Multi-Microgrids for Enhancing Power System Resilience

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08, 2019

Outline

1 **Background**

2 **Model Framework**

3 **Mathematical Formulations**

4 **Discussions**

Outline

Generation
Transmission
Distribution
Customers

Power station
substation
substation
Power station

Transmission network
substation
substation

substation
substation
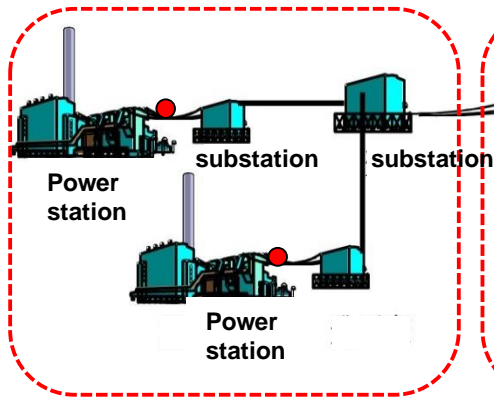
Distribution substation
Distribution substation
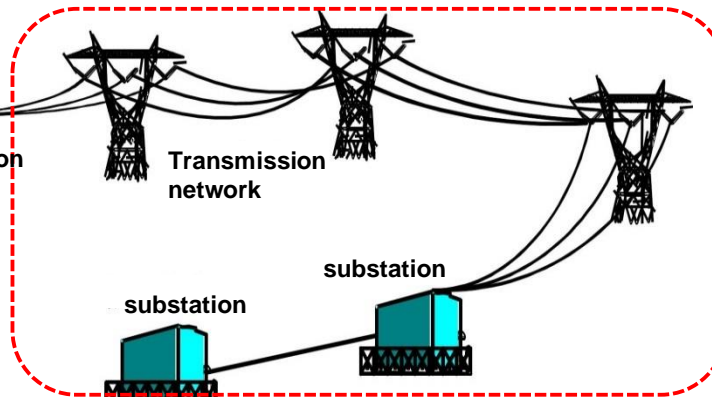
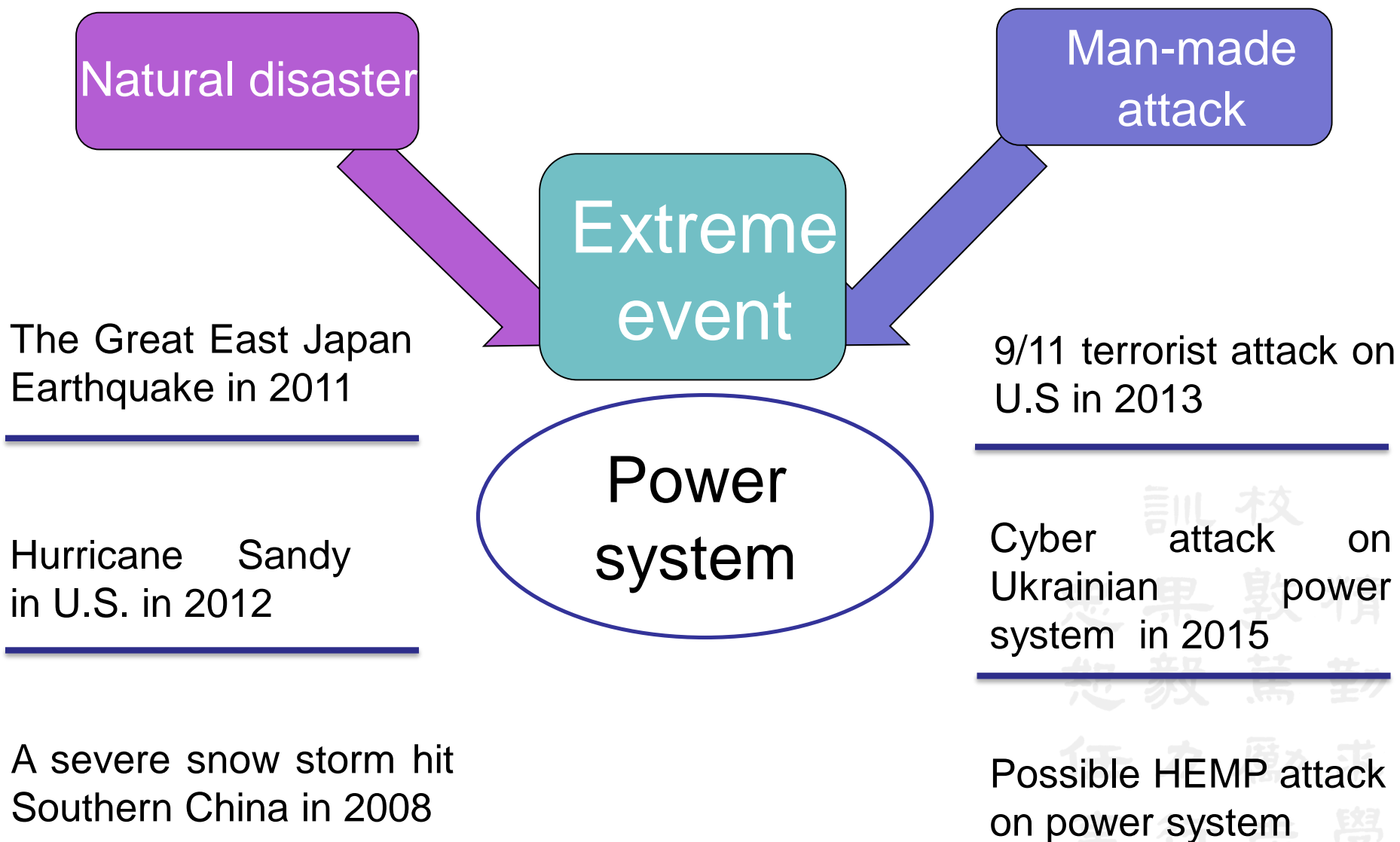Power system is one of the largest and most complex artificial dynamic systems in the world.

The safe and stable operation of the power system directly affects the development of the national economy and national security.

Natural disaster

Man-made attack

Extreme event

Power system

The Great East Japan Earthquake in 2011

Hurricane Sandy in U.S. in 2012

A severe snow storm hit Southern China in 2008

9/11 terrorist attack on U.S in 2013

Cyber attack on Ukrainian power system in 2015

Possible HEMP attack on power system

➤ Concept of power system resilience
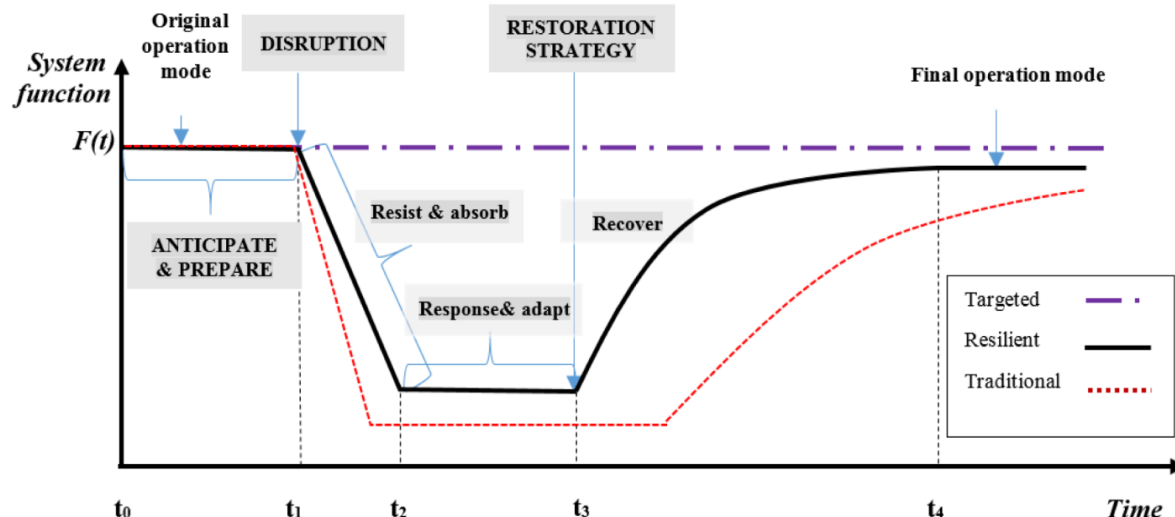
➤ Microgrids has been proved to be a practical way for resilience

Sendai Microgrid helped restoration during and after the Great East Japan Earthquake in 2011

➢ Researches about microgrids for resilience enhancement

Before Event	During Event	After Event
Proactive Operation	**Emergency Response**	**Rapid Recovery**
• Proactive Reconfiguration [1] • Pre-disturbance Resources scheduling [2] • Microgrids DG Allocation [3]	• Distribution Systems Defensive Sectionlization and Microgrids Formation [4] • Microgrids Reconfiguration [5]	• Critical Load Restoration Path Optimization [6] • Networked Microgrids for Restoration [7]

- [1] Amirioun M H , Aminifar F , Lesani H . Resilience-Oriented Proactive Management of Microgrids Against Windstorms[J]. IEEE Transactions on Power Systems, 2017, PP(99):1-1.
- [2] Gholami A , Shekari T , Grijalva S . Proactive Management of Microgrids for Resiliency Enhancement: An Adaptive Robust Approach[J]. IEEE Transactions on Sustainable Energy, 2017:1-1.
- [3] Z. Wang, B. Chen, J. Wang, J. Kim and M. M. Begovic, "Robust Optimization Based Optimal DG Placement in Microgrids," in IEEE Transactions on Smart Grid, vol. 5, no. 5, pp. 2173-2182, Sept. 2014.
- [4] Chen C , Wang J , Qiu F , et al. Resilient Distribution System by Microgrids Formation After Natural Disasters[J]. IEEE Transactions on Smart Grid, 2015, 7(2):1-1.
- [5] 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," Appl Energy, 199 (2017), pp. 205-216
- [6] Gao H , Chen Y , Xu Y , et al. Resilience-Oriented Critical Load Restoration Using Microgrids in Distribution Systems[J]. IEEE Transactions on Smart Grid, 2016:1-1.
- [7] Z. Wang, B. Chen, J. Wang and C. Chen, "Networked Microgrids for Self-Healing Power Systems," in IEEE Transactions on Smart Grid, vol. 7, no. 1, pp. 310-319, Jan. 2016.

➢ Networked microgrids designed for critical users can effectively improve the security of regional power supply.
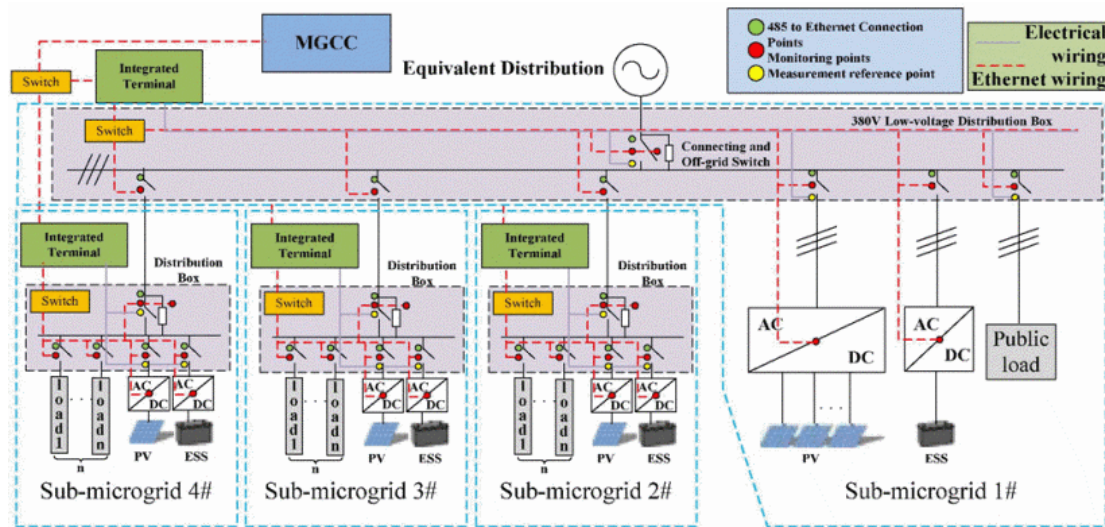
An illustration of networked microgrids [1]

➢ Mutual resources complementarity makes networked microgrids more economical and efficient in normal operation and resilience enhancement.

• [1] Z. Xu, Y. Zhang, X. Long, P. Yang, Q. Zheng and Y. Liang, "Day-ahead economic optimization dispatch of Multi-microgrids with single/three phase structure considering unbalance constraint," 2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Xi'an, 2016, pp. 1134-1138.

Outline

➢ Hierarchical Microgrids Optimization Model

A power interruption occurs

Stage I — Each microgrid schedules the dispatchable DGs, energy storage, controllable loads to minimize load curtailment and operation cost

Stage II — Microgrids with load curtailment will receive power support from those with power surplus
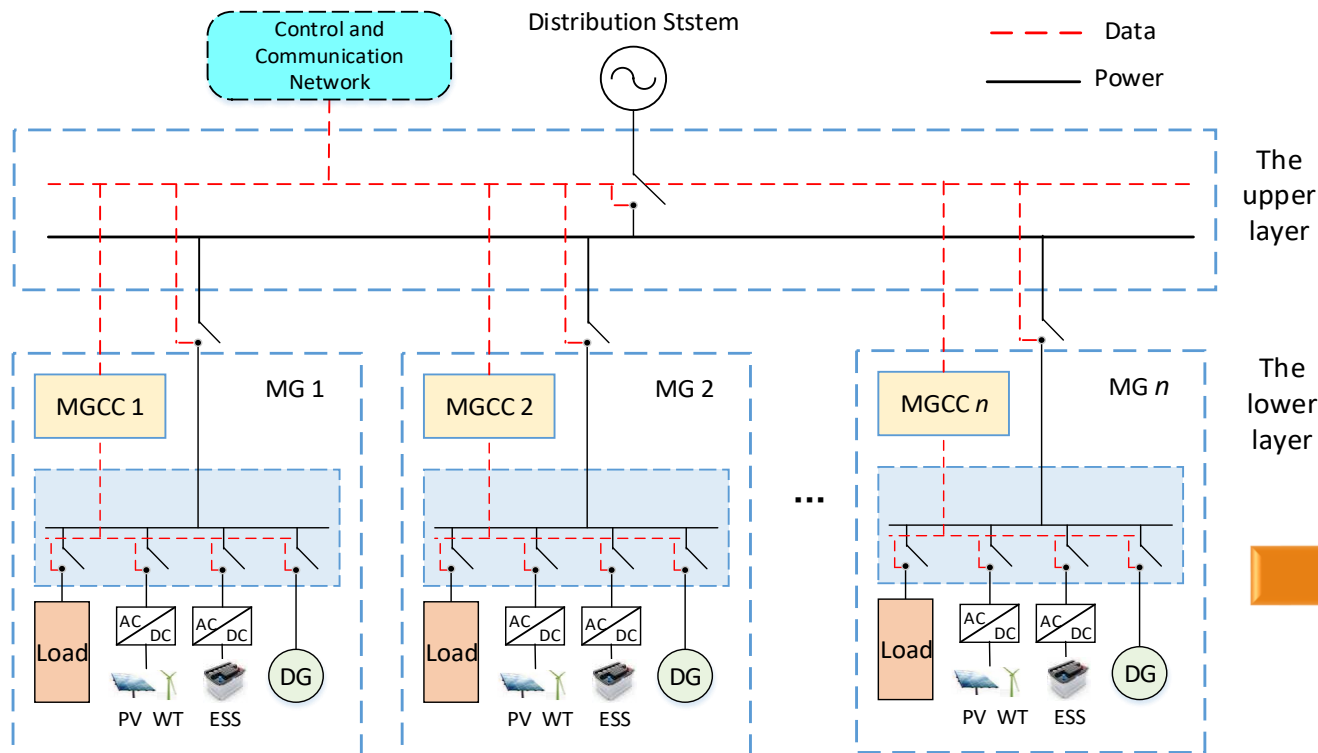
The communication network and tie line are on the upper layer, responsible for data communication and power exchange.

The individual microgrid central controllers (MCC) are on the lower layer, responsible for the operation and management of the corresponding MGs.

➢ Model Implementation

> ➢ Rolling horizon scheduling

To reduce the influence caused by predication errors of uncertain factors such as renewable energy output and load, stage I and stage II will be repeated in every timeslot during the outage.

| 7:00 | 7:30 | 8:00 | 8:30 | 9:00 | 9:30 | 10:00 | 10:30 | 11:00 | 11:30 | ... |

| 7:00 | 7:30 | 8:00 | 8:30 | 9:00 | 9:30 | 10:00 | 10:30 | 11:00 | 11:30 | ... |

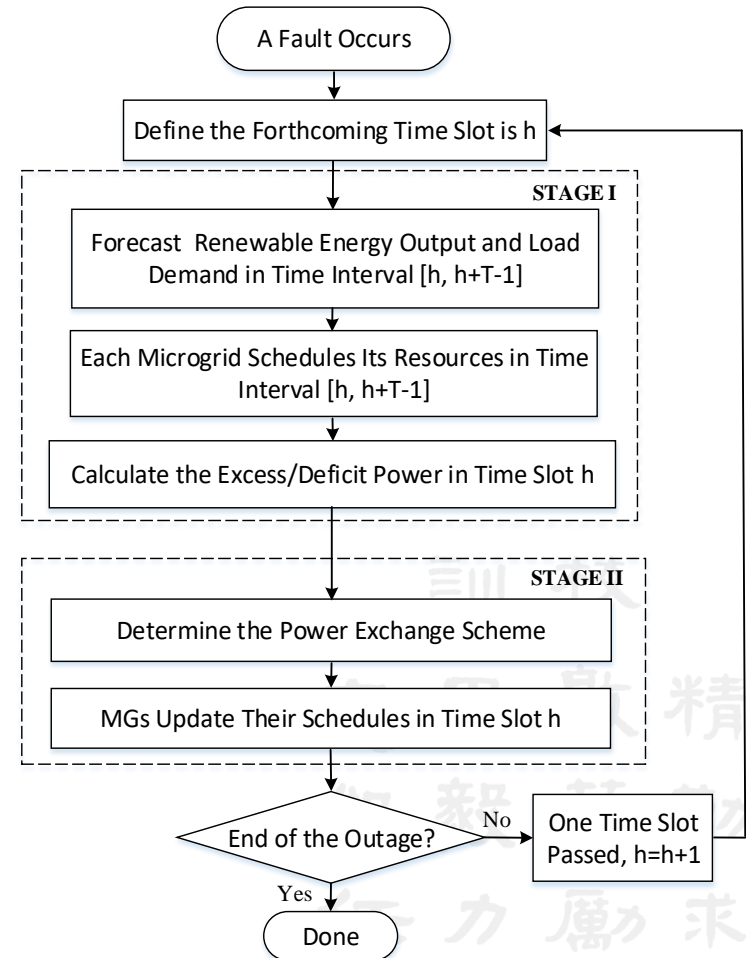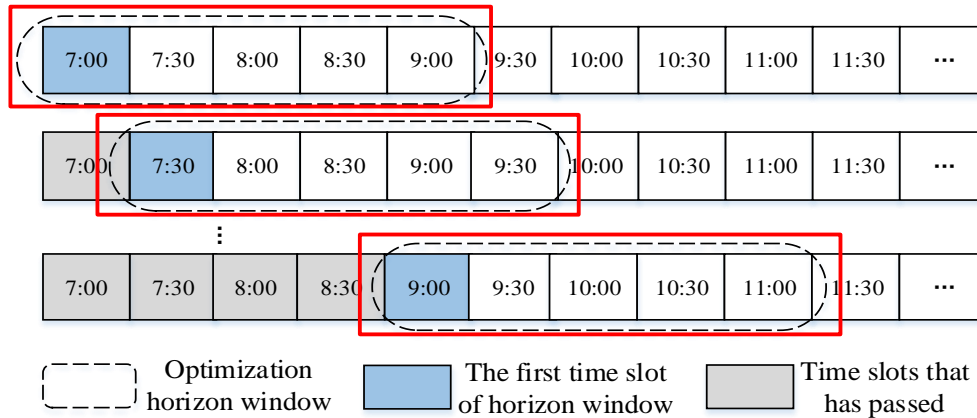| 7:00 | 7:30 | 8:00 | 8:30 | 9:00 | 9:30 | 10:00 | 10:30 | 11:00 | 11:30 | ... |

- ⌐ ¬ Optimization horizon window
- ■ The first time slot of horizon window
- ■ Time slots that has passed

Flowchart:

A Fault Occurs
↓
Define the Forthcoming Time Slot is h ←

STAGE I
- Forecast Renewable Energy Output and Load Demand in Time Interval [h, h+T-1]
  ↓
- Each Microgrid Schedules Its Resources in Time Interval [h, h+T-1]
  ↓
- Calculate the Excess/Deficit Power in Time Slot h

STAGE II
- Determine the Power Exchange Scheme
  ↓
- MGs Update Their Schedules in Time Slot h
  ↓
End of the Outage? — No → One Time Slot Passed, h=h+1
↓ Yes
Done

Demand Side Management

> A load classification method is designed for isolated microgrids, in which load is divided into three categories:

Fixed load	Interruptable load	Shiftable load
Basic electrical equipment. Noncontrollable and should be satisfied preferentially.	Can be curtailed according to priority to meet power balance constraints	Can be transferred from time slots with deficit power to those with sufficient power

> For shiftable load, denotes $D_i(t, t')$ as the quantity of load transferred from time slot t to t'. The net value of shiftable load i transferred out from time slot t_0 can be formulated as follows:

$$\Delta L_i^{sh}(t_0) = \sum_{t=max\{t_0-t_i^S+1,h\}}^{t_0} \sum_{t'=h}^{h+T-1} \left(D_i(t,t') - D_i(t',t) \right)$$

- Outflow capacity constraint
- Load balance constraint

$$\Delta L_i^{sh}(t) \ll L_i(t) \qquad \sum_{t=h}^{h+T-1} \Delta L_i^{sh}(t) = 0$$

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⬆ Stage I

➤ Objective Function：

> **Generation cost of dispatchable DGs**

$$Min \sum_{t=h}^{h+T-1} \left\{ \sum_{i \in G_n} \left[\Delta t \times F_i\left(P_i^G(t)\right) + SU_i(t) + SD_i(t) \right] + \Delta t \sum_{i \in S_n} C_i^{dch} P_i^{dch}(t) + \Delta t\, \rho_i^{int} \sum_{i \in L^{int}_n} P_i^{int}(t) \right\} + p_i^s \sum_{i \in L^{sh}_n} \sum_{t=h}^{h+T-1} \sum_{t'=h}^{h+T-1} D_i(t,t')$$

$$SU_i(t) = \max\{0, [U_i(t) - U_i(t-1)] \times C_i^{SU}\}$$
$$SD_i(t) = \max\{0, [U_i(t-1) - U_i(t)] \times C_i^{SD}\}$$

> **Energy discharge cost and load curtailment penalty price**

> **Transfer penalty of shiftable load**

➤ Constraints：

1) AC power flow constraints

2) Distributed generators constraints

3) Energy storage constraints

4) Load constraints

⬆ Stage I

➢ AC OPF and piecewise Linearization ＊:

Motivation DC OPF solution can be infeasible even when sufficient reactive power generation capacity is compensated locally in each island [1].

$$P_{ij} = G_{ij}(V_i^2 - V_iV_j \cos(\theta_i - \theta_j)) - B_{ij}\left(V_iV_j \sin(\theta_i - \theta_j)\right)$$

$$Q_{ij} = -B_{ij}(V_i^2 - V_iV_j \cos(\theta_i - \theta_j)) - G_{ij}\left(V_iV_j \sin(\theta_i - \theta_j)\right)$$

⬇

$$P_{ij} = G_{ij}(V_i - V_j - r_{(i,j)} + 1) - B_{ij}(\theta_i - \theta_j)$$

$$Q_{ij} = -B_{ij}(V_i - V_j - r_{(i,j)} + 1) - G_{ij}(\theta_i - \theta_j)$$

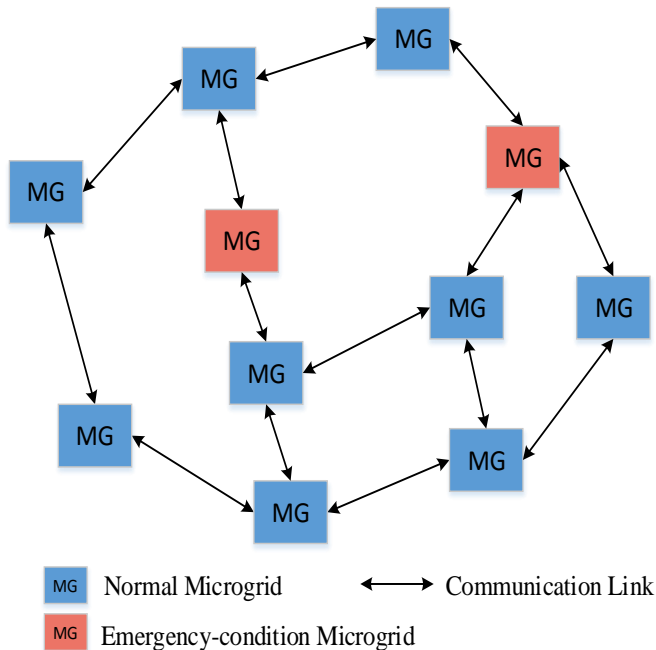Linear approximation of $\cos(\theta_i - \theta_j)$:
$$r_{(i,j)} = d_{(i,j)}(\theta_i - \theta_j) + e_{(i,j)}$$

＊ Time index t of variables $P_{ij}(t)$, $V_i(t)$, $\theta_i(t)$ are omitted for simplicity

[1] P. A. Trodden, W. A. Bukhsh, A. Grothey, and K. I. M. McKinnon, "MILP formulation for controlled islanding of power networks," Int. J. Elect. Power Energy Syst., vol. 45, no. 1, pp. 501–508, 2013.

Stage II

➢ **Information Consensus in Multi-microgrids System**

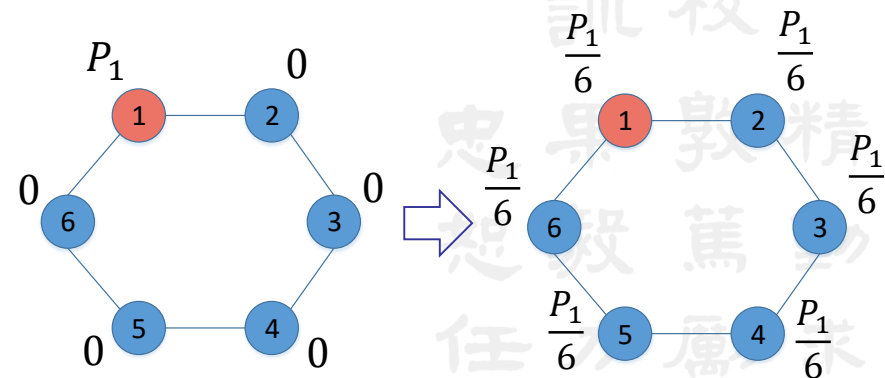$$X_n(k+1) = X_n(k) + \tau \cdot \sum_{m \in NEI_n} \left(X_m(k) - X_n(k) \right)$$

Iteration

$$\tilde{X}_n = \frac{1}{N} \sum_{n=1}^{n=N} X_n(0)$$

Step size τ satisfies $0 < \tau < 1/\Delta$, Δ is the maximum node out-degree of the system digraph [1]

MG — Normal Microgrid ⟷ Communication Link
MG — Emergency-condition Microgrid

Example:

- [1] Olfati-Saber, R., Fax, J. A. and Murray, R. M. (2007). Consensus and Cooperation in Networked Multi-Agent Systems. Proceedings of the IEEE, vol. 95, pp. 215-233.

Stage II

➢ Obtain the Information of Deficit Power in Emergency-condition MGs

$$X_n(k+1) = \boxed{X_n(k)} + \tau \cdot \sum_{m \in NEI_n} \left(X_m(k) - X_n(k)\right)$$

$$\boldsymbol{P_n^{dt,0}}[\boldsymbol{i}] = \begin{cases} N \times P_n^{dt}, & i = n \\ 0, & i \neq n \end{cases}$$

$$\tilde{X}_n = \frac{1}{N} \sum_{n=1}^{n=N} X_n(0)$$

$$\widetilde{\boldsymbol{P}_n^{dt,0}} = \frac{1}{N} \sum_{n=1}^{n=N} \boldsymbol{P_n^{dt,0}} = \left[P_1^{dt}, P_2^{dt}, \cdots, P_N^{dt}\right]^T$$

➢ Determine the Power Exchange Plan

$$\lambda_{n,h} = \begin{cases} \dfrac{P_{n,h}^{dt}}{\sum_{n=1}^{N} P_{n,h}^{sur}}, & \sum_{n=1}^{N} P_{n,h}^{dt} < \sum_{n=1}^{N} P_{n,h}^{sur} \\[6mm] \dfrac{P_{n,h}^{dt}}{\sum_{n=1}^{N} P_{n,h}^{dt}}, & \sum_{n=1}^{N} P_{n,h}^{dt} \geq \sum_{n=1}^{N} P_{n,h}^{sur} \end{cases}$$

Allocate the power required by emergency-condition microgrids to every normal microgrid according to the proportion of its unused capacity

$$P_{n',n,h} = \lambda_{n,h}\, P_{n',h}^{sur}$$

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Conclusions

> The proposed hierarchical optimization model for multi-MGs has the following merits:

Rolling horizon optimization to reduce uncertainty influence

Load classification to increase flexibility

AC power flow to avoid island infeasibility

Distributed communication for emergency condition

➤ In future study, the following researches can be carried out:

1. Model of hazards influence on microgrids

- Possible components faults under different disasters in microgrids
- Component fragility curve / Failure simulation

2. Dynamic microgrids formation and reconfiguration

- Using dynamic microgrids reconfiguration to accommodate the environment in real time and support critical load

3. Cyber security for microgrids

- Cyber-attack is also a key topic for power security

Thank you for attention!