrids Formation^[4]
- Microgrids Reconfiguration^[5]

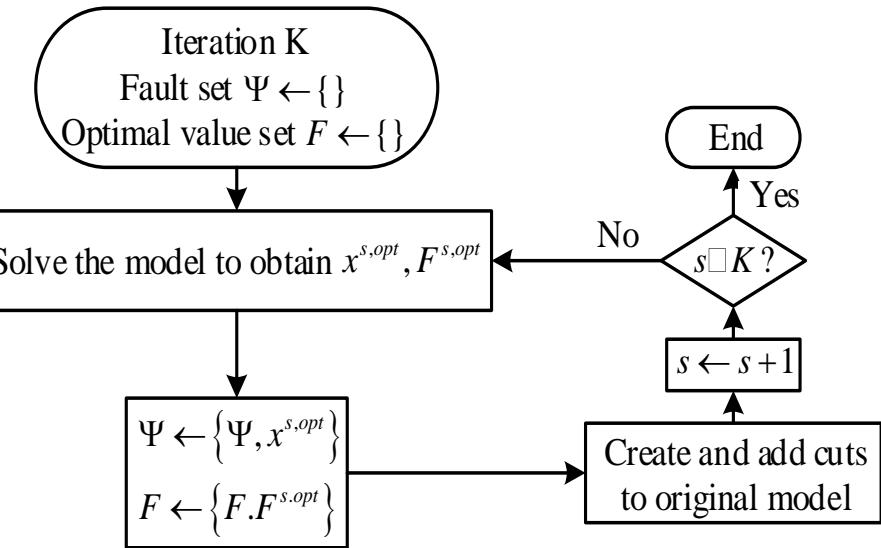
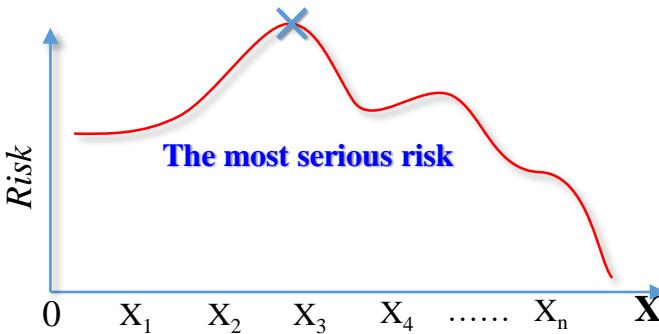
Rapid Recovery

- Critical Load Restoration Path Optimization^[6]
- Networked Microgrids for Restoration^[7]



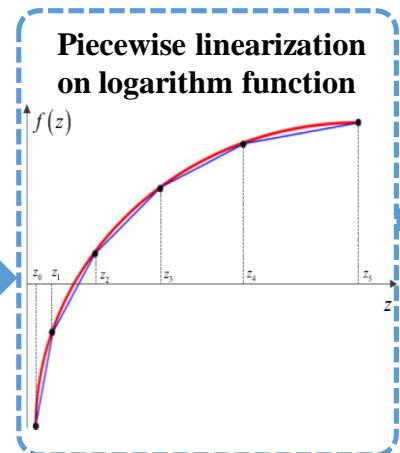
Assessment for Resilience

- Traditional reliability assessment method (Monte Carlo simulation) cannot efficiently **capture high-impact, low-frequency events**
- Computational tractable** risk assessment model using optimization method for **extreme events**



Flow chart of contingency ranking

$$\begin{aligned} & \max_{y_l} \prod_{l=1}^{N_l} p_l^{(1-y_l)} (1-p_l)^{y_l} \sum_{j=1}^{N_b} a_j (D_j^{\max} - D_j) \quad \text{Upper layer} \\ \text{s.t. } & y_l \in \Theta \\ & (P_i, D_j, F_{l-ij}, \theta_i, R_i) = \arg \min_{P_i, D_j, F_{l-ij}, \theta_i} \sum_{j=1}^{N_b} a_j (D_j^{\max} - D_j) \quad \text{Lower layer} \\ & P_i^{\min} - R_i \leq P_i \leq P_i^{\max} \\ & 0 \leq R_i \leq P_i^{\min}, \theta_j^{\min} \leq \theta_j \leq \theta_j^{\max} \\ & \sum_{k \in G_j} P_k - \sum_{\forall l | f(l)=j} F_{l-ij} + \sum_{\forall l | f(l)=j} F_{l-ij} = D_j \\ & -M(1-y_l) \leq F_{l-ij} - b_{l-ij} (\theta_i - \theta_j) \leq M(1-y_l) \\ & -F_l^{\max} y_l \leq F_{l-ij} \leq F_l^{\max} y_l, 0 \leq D_j \leq D_j^{\max} \end{aligned}$$



Double Layer

$$\begin{aligned} & \max_y c^T y \\ \text{s.t. } & y \in \Theta \\ & s = \arg \min_s a^T s \\ & s.t. A_{ieq} s = b_{eq} : u_{eq} \\ & A_{ieq} s \leq b_{ieq} : u_{ieq} \\ & B_{eq} s + C_{eq} y = d_{eq} : v_{eq} \\ & B_{ieq} s + C_{ieq} y \leq d_{ieq} : v_{ieq} \end{aligned}$$

Single Layer

$$\begin{aligned} & \max_{x, y, u_{eq}, u_{ieq}, v_{eq}, v_{ieq}} c^T y \\ \text{s.t. } & y \in \Theta \\ & A_{ieq} s = b_{eq} \\ & B_{ieq} s + C_{ieq} y = d_{ieq} \\ & -MS_a \leq A_{ieq} s - b_{ieq} \leq 0 \\ & -MS_b \leq B_{ieq} s + C_{ieq} y - d_{ieq} \leq 0 \\ & B_{ieq} s + C_{ieq} y - d_{ieq} \leq 0 \\ & -M(1 - S_b) \leq v_{ieq} \leq 0 \end{aligned}$$

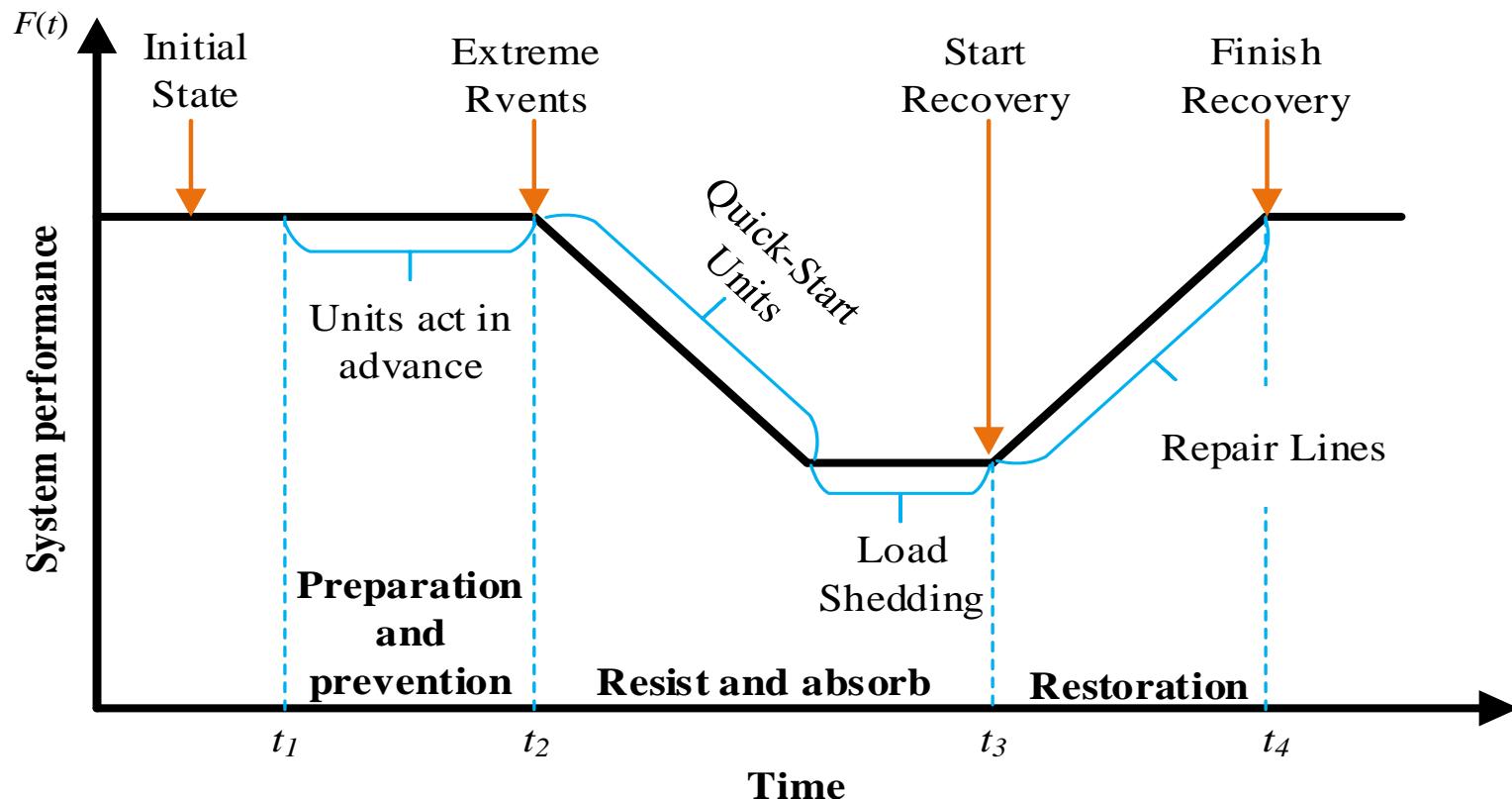
KKT



Resilient Unit Commitment Model

Modeling for the dispatch strategy under three stages

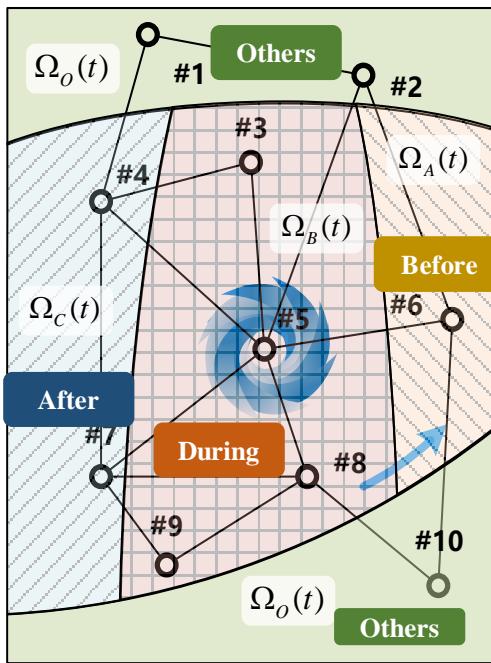
- Co-ordination of unit commitment
 - Fast-start flexibility
 - Repair for critical devices
-
- 1 Unit Commitment
2 Crew Dispatch



Resilient Unit Commitment Model

Aims:

- How to control the **flexible resources** in power systems with the dynamic process of extreme events
- How to **set up the control model** considering the predefense, emergency control and restoration



System dynamic partition

Objective function

$$\min \sum_{t=1}^T \left[\underbrace{\sum_{i \in \Omega_A(t)} F_{i,t}^{\text{pre}} + \sum_{i \in \Omega_B(t)} F_{i,t}^{\text{under}} + \sum_{i \in \Omega_C(t) \cup \Omega_O^l(t)} F_{i,l,t}^{\text{post}}}_{\text{Nodes affected by the extreme event}} + \sum_{i \in \Omega_O} F_{i,t}^{\text{other}} \right]$$

Before Predefense

$$F_{i,t}^{\text{pre}} = \sum_{\forall m \in G_i} (a_m^{\text{pre}} P_{m,t}^g)^2 + b_m^{\text{pre}} P_{m,t}^g + c_m^{\text{pre}} x_{m,t} + C_m^{\text{Pre-UP}} v_{m,t} + C_m^{\text{Pre-DN}} w_{m,t}) + \gamma_i^{\text{Pre}} \Delta D_{i,t}, \forall i \in \Omega_A(t)$$

During Redispatch

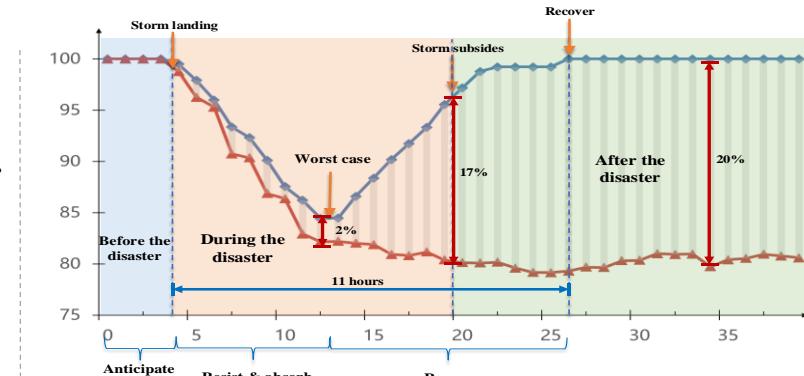
$$F_{i,t}^{\text{under}} = \sum_{\forall m \in G_i} M^g (v_{m,t} \vee w_{m,t}) + C_i^{\text{under-}\Delta p} \Delta D_{i,t}, \quad \forall i \in \Omega_B(t)$$

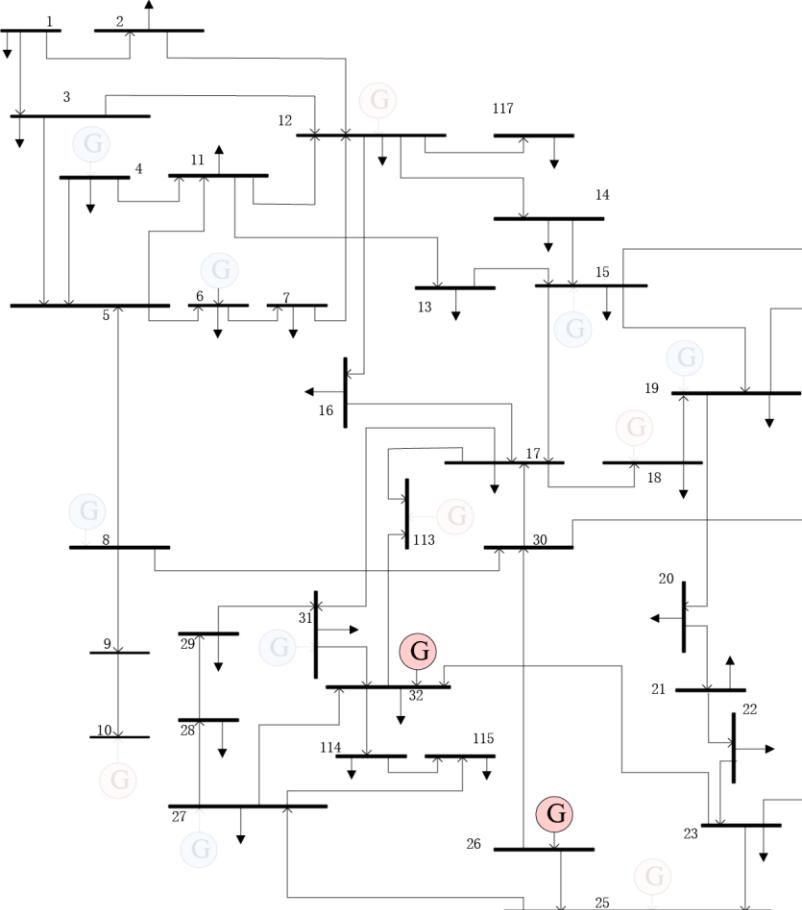
After Restoration

$$F_{i,l,t}^{\text{post}} = \sum_{\forall m \in G_i} (a_m^{\text{post}} P_{m,t}^g)^2 + b_m^{\text{post}} P_{m,t}^g + c_m^{\text{post}} x_{m,t} + C_m^{\text{post-UP}} v_{m,t} + C_m^{\text{post-DN}} w_{m,t}) + C_i^{\text{post-}\Delta p} \Delta D_{i,t} + C_l^{\text{REP}} z_{l,t}$$

Others Maintain power balance and economic operation

$$F_{i,t}^{\text{other}} = \sum_{\forall m \in G_i} (a_m^o P_{m,t}^g)^2 + b_m^o P_{m,t}^g + c_m^o x_{m,t} + C_m^{\text{o-UP}} v_{m,t} + C_m^{\text{o-DN}} w_{m,t}) + \gamma_i^o \Delta D_{i,t}, \quad \forall i \in \Omega_O(t)$$



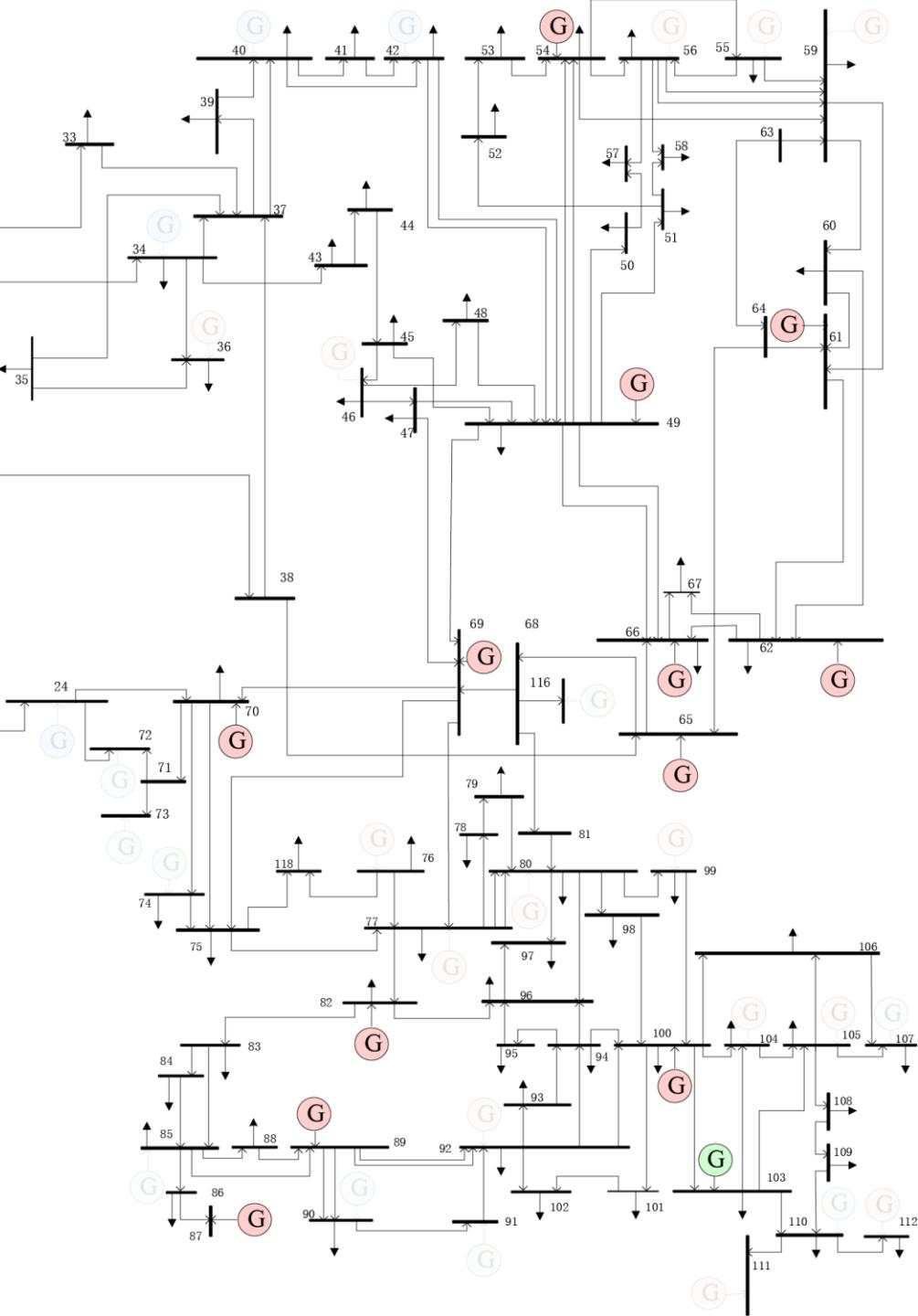


System Description:

118 buses
186 branches
91 load sides
54 thermal units

Time:
00:00

One-line Diagram of IEEE 118-bus Test System





Resilience in Distribution Networks

Aims:

- How to coordinate restoration resources for improving resilience
- The dispatch scheme provided by the existing TSSP model is uneconomical and inflexible

Objective

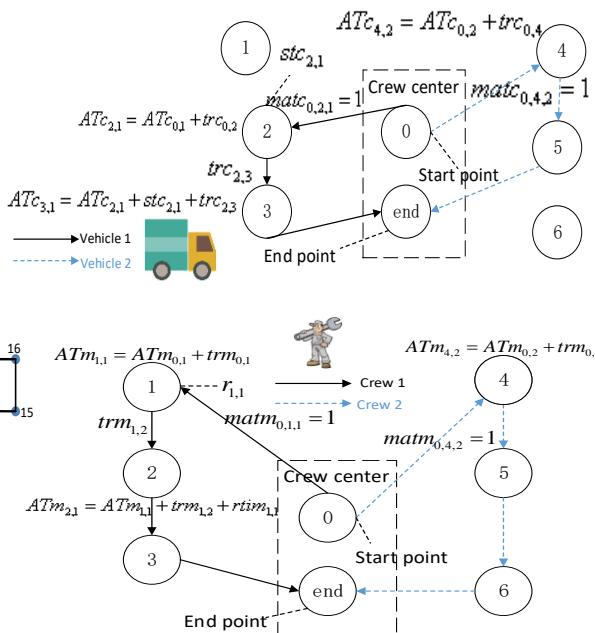
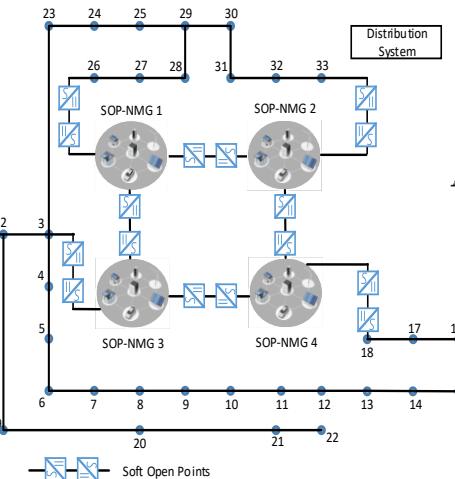
$$obj = \max\left(\sum_{t=1}^T \left(\sum_{i=1}^k v_1 L_{P1i}(t) + \sum_{j=1}^p v_2 L_{P2j}(t) + \sum_{f=1}^q v_3 L_{P3f}(t)\right) \times \Delta t\right)$$

Constraints

- Power Balance Constraints
- Voltage Drop Constraints



- Load Shedding Limits
- Radiality Constraints



$$\sum_{n \in \Omega^{CA}} matc_{0,n,d} - \sum_{m \in \Omega^{CA}} matc_{m,0,d} = 1 \quad \sum_{n \in \Omega^{CA}} matc_{s,n,d} - \sum_{m \in \Omega^{CA}} matc_{m,s,d} = 0$$

$$\delta_{ch}(t) + \delta_{dis}(t) \leq 1 \quad SOC_{min} \leq SOC(t) \leq SOC_{max}$$

$$0 \leq -P_{ch}(t) \leq \delta_{ch}(t) P_{ch_max} \quad 0 \leq P_{dis}(t) \leq \delta_{dis}(t) P_{dis_max}$$

$$E_s^* SOC(t) = E_s^* SOC(t-1) - \eta_{ch} P_{ch}(t) + \frac{P_{dis}^*(t)}{\eta_{dis}}$$

$$(1 - z_{sr}^l(t)) M_{sr_min}^l \leq M_{sr}^l(t) \leq (1 - z_{sr}^l(t)) M_{sr_max}^l$$

$$z_{sr}^l(t) \alpha_{sr}^l \leq \sum_{i=1}^t M_{sr}^l(i) \quad \sum_{\forall(s,r) \in \Omega^l} M_{sr}^l(t) \leq N_{Man}$$

$$z_{sr,t-1}^l \leq z_{sr,t}^l \quad y_{sr}^l(t) \leq z_{sr}^l(t) \quad \sum_{\forall c} rep_{i,c} = 1$$

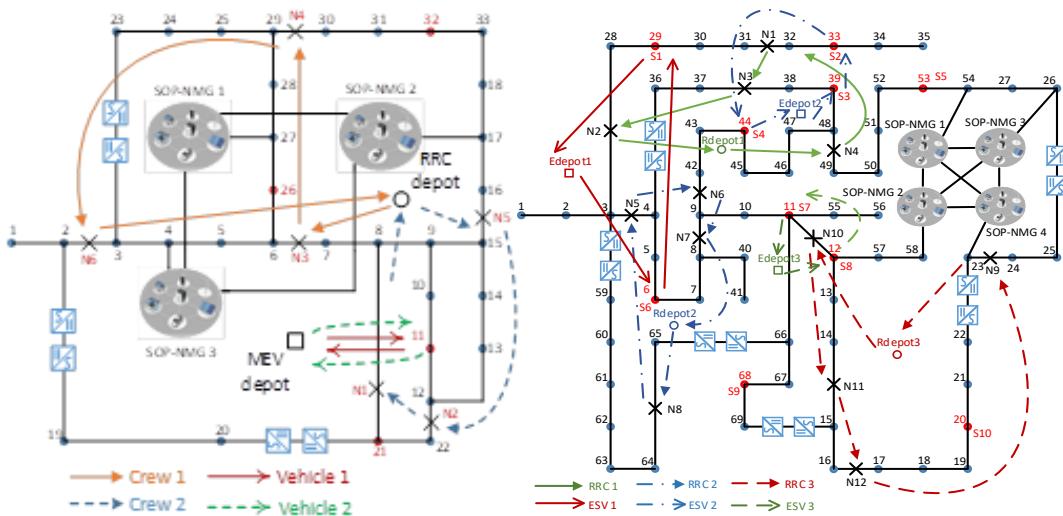
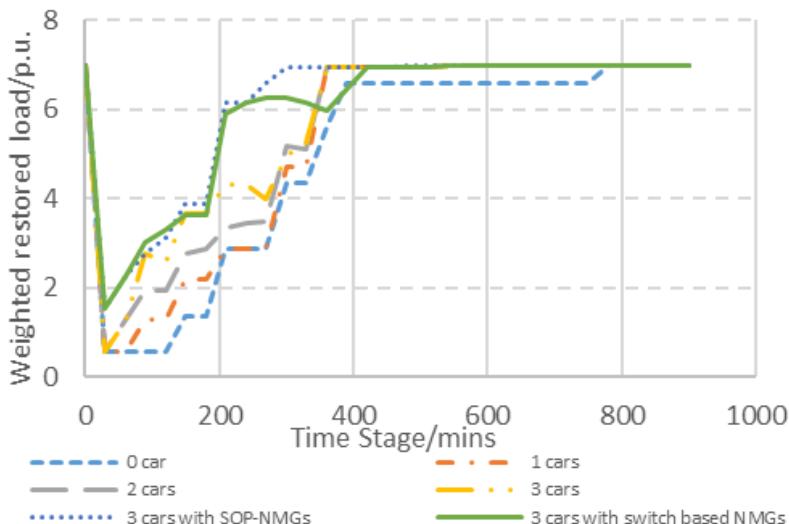
$$rep_{i,c} = \sum_{m \in \Omega^{MA}} matm_{m,i,c} \sum_{n \in \Omega^{MA}} matm_{s,n,c} - \sum_{m \in \Omega^{MA}} matm_{m,s,c} = 0$$



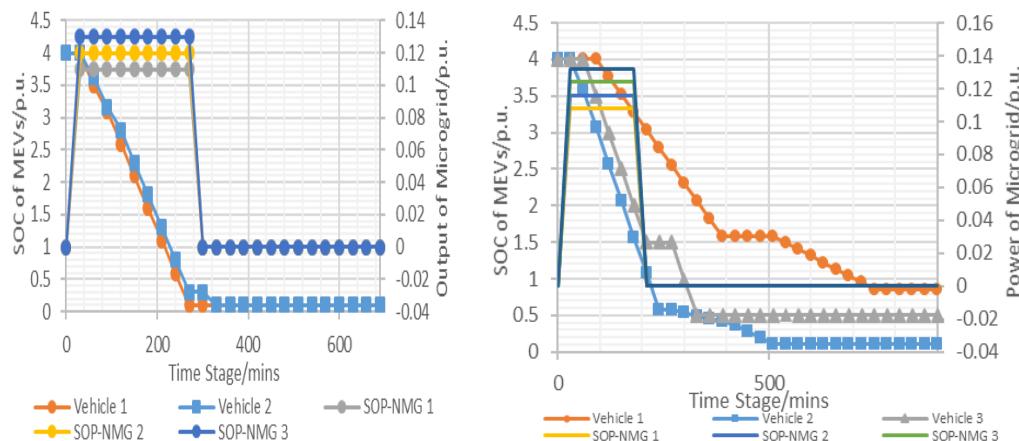
Resilience in Distribution Networks

Response to multiple faults

- Improve the **resilience** of power system.
- Require enough **restoration resources** after natural disasters, including: **routing repair crews** (RRCs), mobile electric vehicles (MEVs), **soft open points-networked microgrids** (SOP-NMGs).
- The **coordination** of restoration resources can pick up load faster.



Route of RRCs and MEVs in the 33/69-bus system



The SOC of MEVs and output of microgrids in 33/69-bus system

T. Ding, Y. Lin, Z. Bie and C. Chen, "A resilient microgrid formation strategy for load restoration considering master-slave distributed generators and topology reconfiguration," *APPLIED ENERGY*, 2017.8, 199: 205-216.



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Thank you & Questions !

