Distributed Power Systems for Enhancing the Resilience, Reliability, Security, and Economics of Electricity Grid

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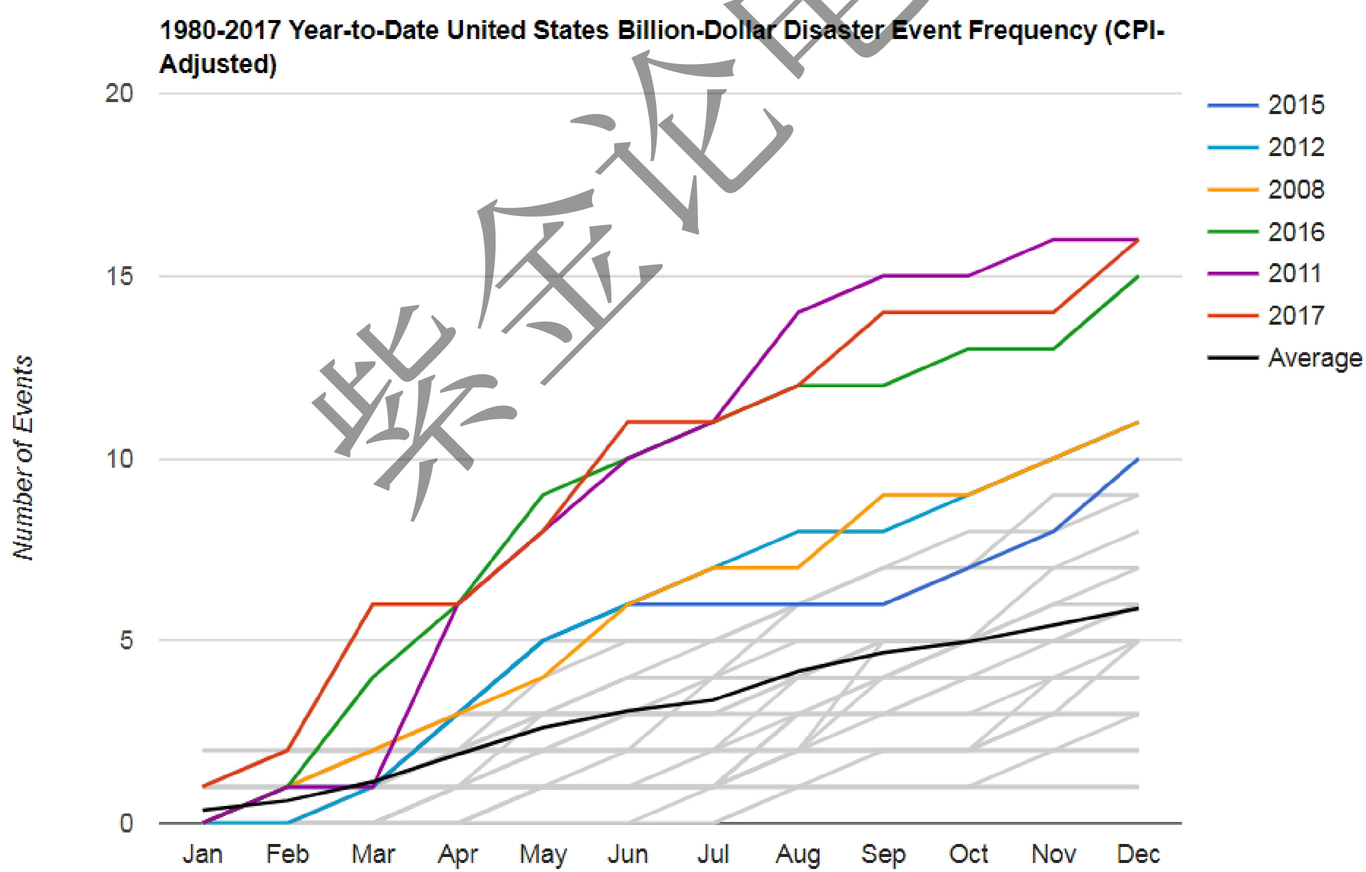
Outline

- Power System Outages
- Managing Distributed Power Systems
- Managing Microgrids in Power Systems
- Adaptive Islanding of Microgrids
- Enhancing the Power System Resilience
- Conclusions

Extreme Events

- A more intense climate change has increased the frequency and the severity of weather-related extreme events throughout the world.
  - In 2017, there have been 5 extreme events with losses exceeding $1 billion each across the U.S.



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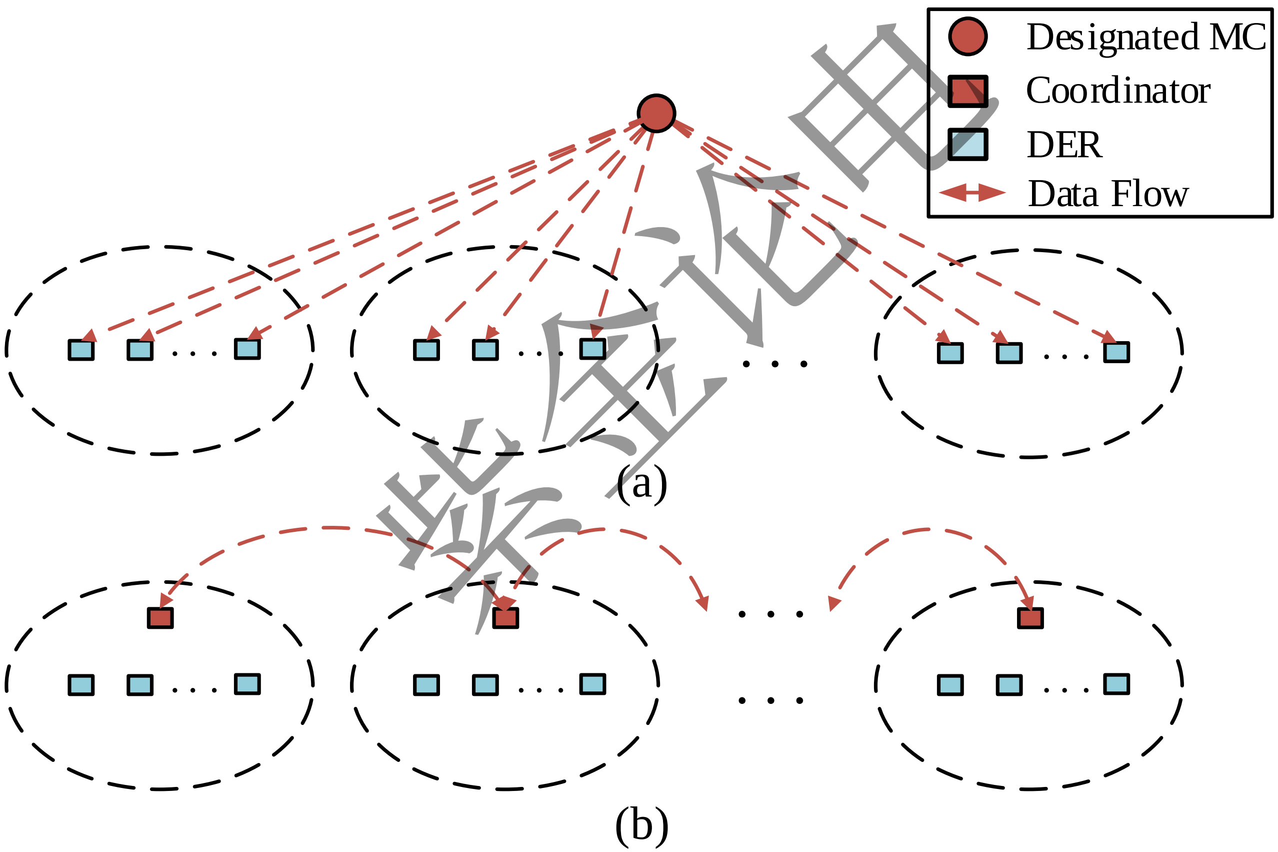
Massive Power Outages

- Although power systems have been designed in accordance with reliability requirements, they are insufficiently prepared for extreme events which have a very high impact on our societal undertakings.
  - Power systems are susceptible to extreme events including severe weather events (e.g., hurricanes, tornados) and catastrophic man-made incidents (e.g., malicious attacks, human operator missteps).

Extreme Event	Origin		Blackout	
	Natural	Man-made	Date	Location
Hurricane	✓		Oct. 2012	U.S.
Wind Storm	✓		Feb. 2008	China
Solar Flare	✓		Mar. 1989	Canada
Flooding	✓		Aug. 2005	U.S.
Earthquake	✓		Mar. 2011	Japan
Thunderstorm	✓		Aug. 2006	Canada
Cyber Attack		✓	Dec. 2015	Ukraine
Equipment Failure		✓	Jul. 2012	India
Technical Error		✓	Aug. 2003	U.S.

Distributed Power System: Unification and Compartmentalization



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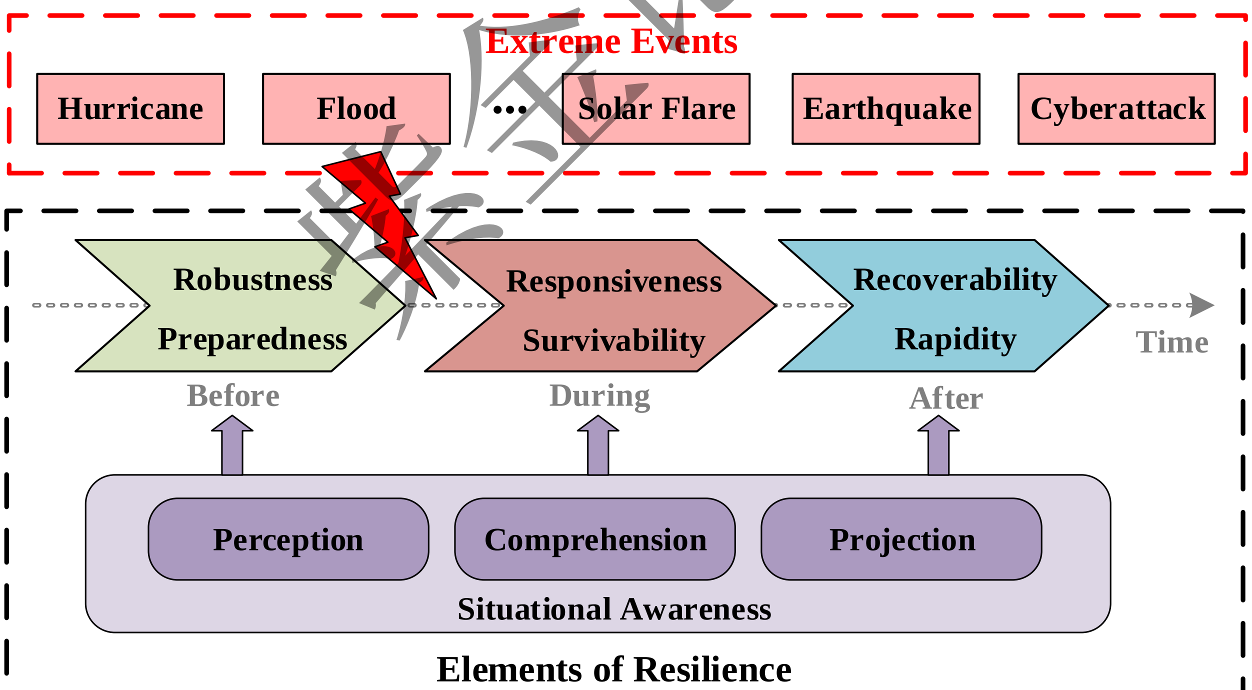
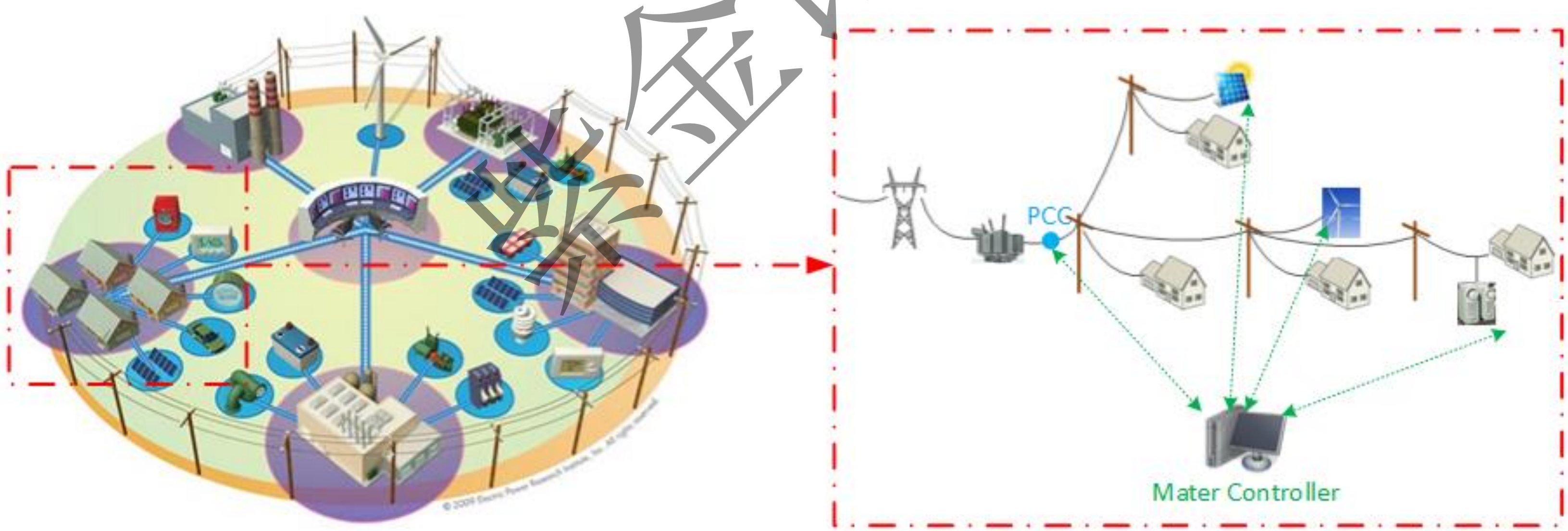
Dynamic Islanding for Power System Resilience

- Power system resilience is defined as the ability of a power system to prepare adequately for, respond comprehensively to, and recover rapidly from major disruptions due to extreme events.
  - A resilient power system will withstand not only the disruptions pertaining to severe weather and climate changes but also catastrophic man-made incidents, and even a combination of such incidents.

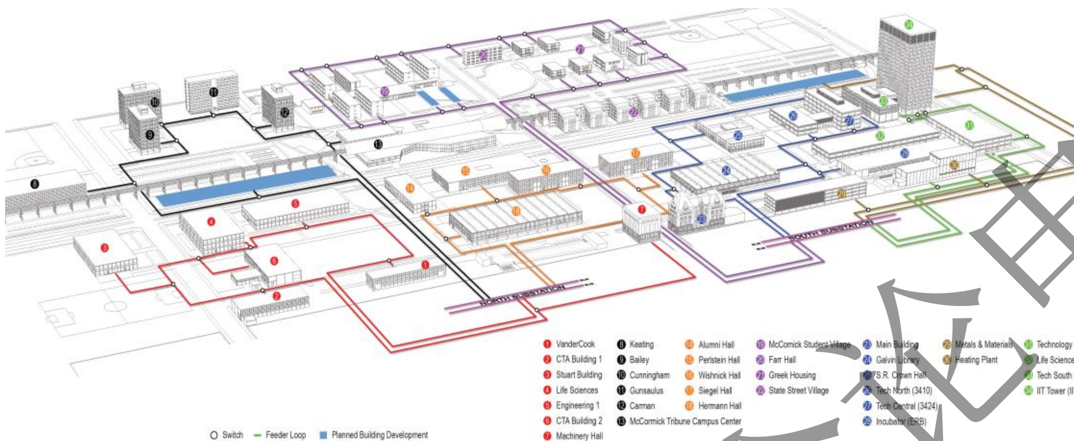


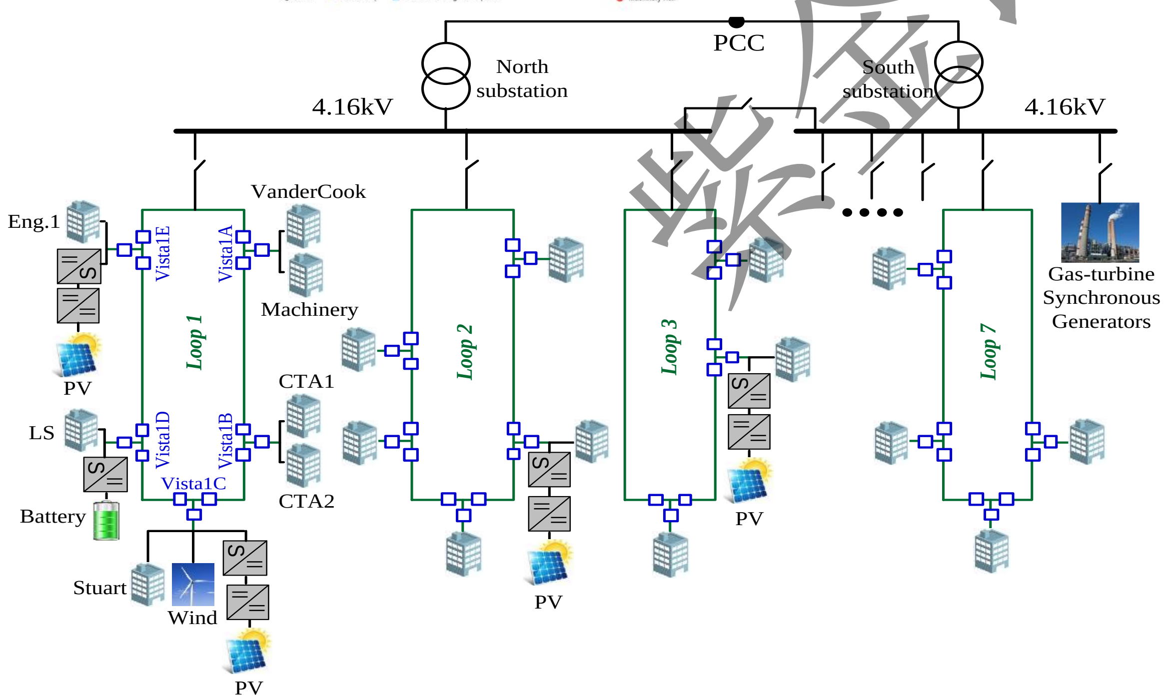
Formation of Microgrids

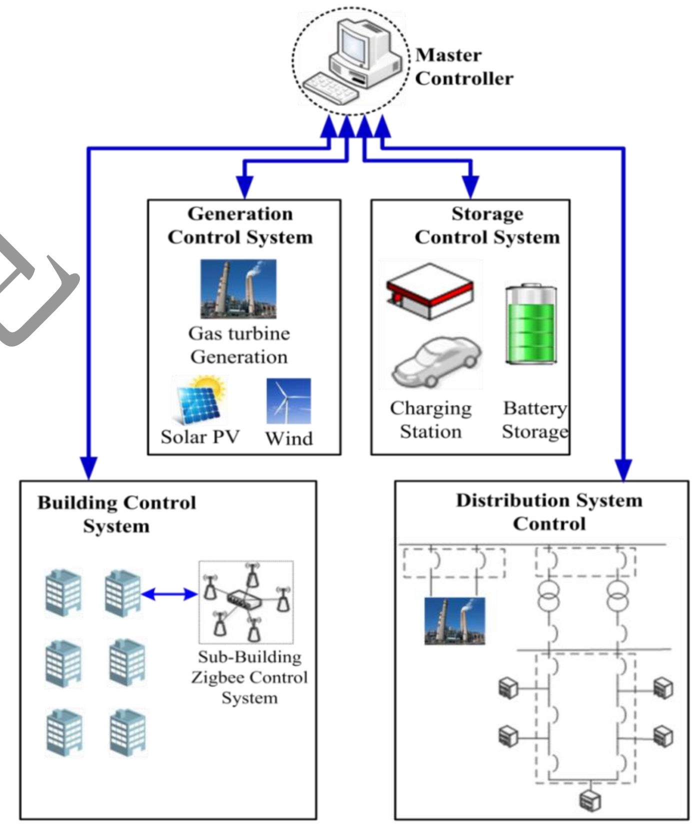
- Microgrids are small-scale self-controllable power systems that interconnect DERs and loads within clearly-defined electrical boundaries.
- Each microgrid interacts with the utility grid through a point of common coupling (PCC) at its boundary.
- Each microgrid is deployed with a microgrid master controller (MGMC) for centrally monitoring and controlling on-site resources.



Loop-Based Microgrid Control

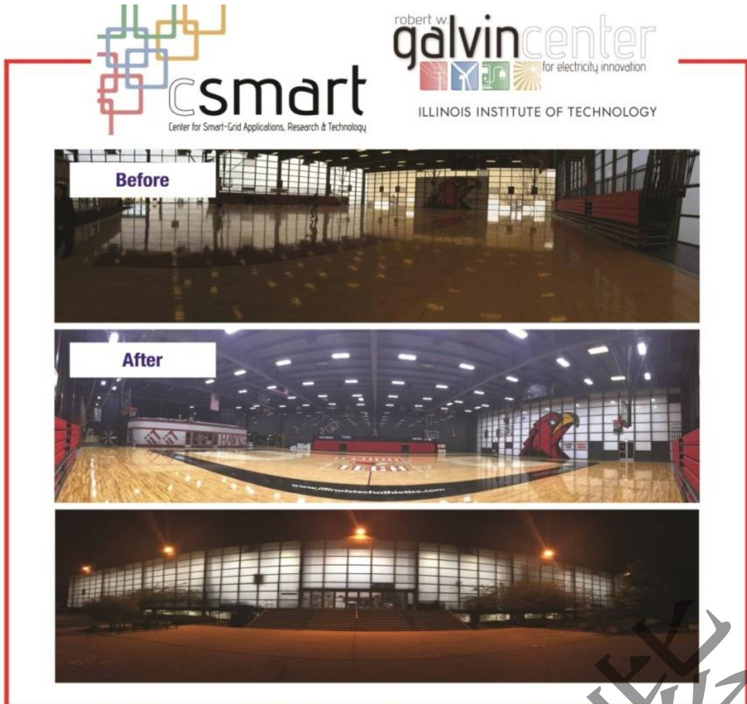


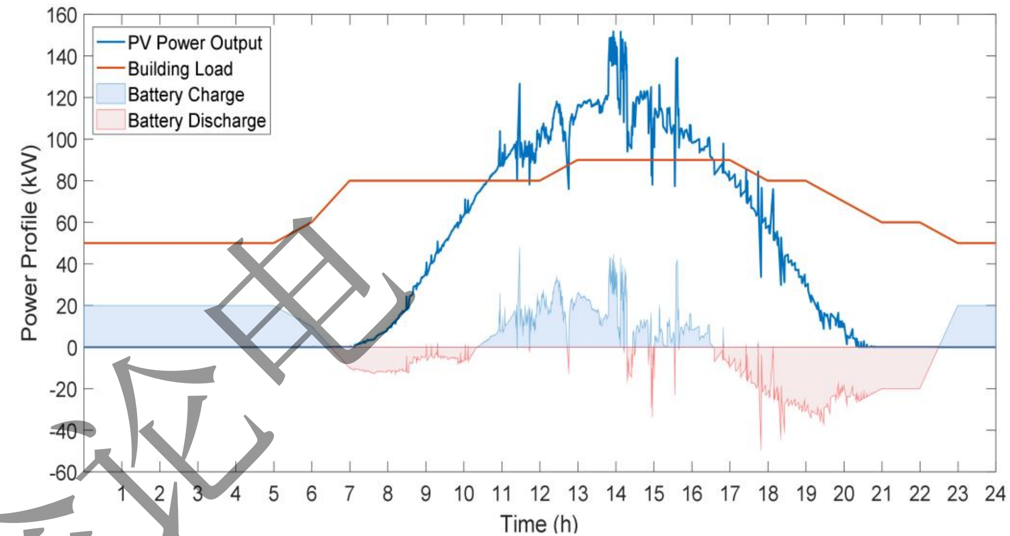


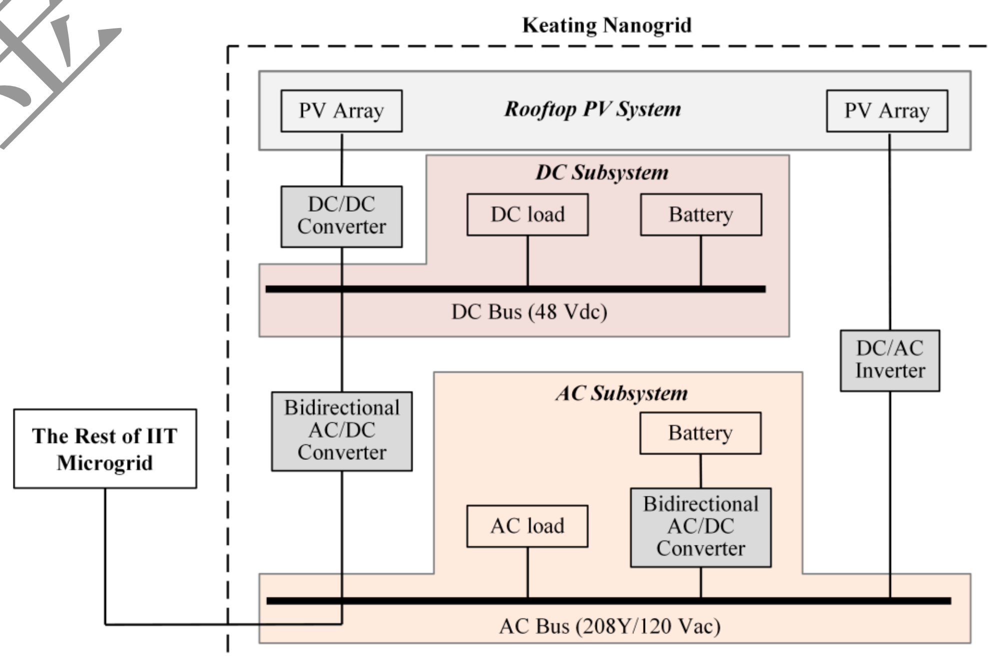


Loop-based microgrid topology introduces additional benefits in enhancing the reliability and resilience of energy supplies.

Operation of Control of Nanogrid

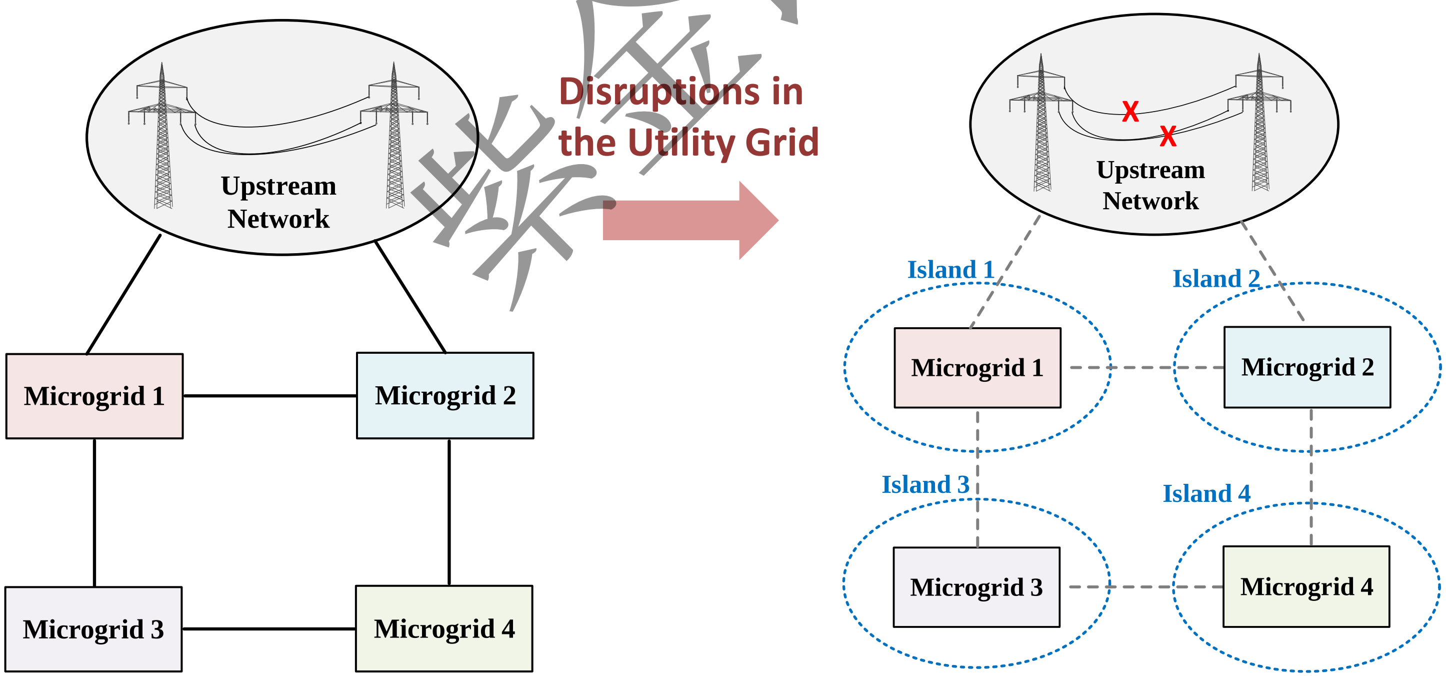






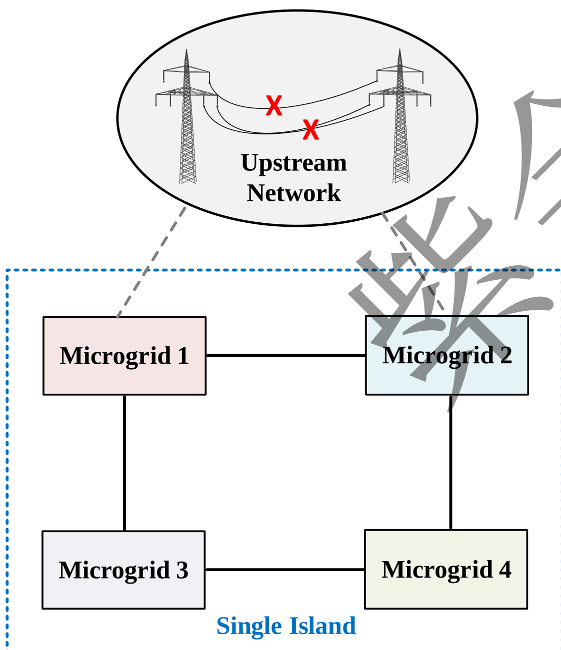
Microgrid Compartmentalization in Emergency Conditions

- Microgrids normally operate in coordination with the utility grid. In cases of utility grid disruptions, each microgrid can island itself and operate independently for sustaining power supplies to local customers.
- Local controllers (LCs) are implemented in each microgrid for realizing finer-grained monitoring and control functions in the island mode.

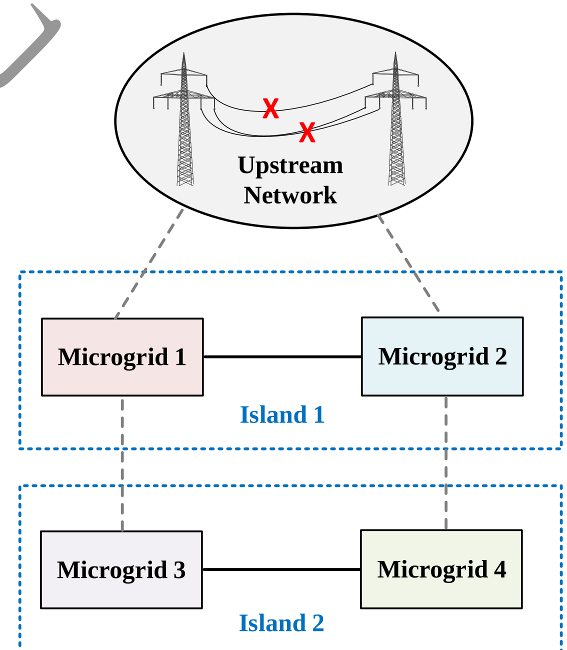


Dynamic Islanding Schemes

- In each aggregated island, interconnected microgrids are enabled to transact energy directly and flexibly for surviving utility grid disruptions.
- The islanding scheme could be adjusted on an on-going basis according to temporal operation characteristics of individual microgrids and the progression of failures in the utility grid.



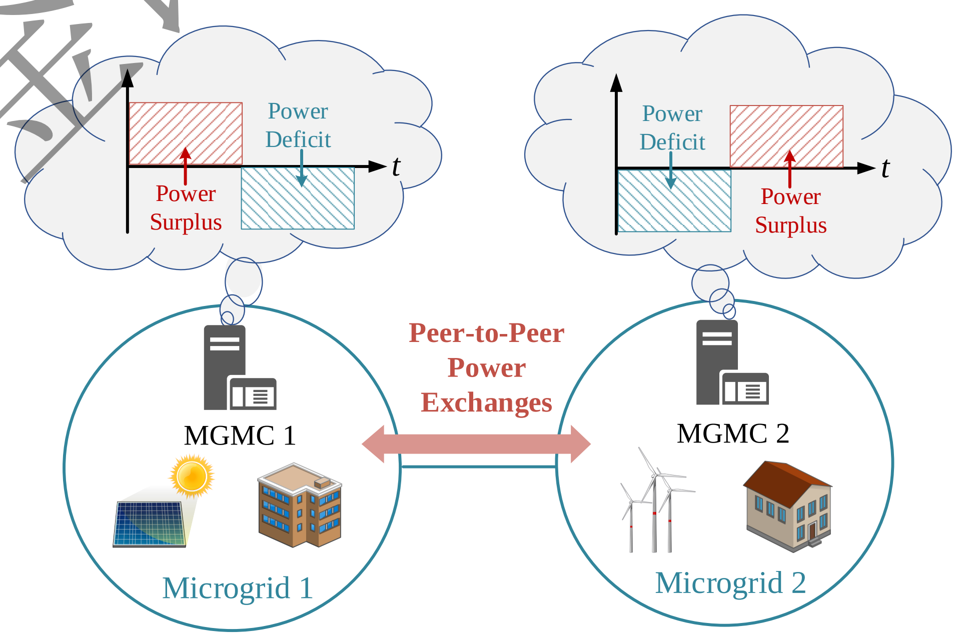
Islanding Scheme A



Islanding Scheme B

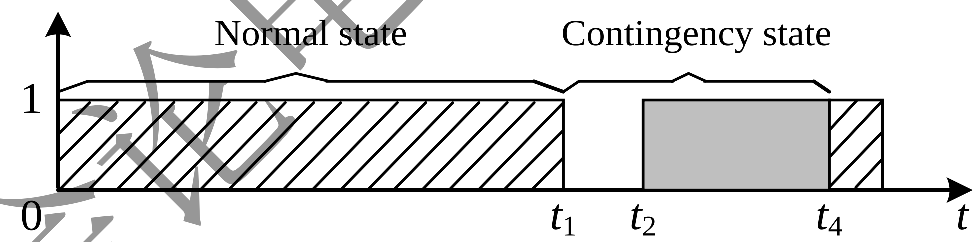
Islanded Power Systems: Peer-to-Peer Power Transactions

- Networked microgrids may often feature diversified profiles of renewable energy generation and power demand.
- Microgrids should be allowed to trade energy directly with their peers (especially when the utility grid is disrupted) in addition to exchanging energy at pre-specified rates with the utility grid.
- With non-discriminatory peer-to-peer energy transactions, microgrids would not only gain an additional degree of flexibility in their operations but also maintain a dynamic power balance in their service territories with reduced dependency on the utility grid.

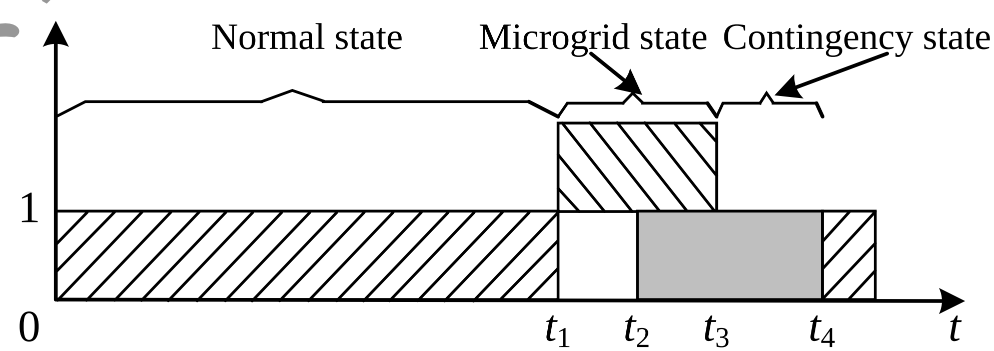


Islanding for Sustaining Local Power

- After isolation from the disrupted utility grid, microgrids sustain local power services by utilizing on-site resources, especially renewable energy-based distributed energy resources (e.g., wind, solar, biomass).
- Islanding the microgrids strategically can also curb the progression of failures and prevent the deterioration of utility grid operating conditions.
- Islanded microgrids will be reconnected to the utility grid seamlessly once the effects of disruptions are completely eliminated at the utility grid side.



Without Microgrids



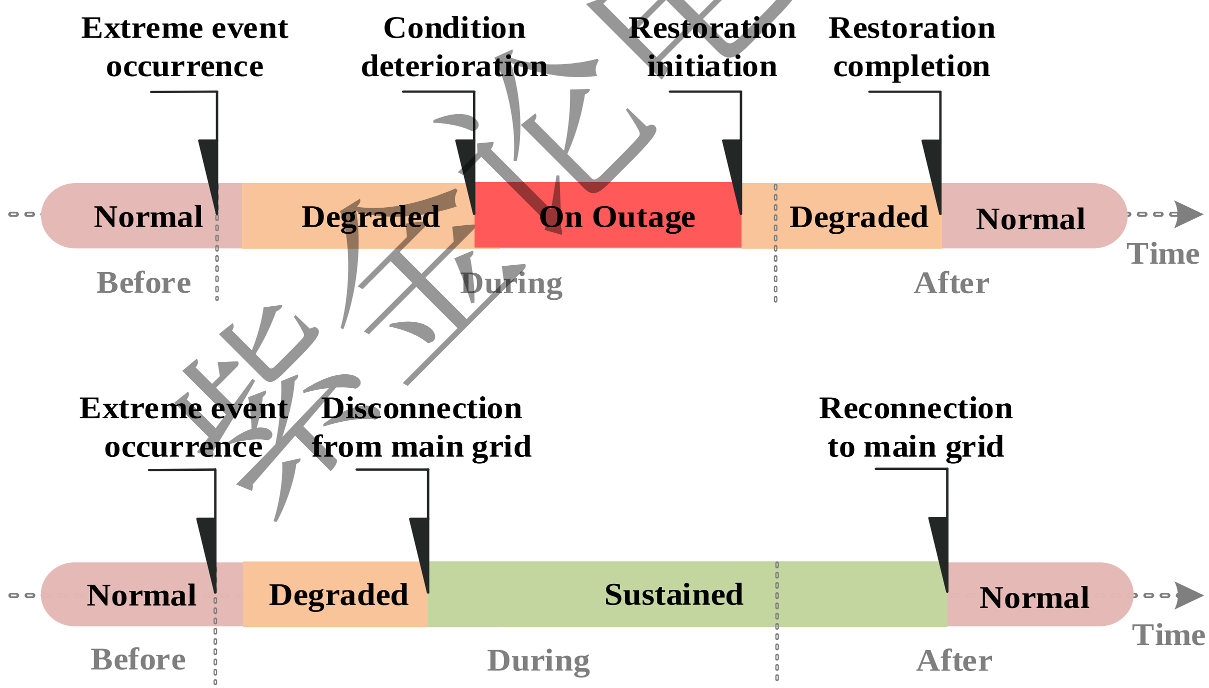
With Microgrids

Microgrid Emergency Operating Conditions

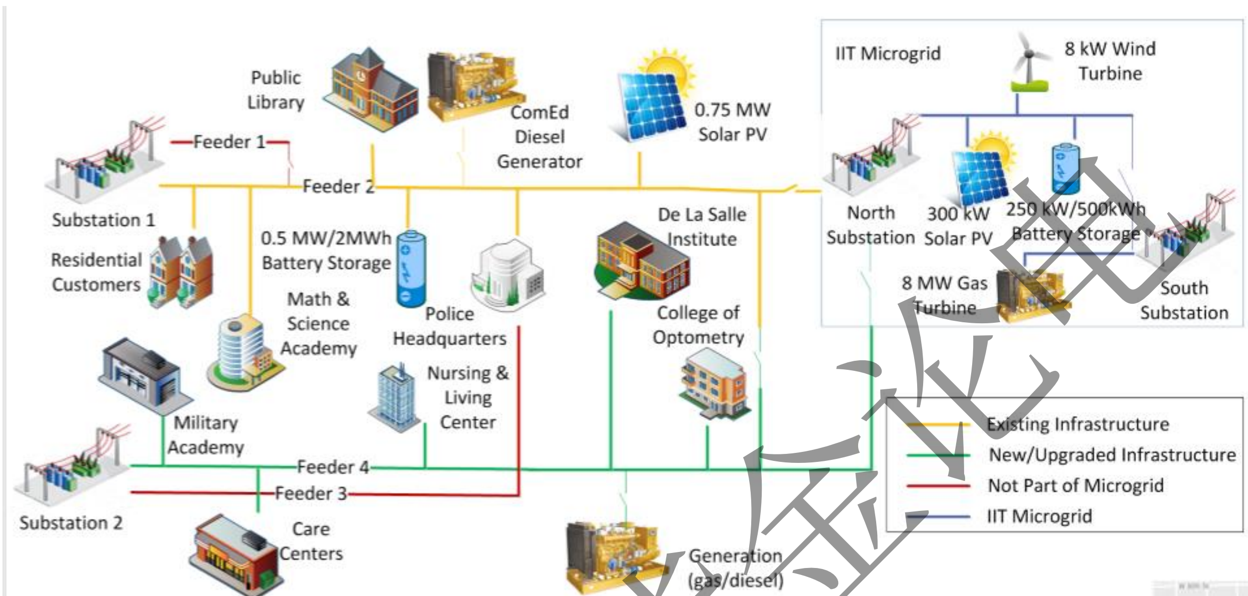
- During the extreme event, the system performance suffers a continuous degradation as the disruptions are prolonged.

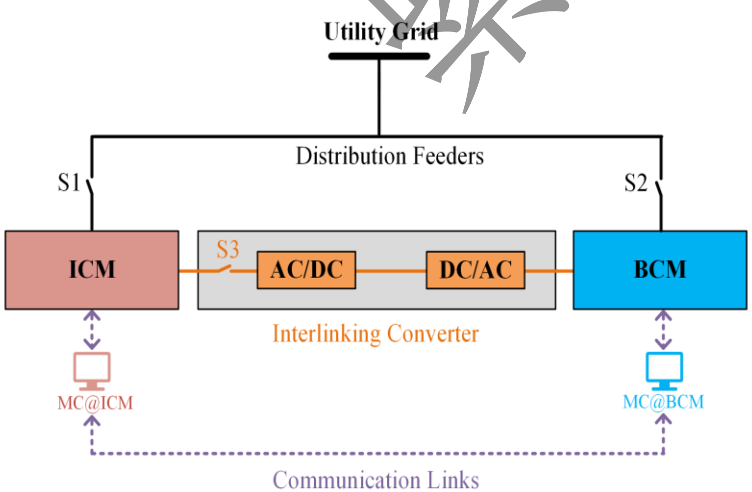
Outside Microgrid

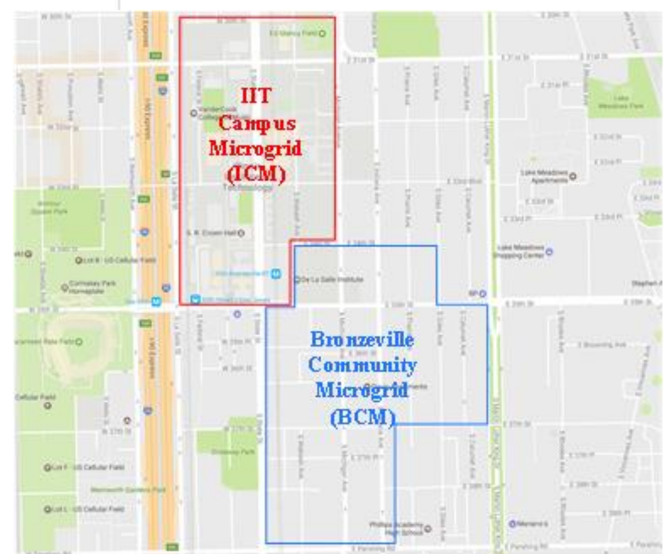
Inside Microgrid



Networked Microgrid Operation

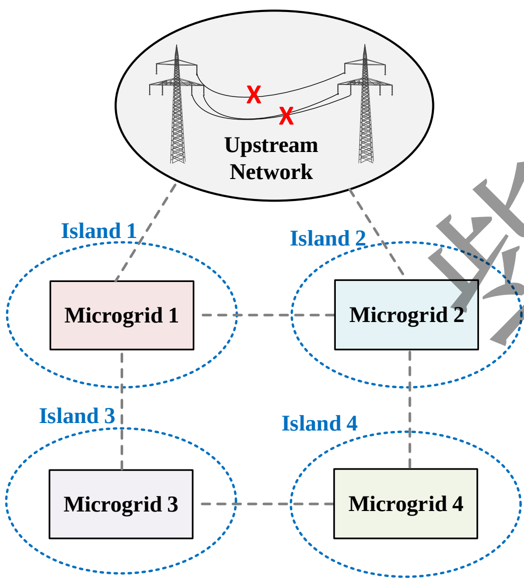




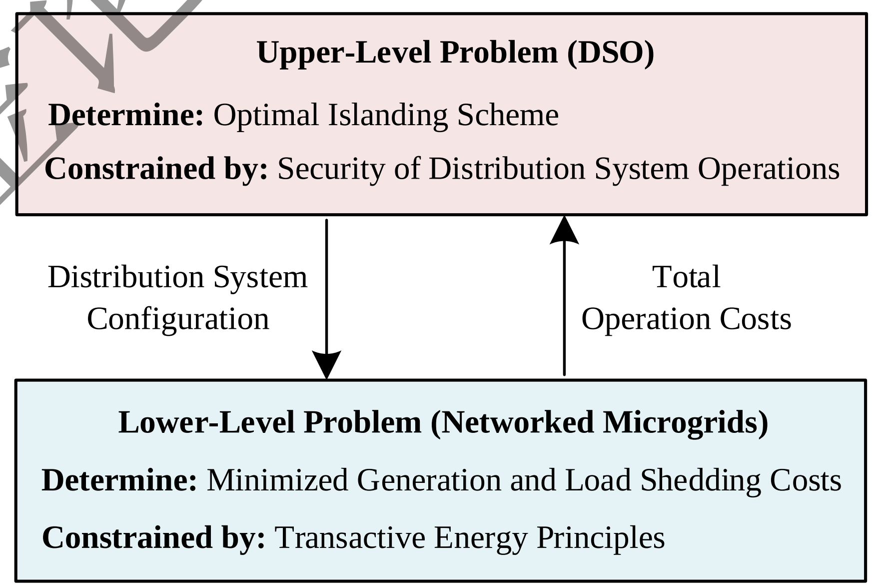


Decision for Optimal Islanding

- Transactive energy facilitates the formation of aggregated islands of multiple microgrids, boosting the flexibility of the islanding process.
- DSO determines and triggers the islanding of networked microgrids in a holistic manner by considering the role of transactive energy, instead of forcing islanded microgrids to rely solely on themselves.



Flexible Energy Trading



Two-Layer Decision-Making Scheme

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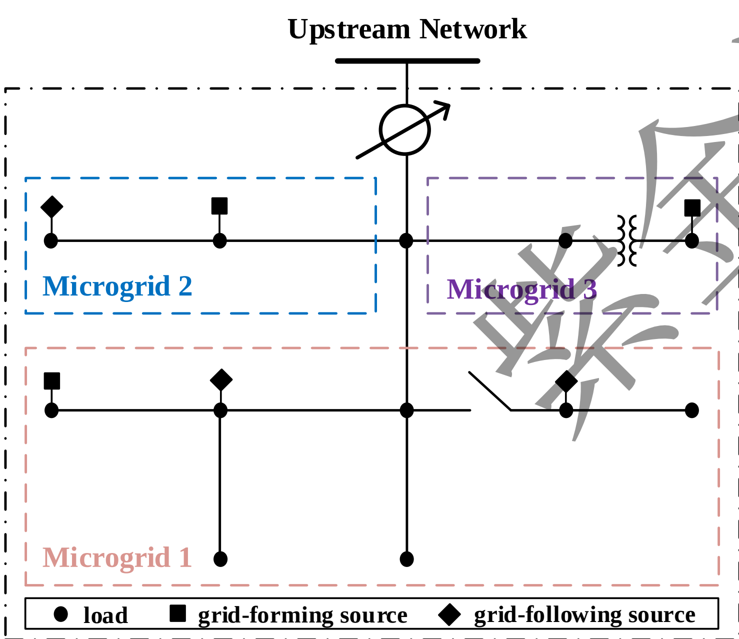
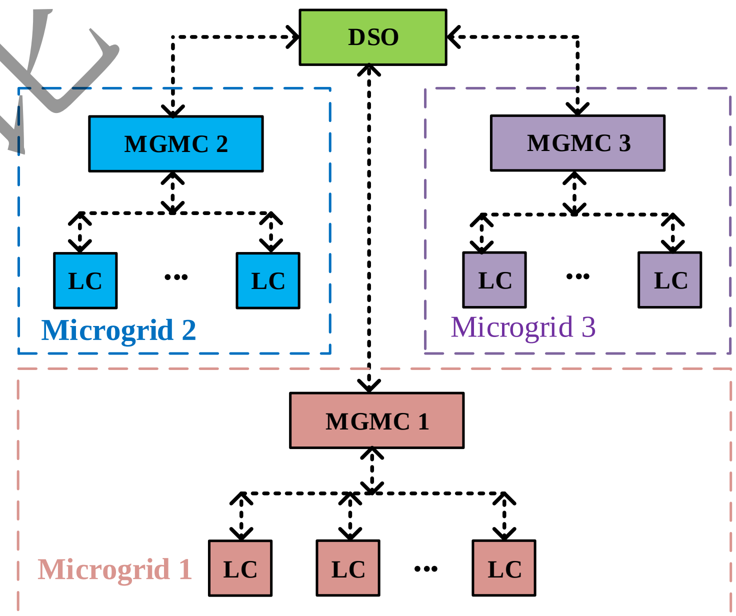
DSO for Networked Microgrids

- Microgrids located in a region can be networked to further improve the efficiency, sustainability, reliability, and resilience of electricity services.
- Networked microgrids would be centrally managed by a distribution system operator (DSO).



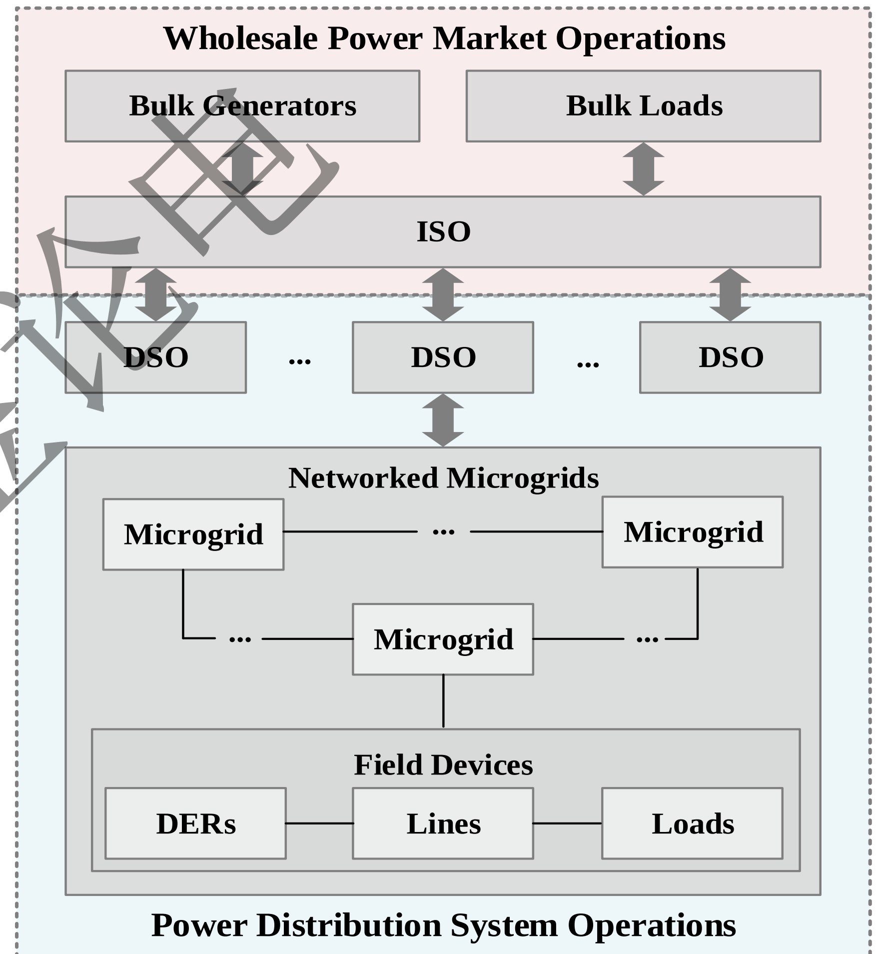
Power Domain



Communication & Control Domain

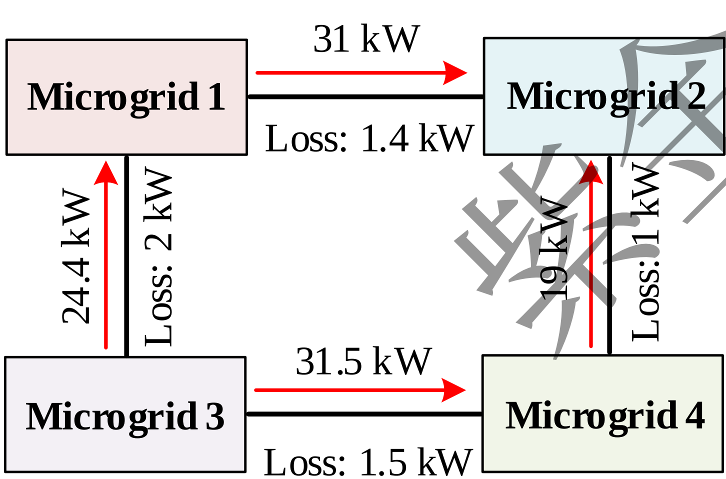
DSO in Power Distribution Systems

- DSO serves the role of tying networked microgrids with bulk power transmission systems.
- DSO gains a holistic view of power distribution system operations and supervises networked microgrids via secure bidirectional communications.
- DSO participates, on behalf of networked microgrids, in the upstream wholesale power market for maximizing the social welfare of the associated power distribution system.

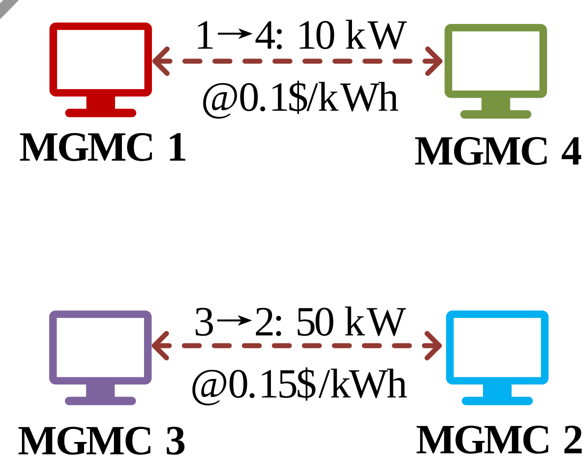


Peer-to-Peer Energy Flow

- Networked microgrids collaborate based on dynamic market signals in a quest for refining electricity services across their service territories.
- The design of transactive energy models is subject to domain-specific physical constraints in addition to common market rules.



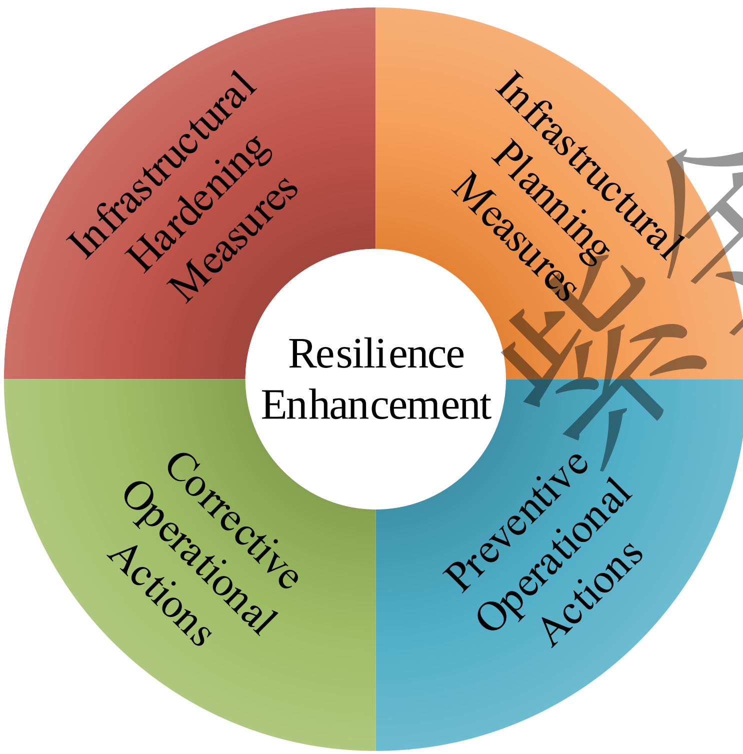
Power Flows

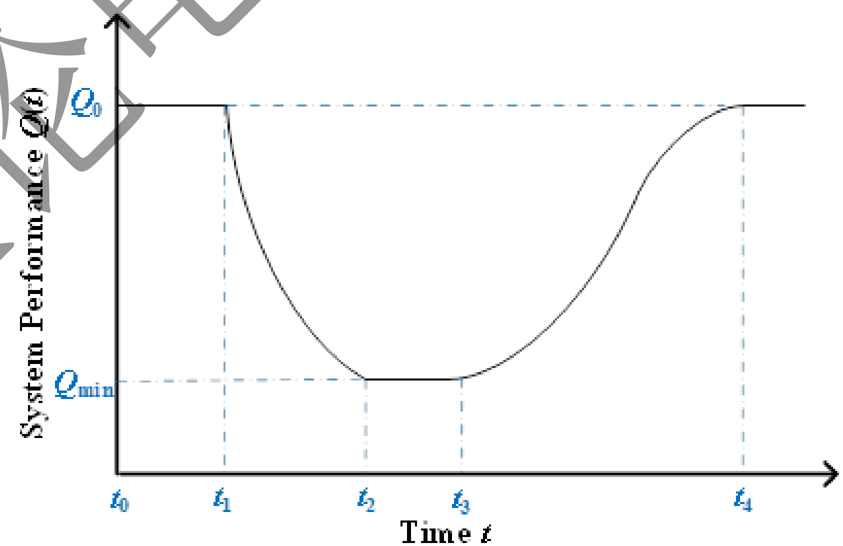


Energy Transactions

Microgrids for Distribution System Enhancement

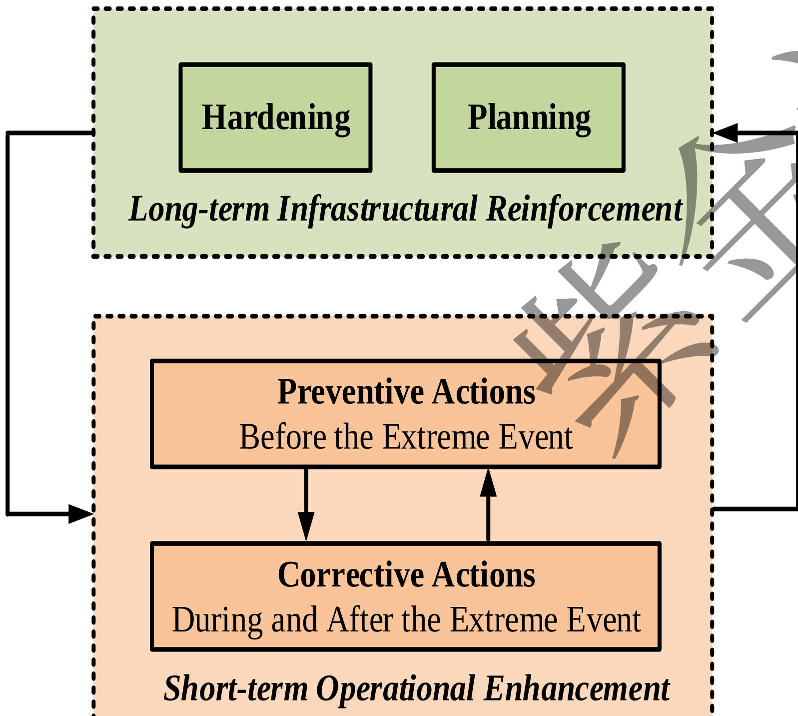
- The unique benefits of networked microgrids are manifested in supporting power system resilience are further explored.





Integrated Decision Framework

- In order to determine the most cost-effective solution to achieving the power system resilience to an extreme event, we consider the interdependency of infrastructural and operational measures, and the interactions of preventive and corrective actions.



- This multi-layer framework presents an inherent leader-follower relationship between infrastructural reinforcement and operational enforcement.
- In order to discover the optimal combination and the sequences for implementing the resilience enhancement measures, stochastic optimization or robust optimization problems can be formulated within this framework.

System Resilience Enhancement

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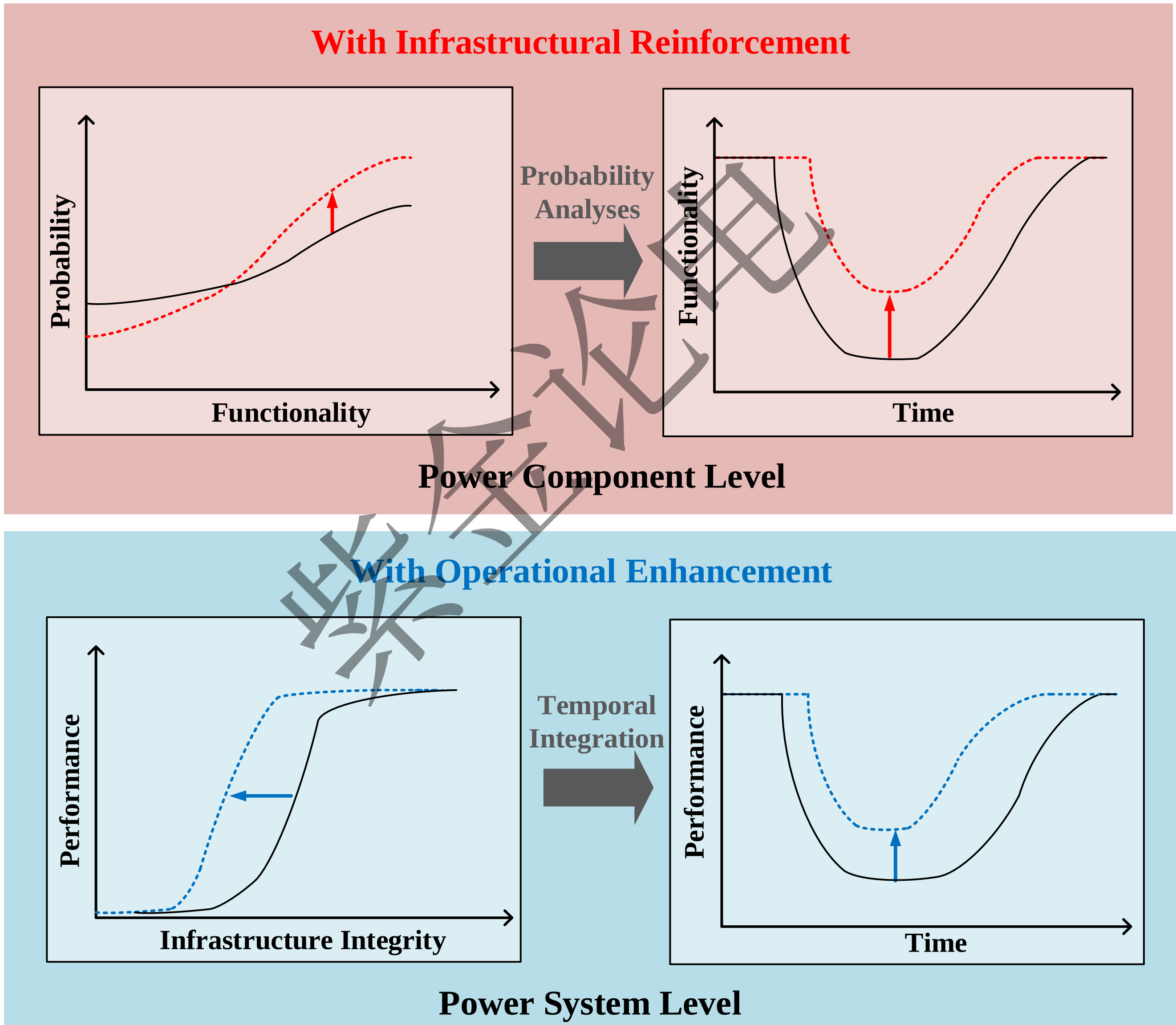

Conclusions

- The development of networked microgrids will drive the conventionally centralized systems to migrate toward distributed localized systems, together with the significant changes in power system management.
- Resilience, as a key attribute of Smart Grid, is central to the efforts into modernizing power systems in the face of the growing number of widespread outages due to extreme events.
- Data analytics will play a key role in managing the power systems resilience via distributed power systems.
- Additional methods and solutions would have to be developed for managing the myriad of data presented in microgrid operation and planning.