武漢大學
WUHAN UNIVERSITY

Research and Development of Microgrid Clusters in China

Xuzhu Dong

Wuhan University

Finland, 2026

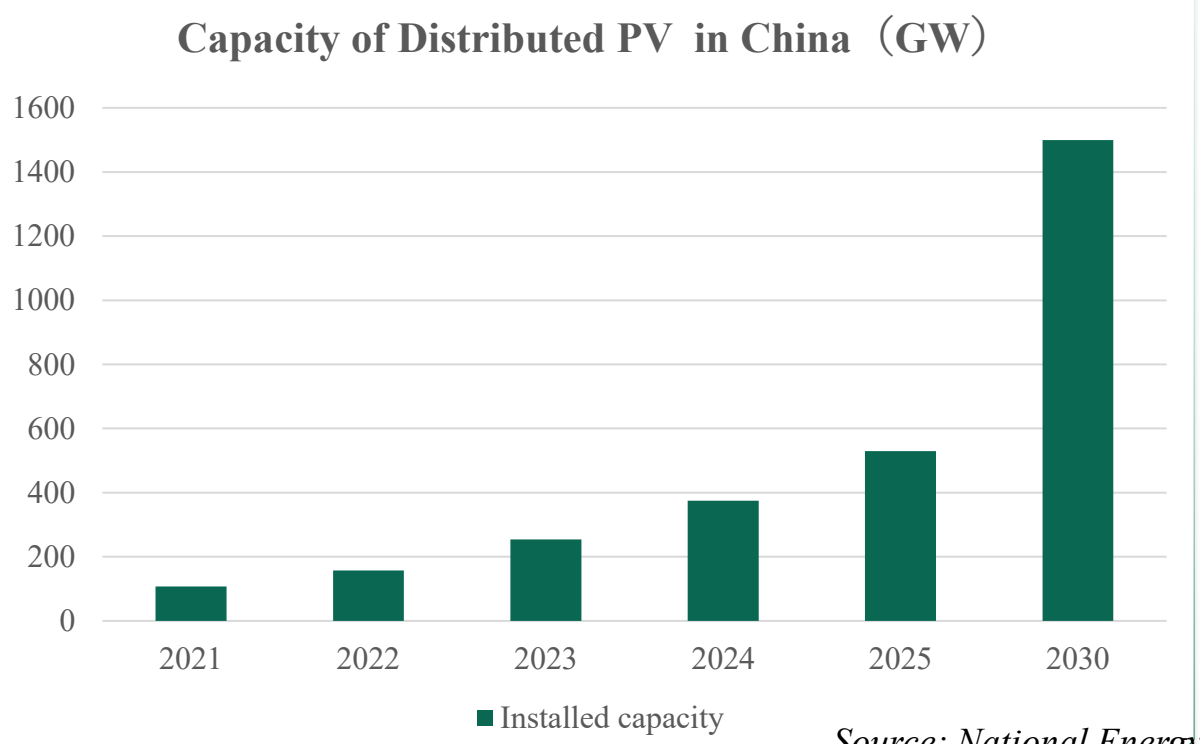
Outlines

1. Background and Motivation
2. Key Technologies
3. Demonstration Projects
4. Conclusion

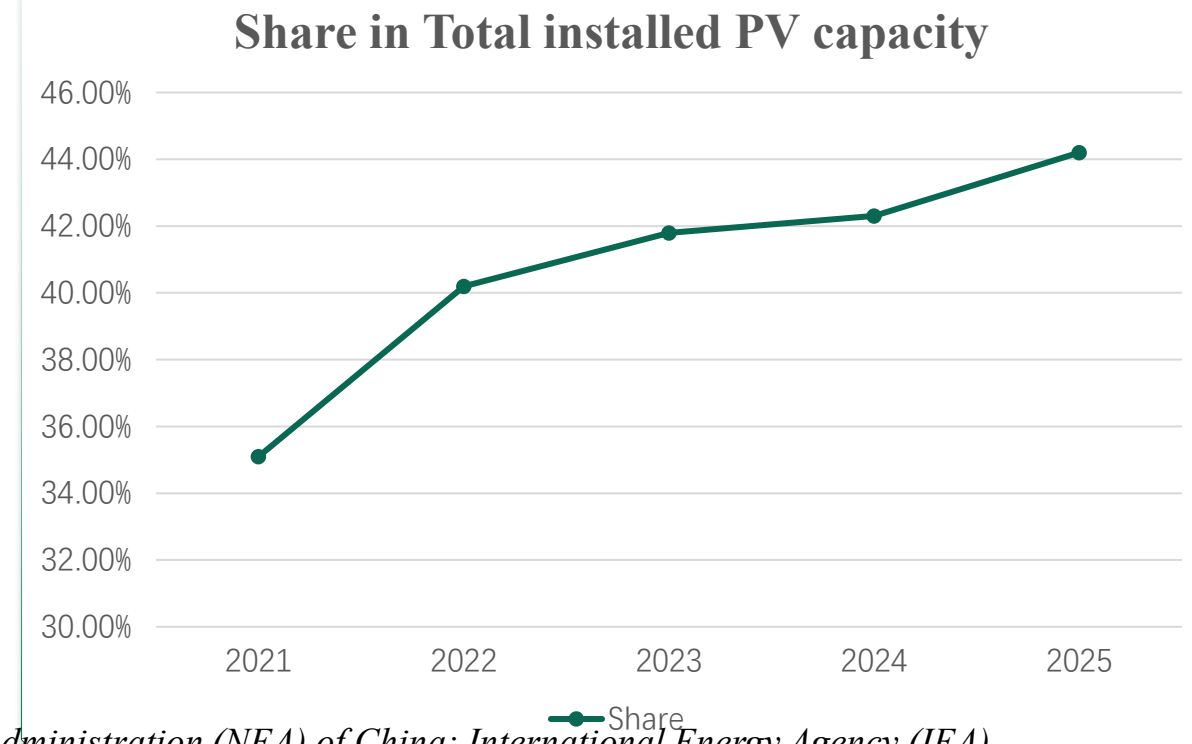
Development of Distributed Renewable Resources in China

- **Driven by the goals of carbon peaking and carbon neutrality, total installed capacity of distributed renewable energy increases quickly.**
- **Annual growth rate of distributed PV keeps over 40% in last five years, and total installed capacity of distributed PV was 530GW by the end of 2025. Distributed wind power was 20GW so far, with a potential explorable capacity of 3000GW.**

Growing Distributed PV Capacity



Share of Distributed PV Capacity

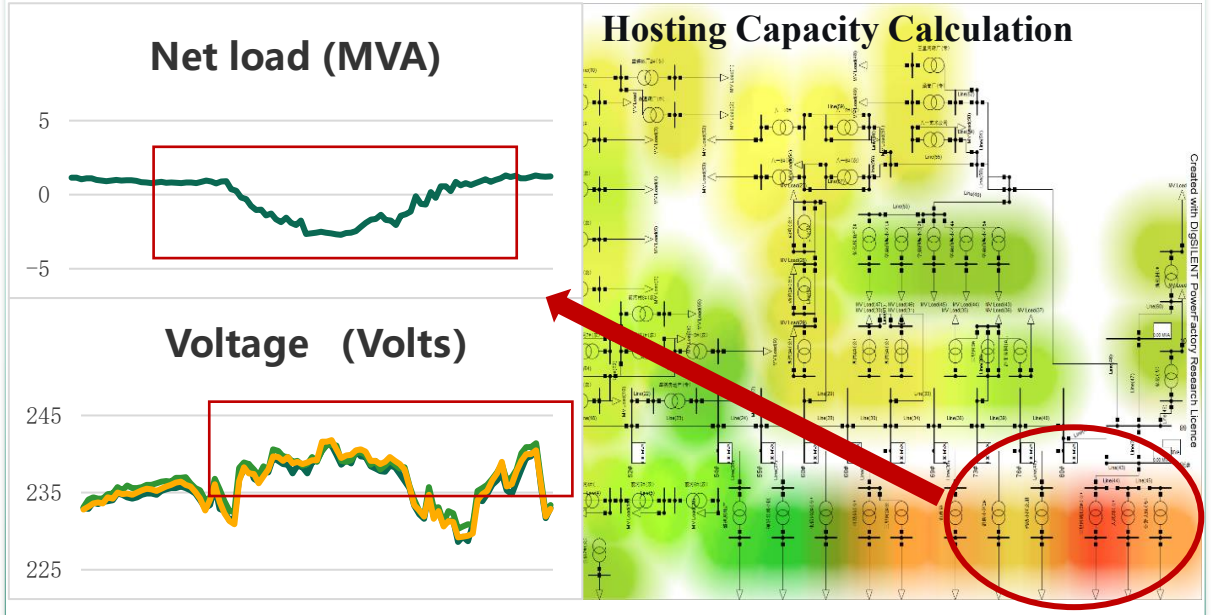


Source: National Energy Administration (NEA) of China; International Energy Agency (IEA)

Microgrids for Integration of Distributed Renewable Resources

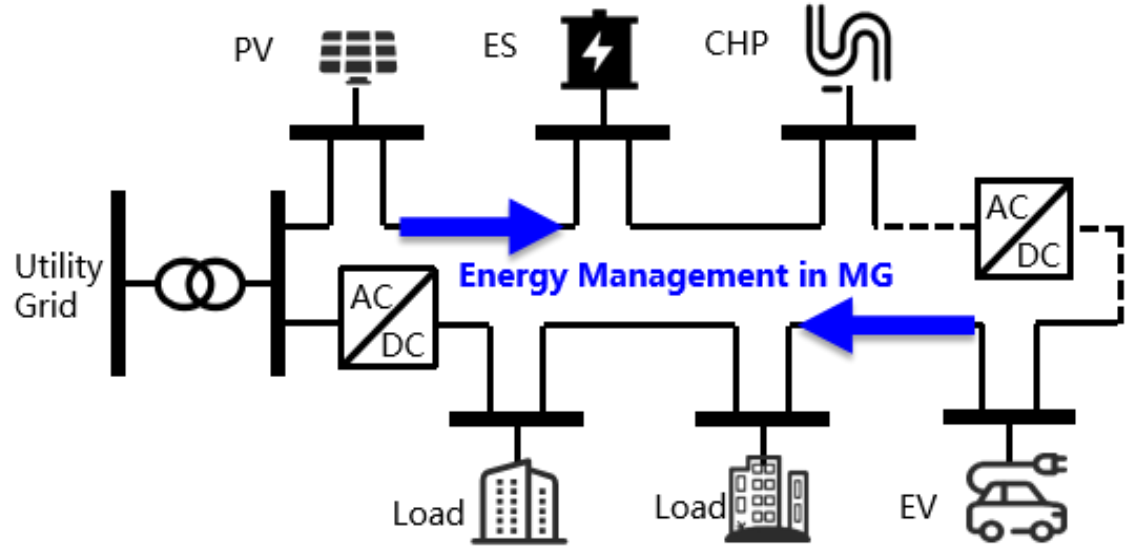
- With integration of increasing PV, a series problems have emerged in Yunnan, Shandong, and other provinces, such as reverse power flow, feeder overvoltage, protection mis-operation.
- Microgrids, with their **self-balancing, self-coordination, self-control and self-management** capabilities, offer an **ideal pathway for PV integration**.

PV Reverse Power Flow and Voltage Violation



Source: PV Net Load and Voltage Curves in a Certain Area of Heqing, Yunnan, China

Microgrids



Self-balancing | **Self-coordination and control** | **Self-management**

From Microgrids to Microgrid Clusters

- **Practical Needs：** Given the limited integration capacity of a single microgrid and the **natural source-load complementarity** among multiple microgrids, the formation of cross-voltage and cross-regional microgrid clusters via wide-area interconnection has emerged in downtowns, industrial parks and villiages.

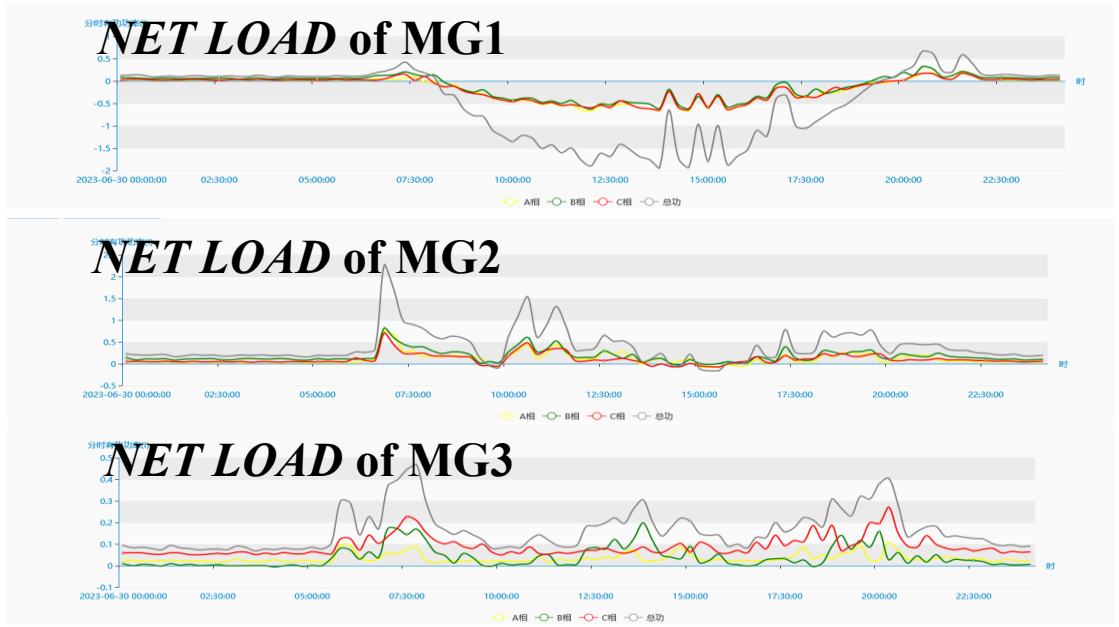
Spatial Distribution of Microgrids



MG1	MG2	MG3
PV(372kW)	PV(92kW)	PV(22kW)
>Load(115kW)	~Load(102kW)	<Load(98kW)

Case: Heqing, Yunnan, China

Source-Load Matching in Microgrids



Differences usually bring about complementarity.

From Microgrids to Microgrid Clusters



Downtown, Blocks - Cluster



Suburb, Districts - Cluster



Industrial parks, Zones - Cluster



Towns, Villiages - Cluster

From Microgrid to Microgrid Clusters

- **Policy Guidance：** Development of microgrids and their clusters has been clearly addressed by China Government. It is projected that by 2030, China's microgrid clusters will enable integration of over 900 GW of distributed renewable energy.
- **Standardization of Microgrid (clusters)：** A series of standards related to microgrid (clusters) have been published in China, including planning, operation, control, market， and equipment.

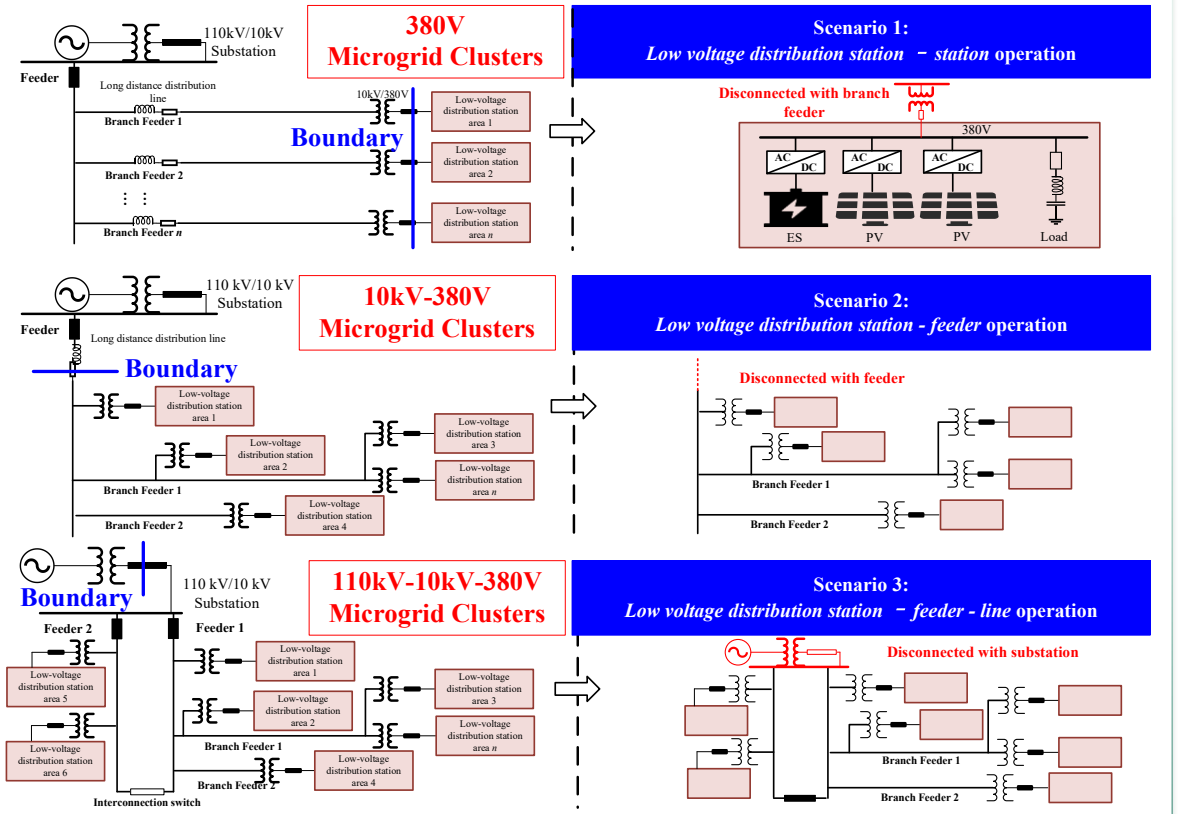
Microgrid (clusters) Standards

Standard No.	Title	Main Content
GB/T 33589-2017	Technical Requirements for Microgrid Connecting to Power System	General principles and technical requirements for microgrid connecting to power system, applicable for voltage levels up to 35 kV
GB/Z 44789-2024	Dynamic Control Requirements for Microgrids	Requirements for frequency and voltage dynamic control, applicable for AC microgrids up to 35 kV
GB/T 42731-2023	Technical Requirements for Microgrids	Basic technical requirements for microgrid systems
GB/T 41995-2022	Technical Specification for Operation Characteristics Evaluation of Grid-Connected Microgrids	Evaluation methods for operation characteristics of grid-connected microgrids
GB/T 43333-2023	Commissioning and Acceptance Specification for Stand-Alone Microgrids	Commissioning procedures and acceptance standards for stand-alone microgrids
GB/T 43334-2023	Technical Requirements for Energy Management System of Stand-Alone Microgrids	Technical requirements for EMS of stand-alone microgrids
GB/Z 34161-2017	Technical Guide for Smart Microgrid Protection Equipment	Technical guidelines for protection equipment in smart microgrids
GB/T 36270-2018	Technical Specification for Microgrid Monitoring and Control Systems	Technical requirements for microgrid monitoring systems
GB/T 36274-2018	Technical Specification for Microgrid Energy Management Systems	Technical requirements for microgrid EMS
GB/T 33593-2017	Technical Specification for Operation Control of Grid-Connected Microgrids	Technical requirements for operation control of grid-connected microgrids

MG Cluster Challenge 1:
Topology flexibility and complex operation

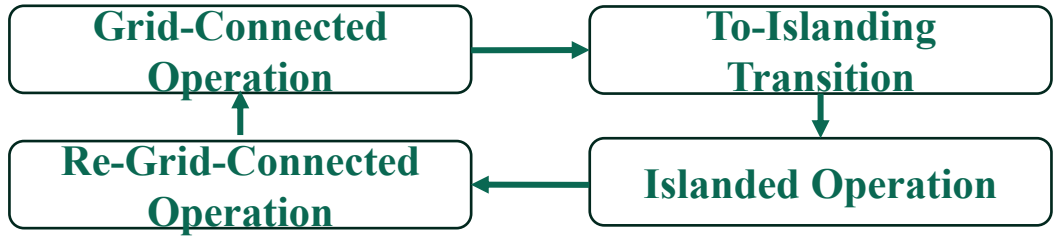
- **Dynamic topology** and **complex operation modes** are the typical features of microgrid clusters.

Dynamic Topology

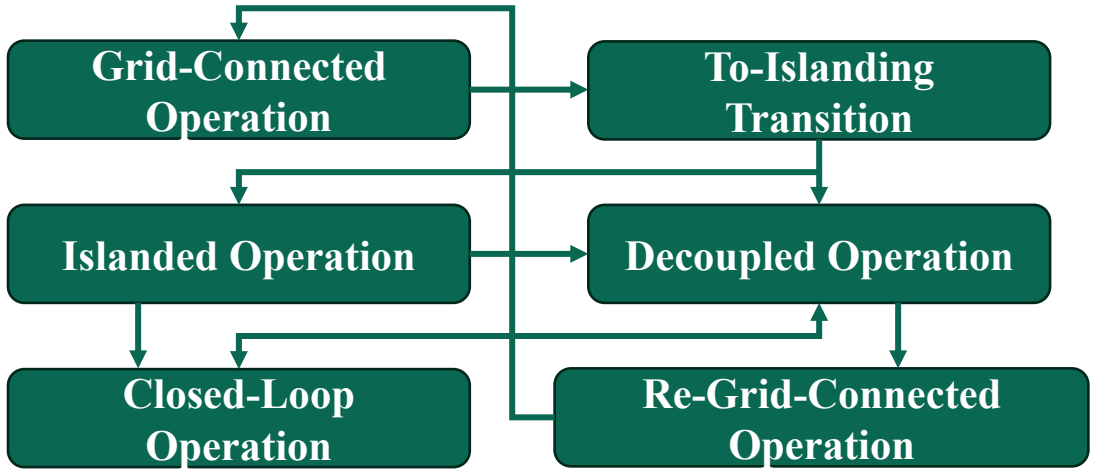


Complex Operation Modes

Microgrid:



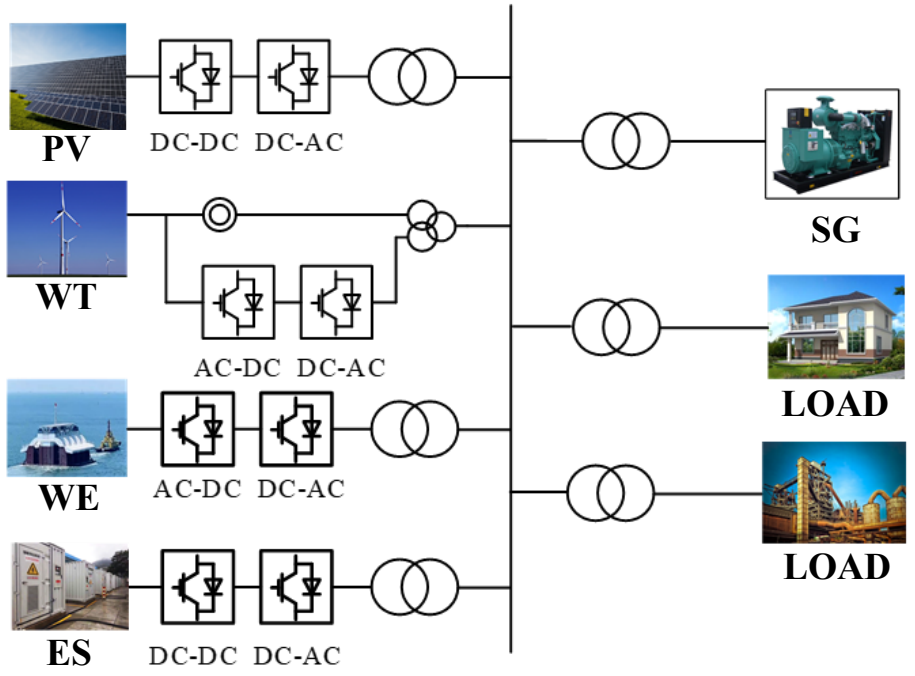
Microgrid Clusters:



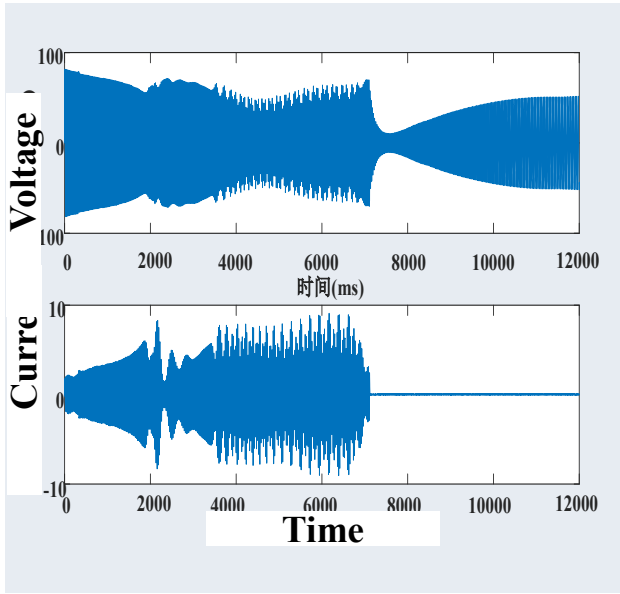
Challenge 2:
Stable Operation with Multiple Power-Electronic Inverters

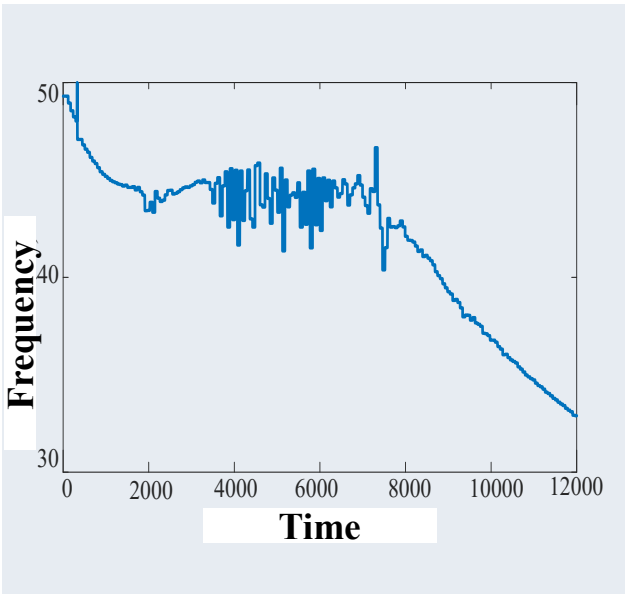
- **High penetration of power electronic devices results in low inertia and weak damping, and then risk to operation safety and stability.**

High-Penetration Power Electronics



Low equivalent inertia → Transient instability

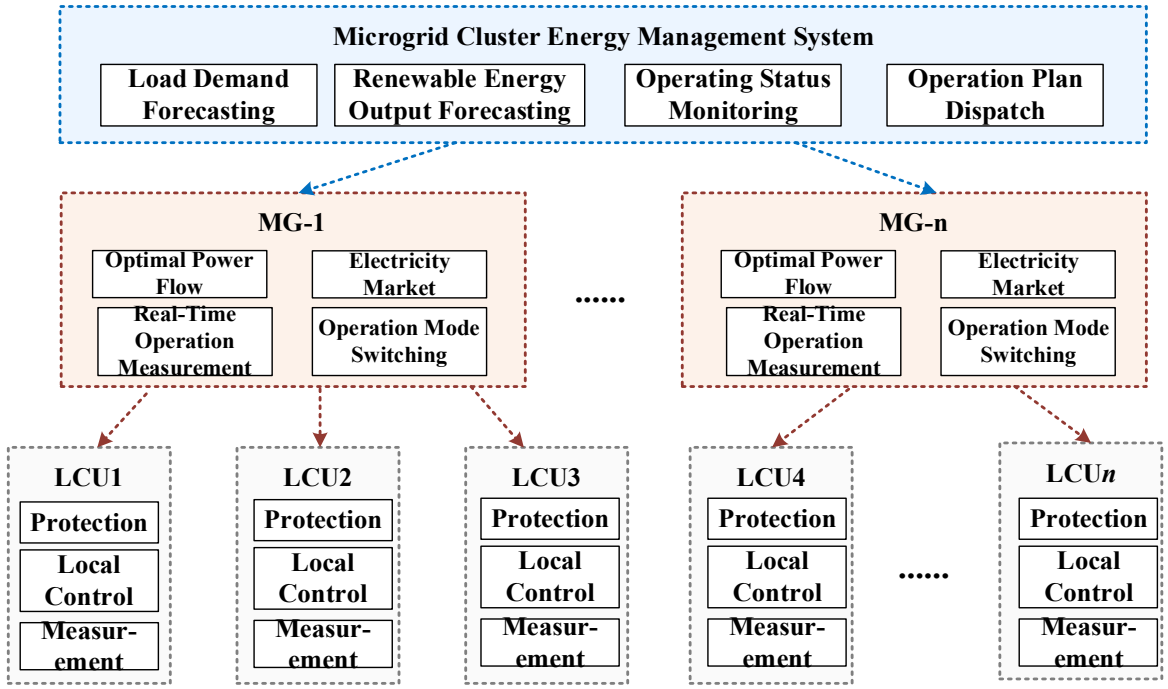


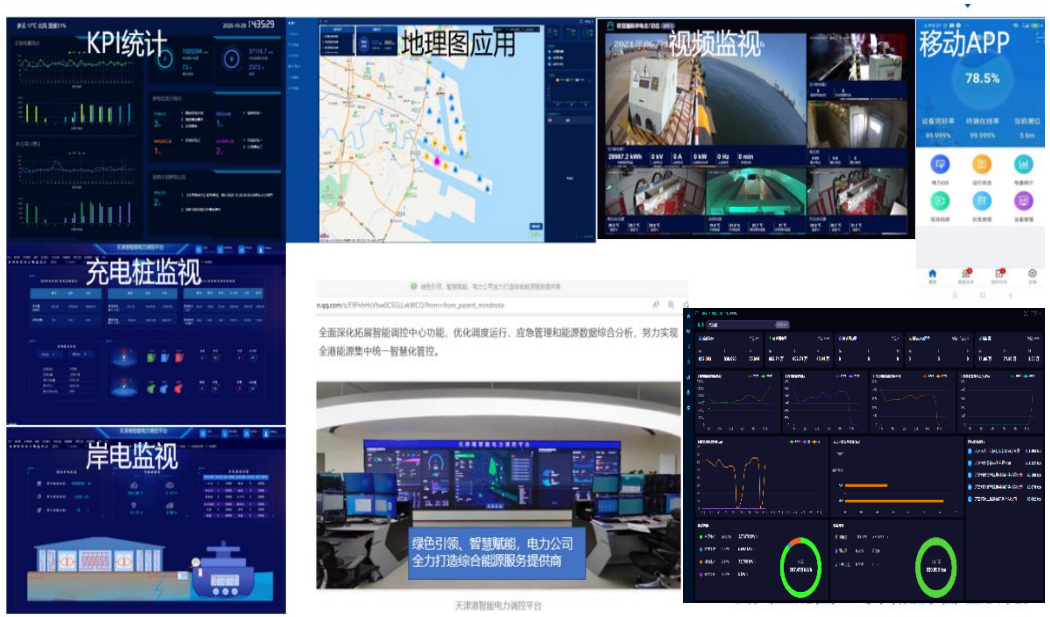


Challenge 3:
Balancing Low-Carbon and Preventive Security under Uncertainties

- Microgrid clusters require **low-carbon** operation under multi-energy uncertainties. Application of **preventive security constraints** is essential to enhance system safety and stability.

Energy Management System for Microgrid Clusters





R&D Framework

Flexible and Adaptive
Microgrid Topology

1、Microgrid Cluster Formation

- AC Microgrid Cluster Formation
- Hybrid AC/DC Microgrid Cluster Formation

Stable and Efficient
Operational strategy

2、Microgrid Cluster Operation

- Source-grid-load-storage Interactive Coordination
- Tie-Line Power Regulation
- Emergency Control

Diversified and Scalable
Power Supply Services

3、AI Application in Microgrid Clusters

- Digital Twin Application in MG Cluster Dispatch and Control
- Microgrid Clusters Status Recognition
- Coordinated Voltage Control on Multi-Agent Reinforcement Learning
- Aggregation, Regulation, and Market Trading of Flexibility Resource in MG Clusters

Outlines

1. Background and Motivation
2. Key Technologies
3. Demonstration Projects
4. Conclusion

1. Microgrid Cluster Formation

Microgrid Cluster Formation

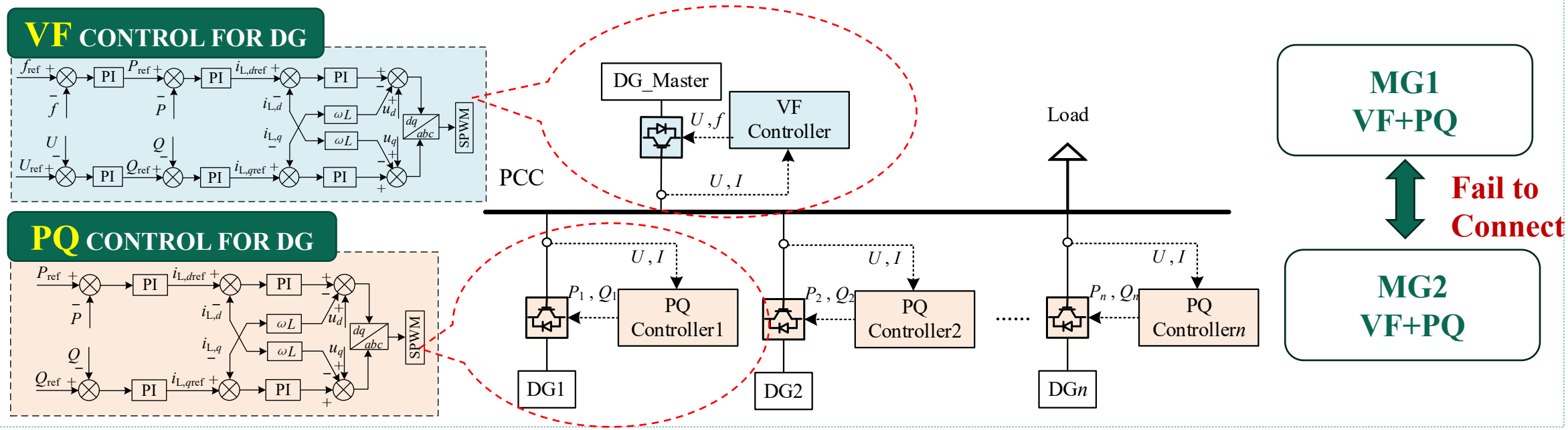
1.1 AC Microgrid Cluster Formation

Problem:

The master–slave control strategy, while it is effective for single-microgrid opeartion, fails to enable wide-area interconnection of microgrid clusters due to control conflicts among master units.

It is fundamentally incapable of adapting to dynamic topologies.

Formation of Microgrid Achieved by Master–Slave Control strategy



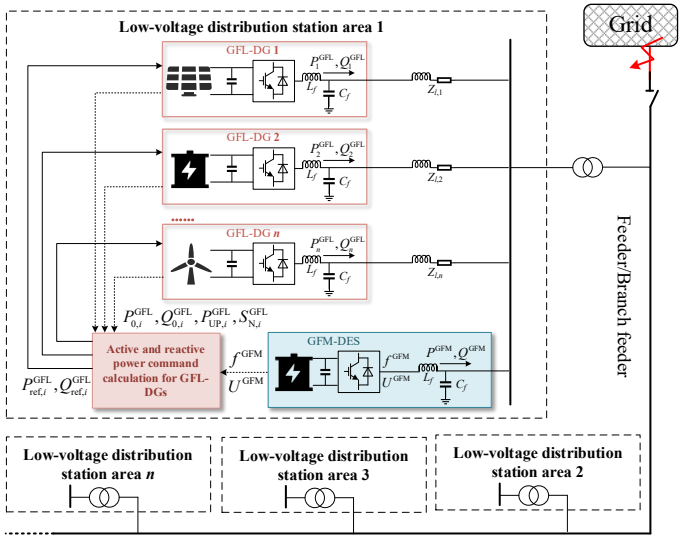
Microgrid Cluster Formation

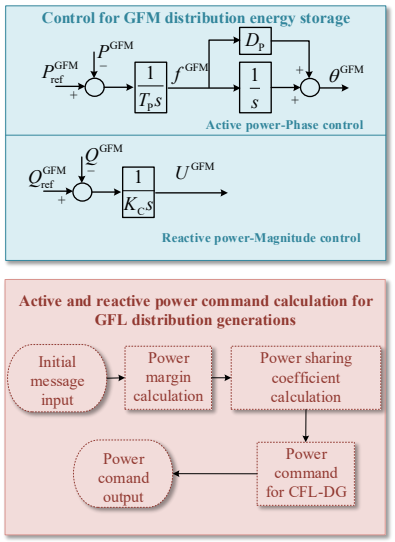
1.1 AC Microgrid Cluster Formation

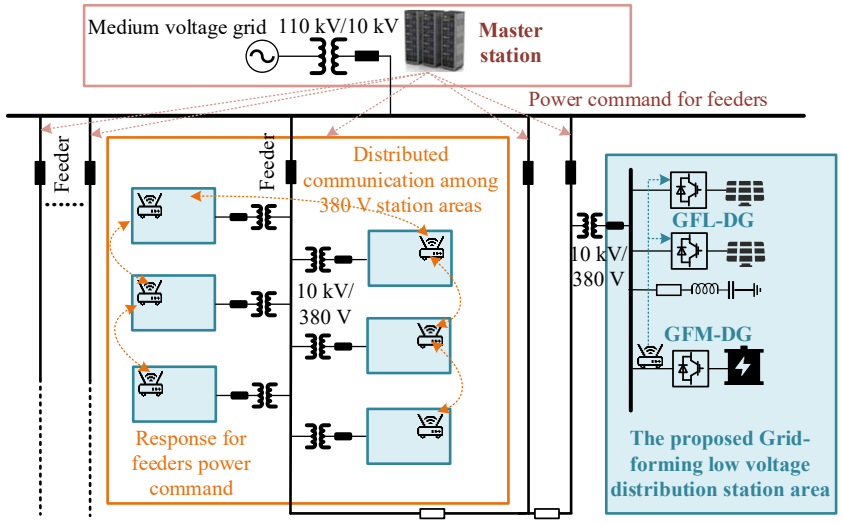
Solution:

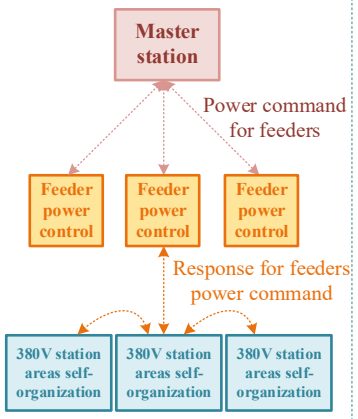
- **Microgrid-Level Control:** Grid-forming Energy Storage + Dynamic Adaptive Droop PV Control→Each microgrid unit exhibits synchronverter-like adaptive interconnection characteristics, rather than a rigid VF source or a slave-type current source.
- **Microgrid-Clusters-Level Control:** Decentralized interactive control is adopted among multiple microgrid units, enabling plug-and-play capability and wide-area power self-balancing for each microgrid unit.

Formation of Microgrid clusters for adaptive parallel operation









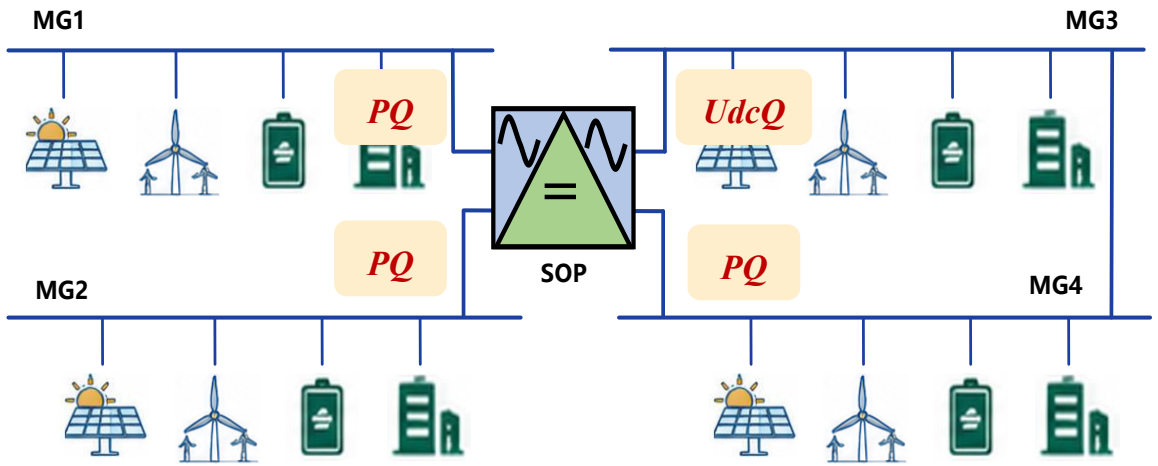
Microgrid Cluster Formation

1.2 Hybrid AC/DC Microgrid Cluster Formation

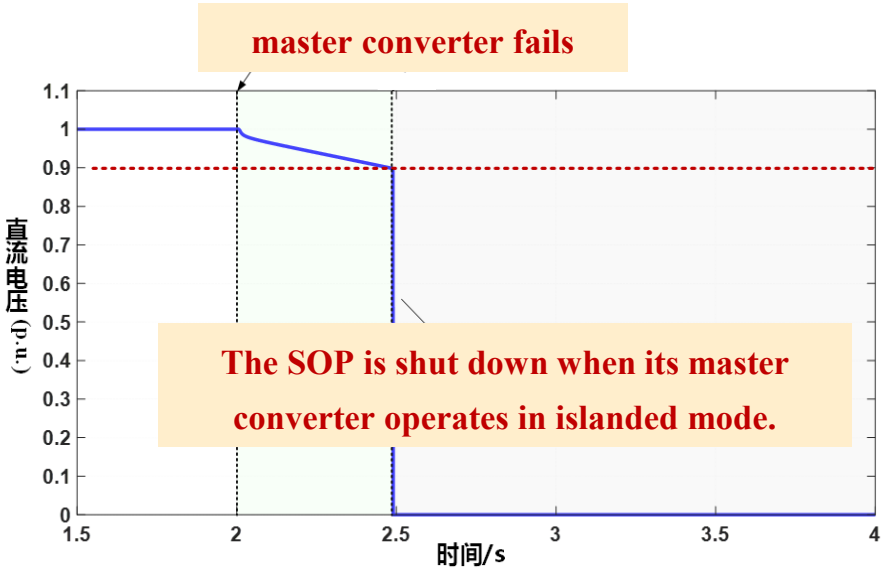
DC interconnection provides new approach for Microgrid Cluster Formation.

Problem:

Hybrid AC/DC microgrid cluster formation mainly relies on Soft Open Point (SOP)-based interconnection switch. However, their **master-slave structure** with typical $U_{dc}Q/PQ$ control makes **stability dependent on master converter**. **Master converter islanding or failure** may therefore **destabilize the system**.



Schematic Diagram of Microgrid Clusters Interconnected via DC Interconnection



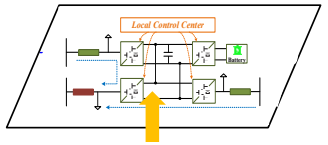
Microgrid Cluster Formation

1.2 Hybrid AC/DC Microgrid Cluster Formation

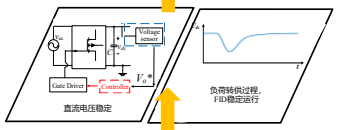
Solution:

- **Multi-terminal peer-to-peer grid-forming SOP:** It combines AC voltage grid-forming control, hierarchical DC voltage control, and multi-terminal power coordination, enabling all converters to jointly regulate DC voltage and maintain cluster-level power balance through coordinated inter-MG power transfer.
- It supports grid-connected, multi-microgrid islanding and load transfer operation.

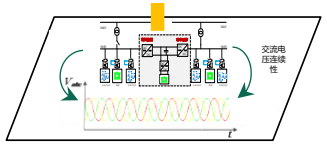
Hybrid AC/DC Microgrid Cluster Formation



multi-terminal power coordination

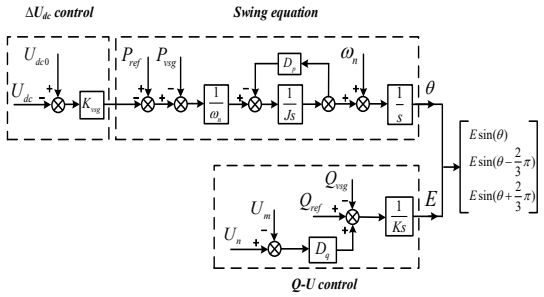


hierarchical DC voltage control

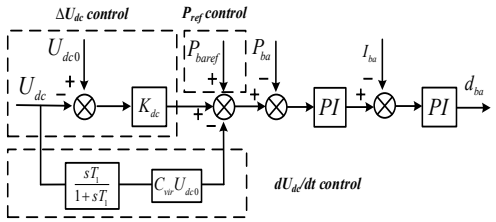


AC voltage grid-forming control

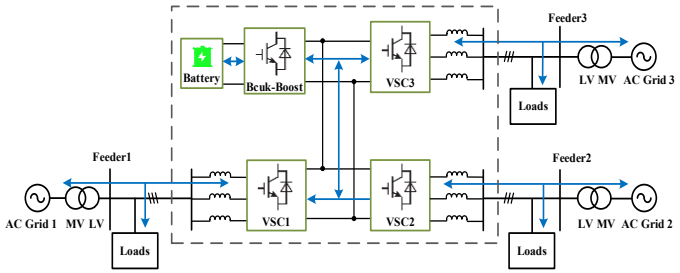
- DC/AC converter:



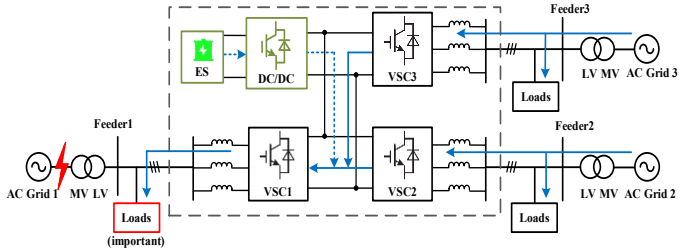
- DC/DC converter:



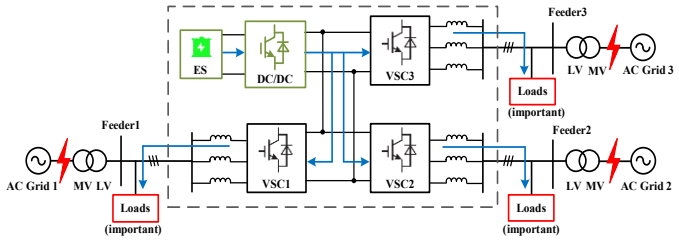
Schematic diagram of typical operation



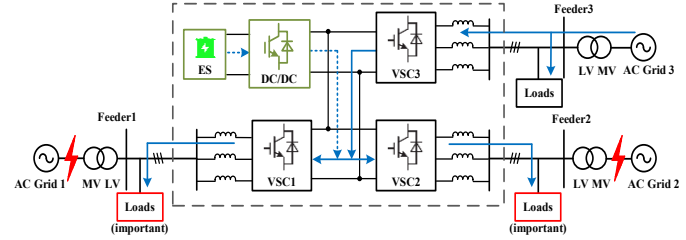
grid-connected operation



load transfer operation (a)



Multi-microgrid islanding operation



load transfer operation (b)

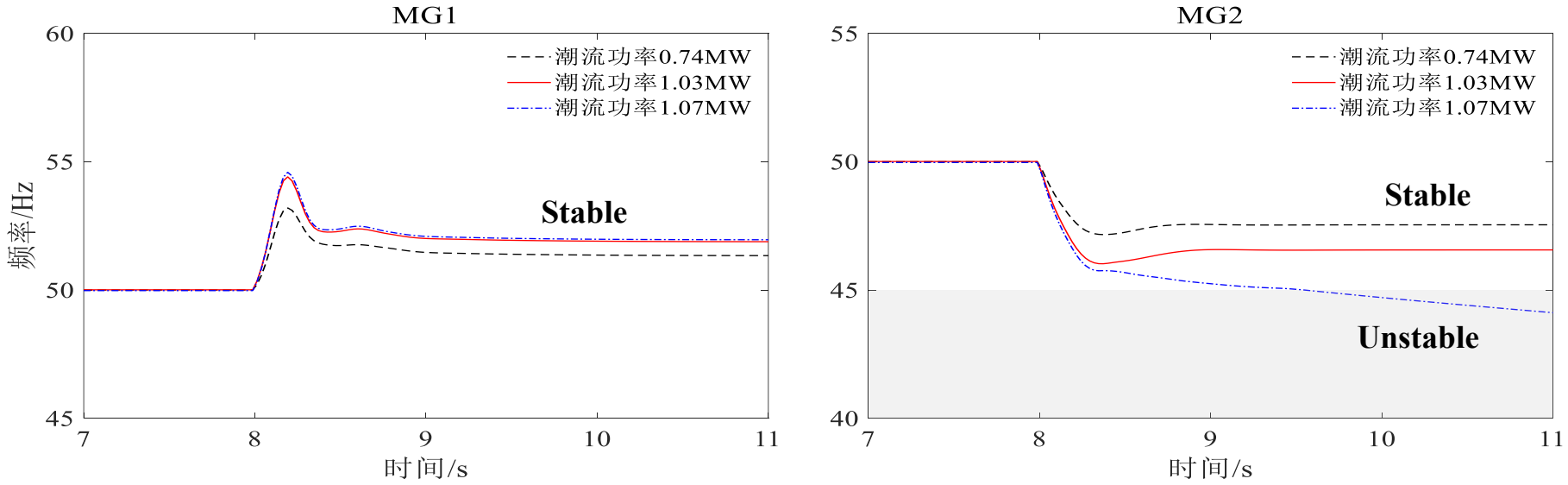
2. Microgrid Cluster Operation

Microgrid Cluster Operation

2.1 Tie-Line Power Regulation for Microgrid Clusters

Problem:

Due to variation of PV output and load, as well as equipment fault, power deviation from the scheduled values at the tie line of two microgrids may occur, and then result in frequency instability in the weak isolated MG cluster.



With variation of inter-microgrid power support, a tie-line outage may trigger frequency instability across the entire system.

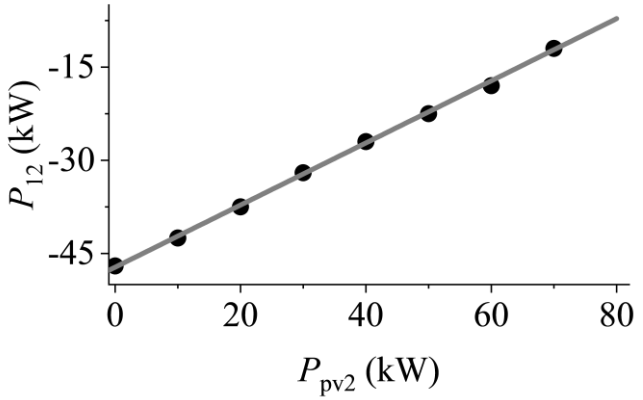
Microgrid Cluster Operation

2.1 Tie-Line Power Regulation for Microgrid Clusters

Solution:

- A sensitivity-based tie-line power regulation strategy for microgrid clusters is proposed.
- The sensitivities of tie-line power to BESS and PV outputs are calculated, and BESS/PV inverters are sequentially regulated according to the sensitivity ranking to track the scheduled tie-line power.

Sensitivity-Based Regulation Strategy



$$A_{mn,pvi} = \frac{\partial P_{mn}}{\partial P_{pvi}} \qquad A_{mn,esi} = \frac{\partial P_{mn}}{\partial P_{esi}}$$

Calculation of power sensitivity to ES, PV

$$\Delta P_{mn} = P_{mn,\exp} - P_{mn}$$

Difference between expected power and current power of the tie-line

Required BESS/PV Adjustment

1) Required BESS Adjustment

$$P_{esi,exp} = sign\left(\frac{\Delta P_{mn}}{A_{mn,esi}}\right) \times \min\left(\left|\frac{\Delta P_{mn}}{A_{mn,esi}}\right|, P_{ch,max,i}\right)$$

2) Required PV Adjustment

- Based on ΔP_{mn} and DG load rate: select target MG and PV increase/decrease mode.

$$P_{pv,exp1} = sign\left(\frac{\Delta P_{mn}}{A_{mn,pv}}\right) * min\left(\left|\frac{\Delta P_{mn}}{A_{mn,pv}}\right|, P_{pv,max\,1}\right)$$

$$P_{pv,exp2} = sign\left(\frac{\Delta P_{mn}}{A_{mn,pv}}\right) * min\left(\left|\frac{\Delta P_{mn}}{A_{mn,pv}}\right|, P_{pv,max\,2}\right)$$

Microgrid Cluster Operation

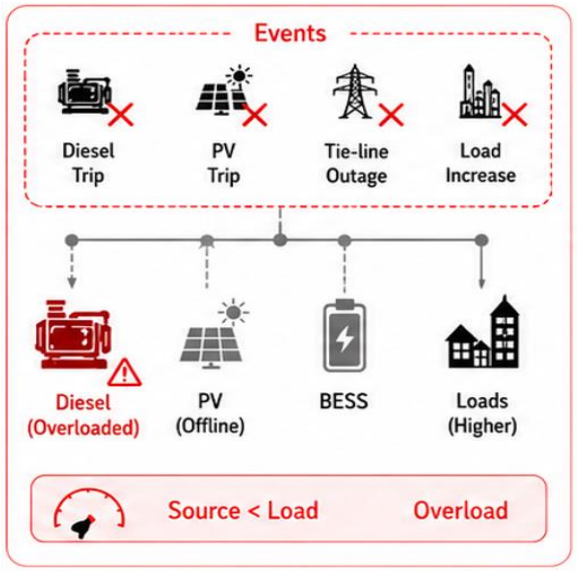
2.2 Emergency Control

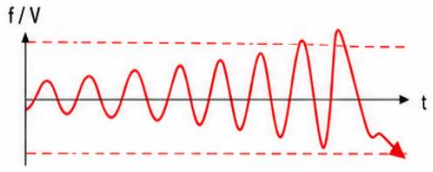
Problem:

Disturbances (e.g., PV/DG tripping, tie-line outages) in microgrid clusters trigger rapid power imbalances, leading to two extreme scenarios:

- **Source < Load:** Severe capacity mismatch may result in diesel generator overloading and then system collapse
- **Source > Load:** Slow DG response causes transient frequency and voltage violation.

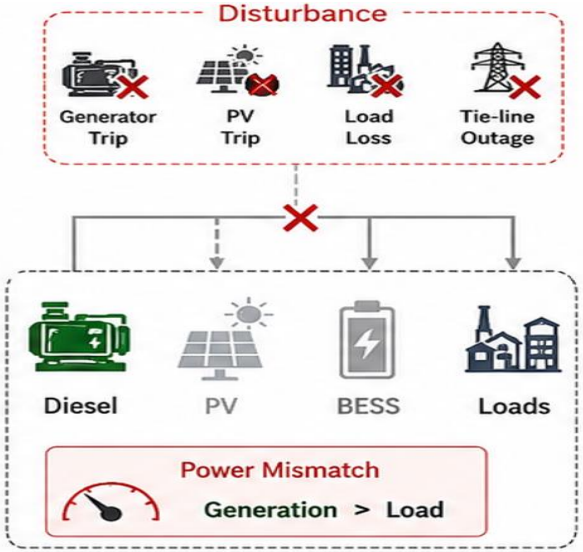
➢**Generator/Load Shedding (Source < Load)**

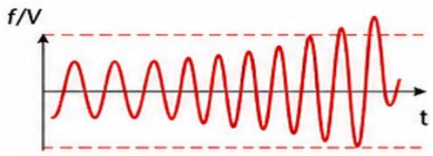




Source-Load Capacity Mismatch

➢**Active Support (Source > Load)**





Dynamic Response Mismatch

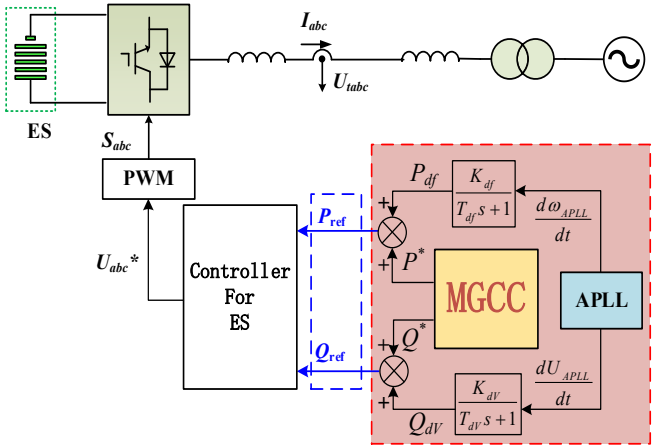
Microgrid Cluster Operation

2.2 Emergency Control : Active Power Support (Source > Load)

Solution：

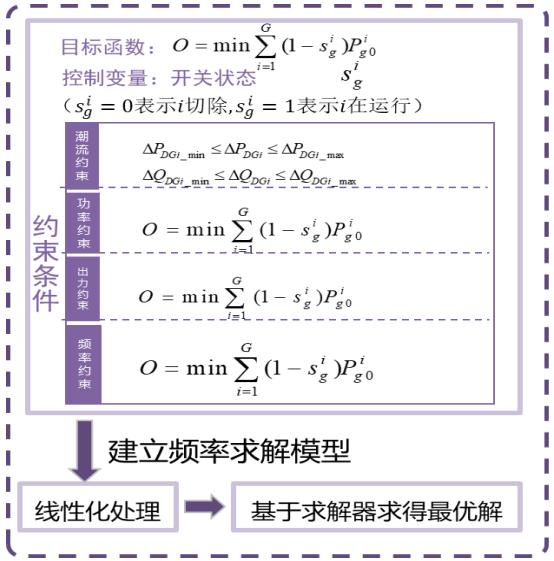
- **Proposed strategy:** Phase/amplitude-locked emergency power support (<200ms) + transient-constrained shedding
- **Dual defense:** Dynamic support + active load shedding/regulation

➢Solution based on APLL

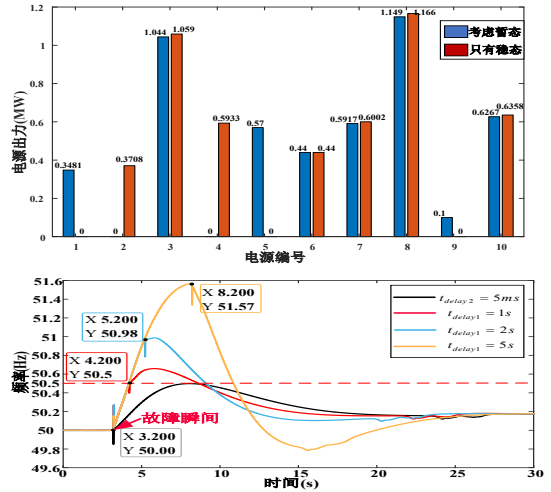


- **Power support response time:** ≤200 ms

➢Emergency Load Shedding with Transient Constraints



➢Shedding-Regulation Integrated into Emergency Control



- **Transient-constrained emergency source and load shedding**
- **Combined with converter-active power support**

3. AI Application in Microgrid Clusters

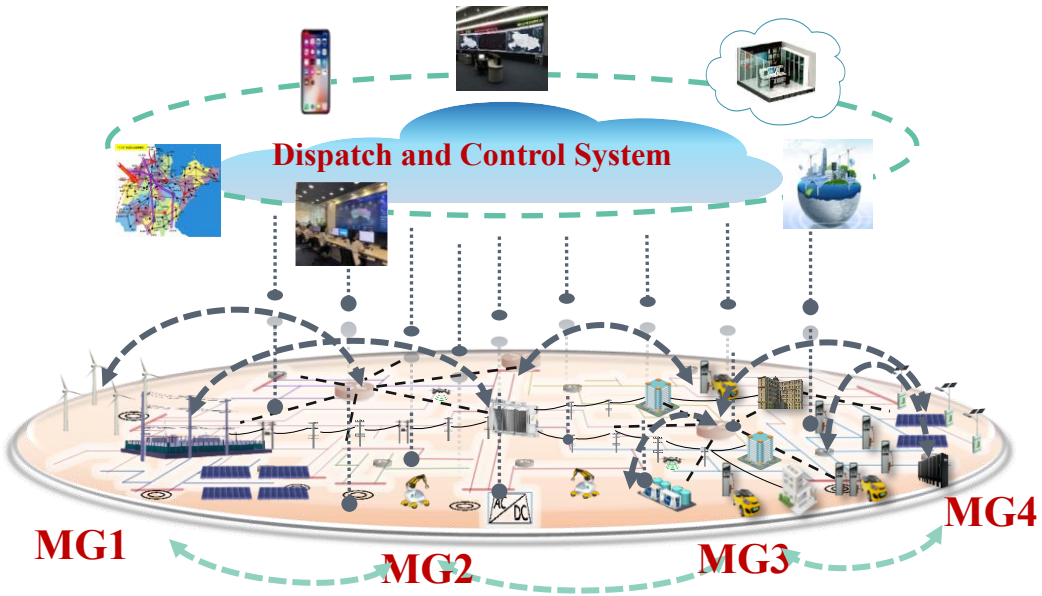
AI Application in Microgrid Clusters

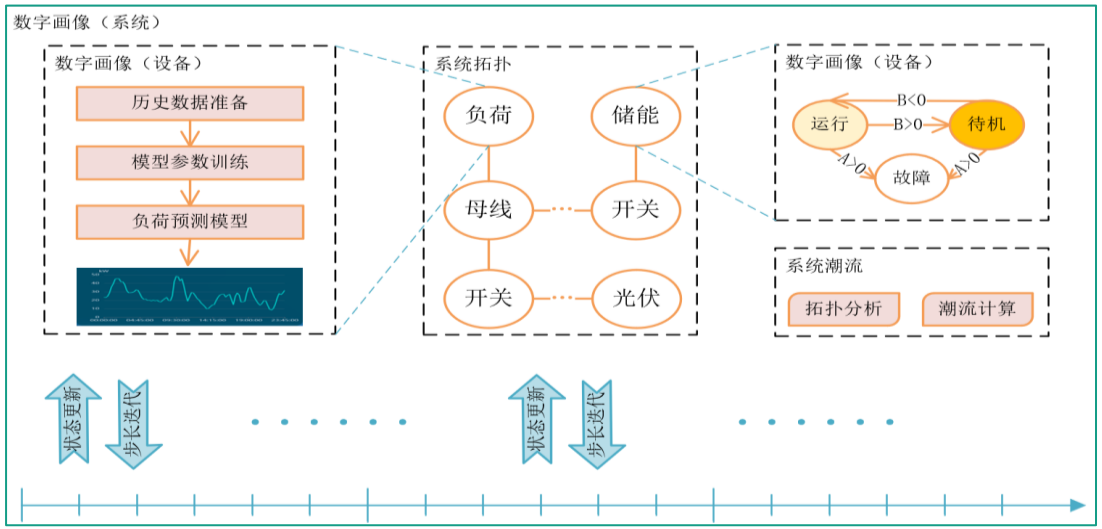
3.1 Digital Twin Application in MG Cluster Dispatch and Control

Problem:

Dispatch of microgrid clusters is challenged by **multi-level coupling among equipment, MGs, and the cluster layer**. Dynamic topology, inter-MG power exchange, mode transitions, and source-load-storage interactions make real-time state mapping and dispatch decision-making difficult.

Digital Twin Dispatch and Control System





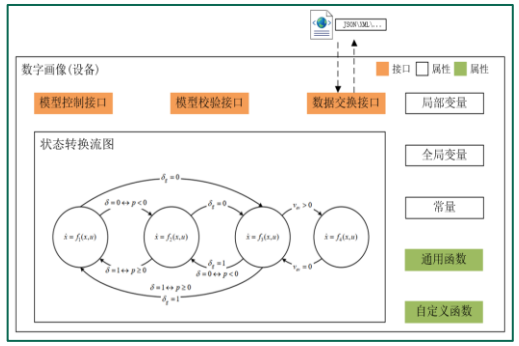
AI Application in Microgrid Clusters

3.1 Digital Twin Application in MG Cluster Dispatch and Control

Solution:

- **Hierarchical Twin Modeling:** Developing equipment-, MG-, and cluster-level digital twin models.
- **Mechanism-Data Fusion:** Mechanism-based models and data-driven models are integrated to correct model deviations using real-time measurements and disturbance response data.
- **Dispatch and Control Support:** The platform supports online state mapping, trend simulation, strategy rehearsal, and dispatch decision-making for microgrid clusters.

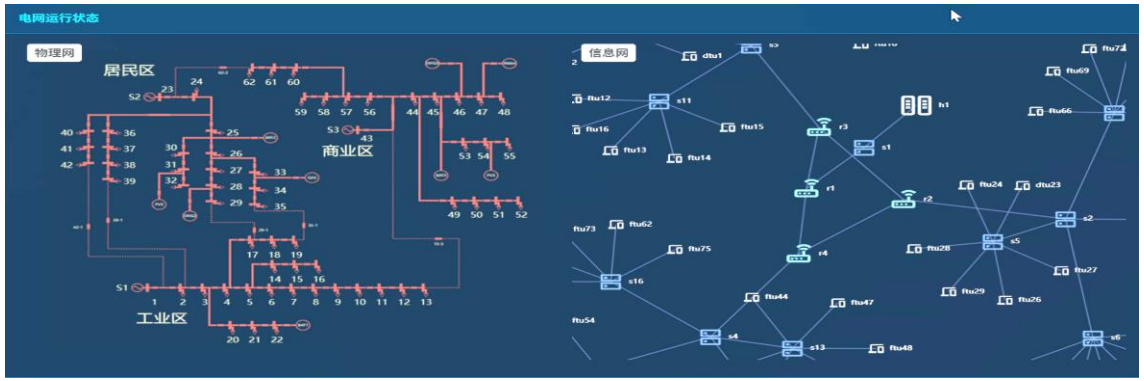
Equipment Twin Modeling





Standardized Definition of Equipment Models → Instantiation → Equipment-Level Twin

System Twin Modeling



'Dynamic Digital Twin' of Physical Microgrid Clusters

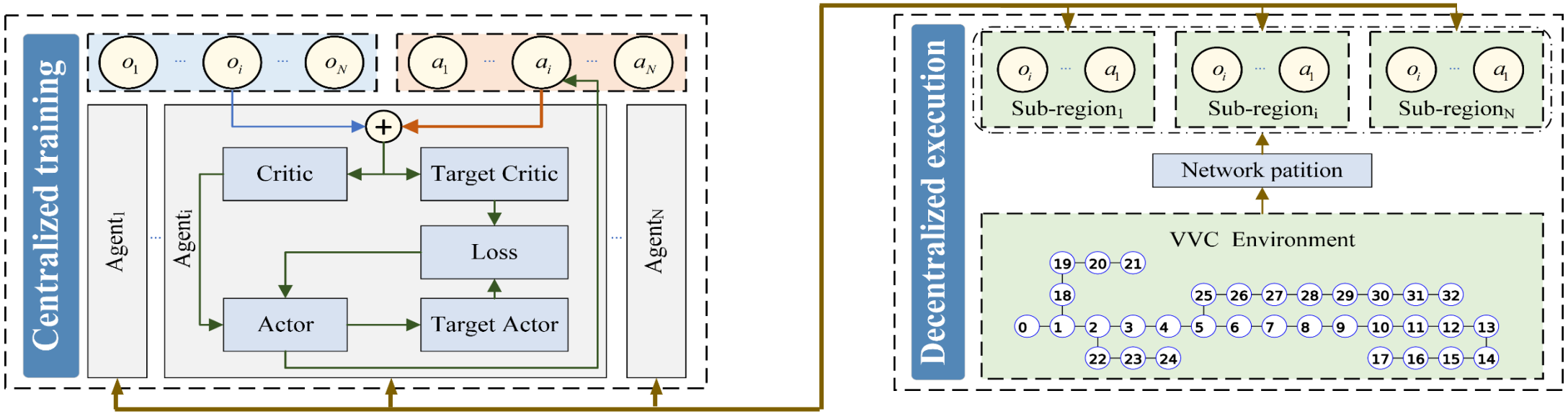
AI Application in Microgrid Clusters

3.2 Coordinated Voltage Control on Multi-Agent Reinforcement Learning

Problem：

Controlled equipment in microgrid clusters has clear **spatiotemporal characteristics**, involving multi-region coordinated management and control. **Microgrid clusters with high-renewable-penetration** contain **high-dimensional decision objects** and **massive operational scenarios**, making real-time, scalable, and coordinated voltage regulation challenging.

Multi-Agent Reinforcement Learning



AI Application in Microgrid Clusters

3.2 Coordinated Voltage Control on Multi-Agent Reinforcement Learning

Solution:

- **Sensitivity-Based Zoning:** Nodes with strong electrical coupling and similar voltage characteristics are grouped into coordinated control regions based on voltage sensitivity and electrical distance.
- **Multi-Agent Voltage Control:** MGs, BESSs, PV inverters, and flexible SOPs are modeled as agents within a multi-agent reinforcement learning framework for coordinated voltage regulation.
- **Centralized Training, Decentralized Execution:** The models are trained using cluster-level information and executed locally by each agent, enabling scalable and coordinated voltage control.

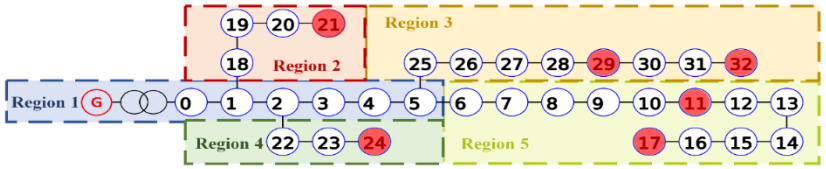
$$Q = \frac{1}{2m}\sum_{i,j}\left(A_{ij} - \frac{k_i k_j}{2m}\right)\delta(c_i, c_j)$$

$$A_{ij} = 1 - \frac{D_{ij}}{\max\limits_{m,n} D_{mn}}$$

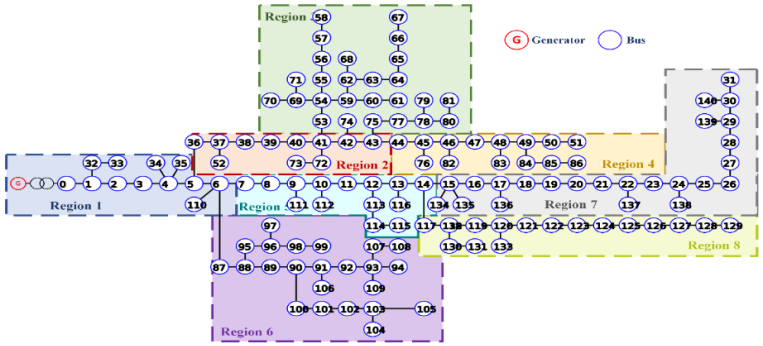
$$D_{ij} = S_{QU}^{ii} + S_{QU}^{jj} - S_{QU}^{ij} - S_{QU}^{ji}$$

$$\delta(c_i, c_j) = \sum\nolimits_g \delta(c_i, g)\delta(c_j, g)$$

- Cluster Comprehensive Performance Indicator: Electrical distance considering reactive-voltage sensitivity and regional voltage regulation capability
- Louvain Community Detection Algorithm: Optimal Zoning Solution



IEEE 33-Bus Zoning Results



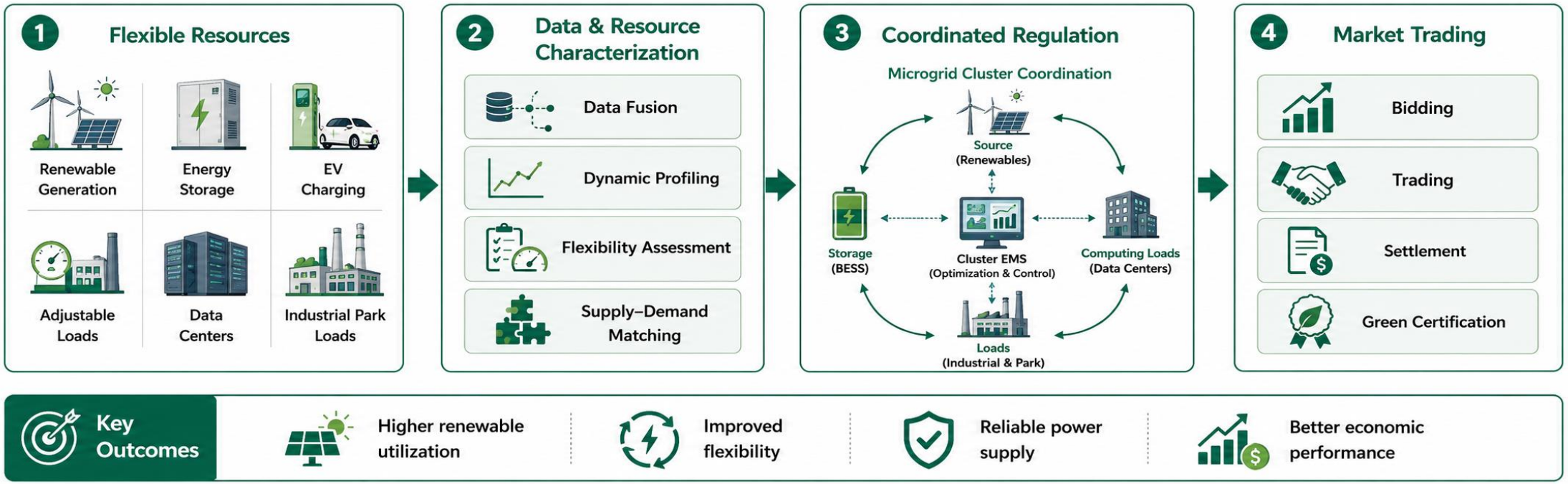
IEEE 141-Bus Zoning Results

AI Application in Microgrid Clusters

3.3 Aggregation, Regulation, and Market Trading of Flexibility Resource in MG Clusters

Problem：

Flexible resources in microgrid clusters are dispersed, heterogeneous, and time-varying, with **different response capabilities**, **reliability constraints**, and **market attributes**. This makes flexibility quantification, coordinated regulation, and verifiable green-electricity trading difficult across MG unit, cluster, and system levels.

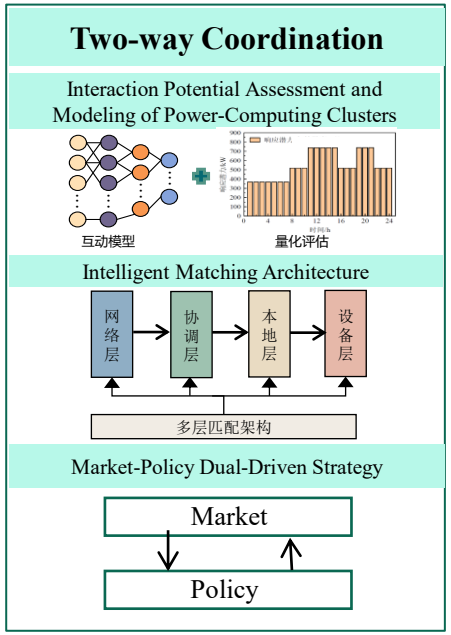


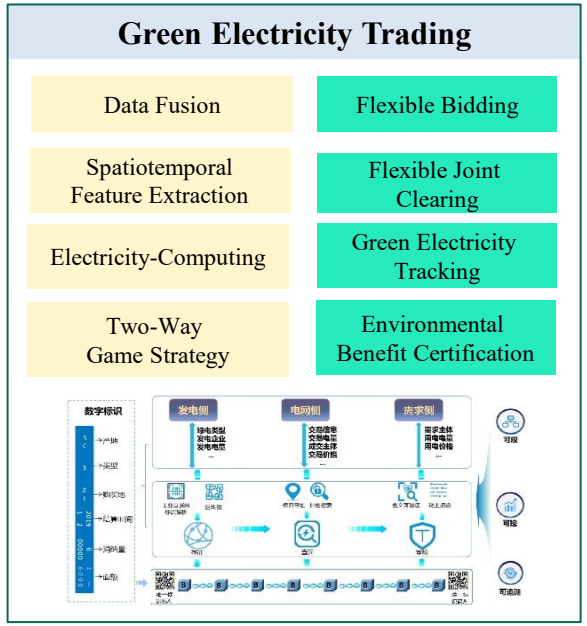
AI Application in Microgrid Clusters

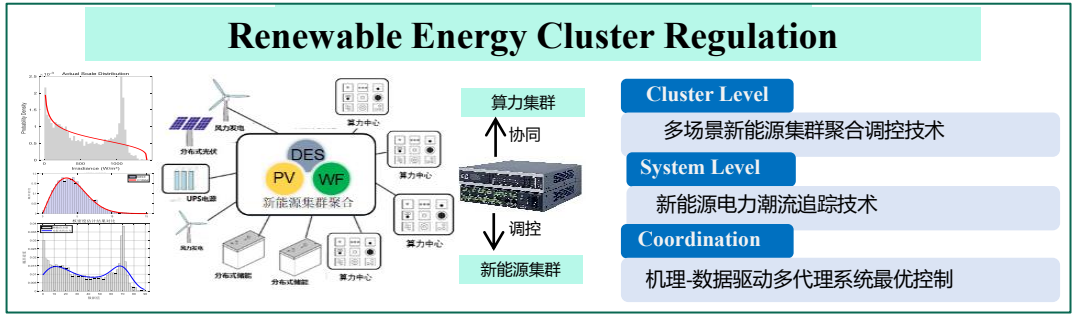
3.3 Aggregation, Regulation, and Market Trading of Flexibility Resource in MG Clusters

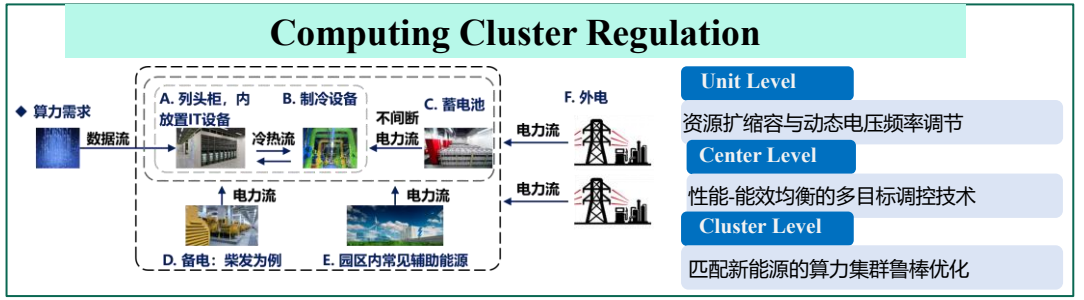
Solution:

- **Two-Way Power-Computing Coordination:** Assess interaction potential and match renewable generation, storage, and computing loads for coordinated cluster operation.
- **Green Electricity Trading:** Integrate data fusion, flexible bidding, joint clearing, and green electricity tracking to support market-based resource coordination.
- **Multi-Level Cluster Regulation:** Coordinate renewable clusters and computing load clusters across unit, center, cluster, and system levels.









Outlines

1 Background and Motivation

2 Key Technologies

3 Demonstration Projects

4 Conclusion

Multi-Island Microgrid Clusters

■ Zhoushan ±200kV Five-Terminal Flexible DC Microgrid Cluster, Zhejiang

Basic Information:

Project Status: **World's first five-terminal flexible DC project** and a key milestone of China's microgrid cluster technology
Project Scale: Connects five major islands including Dinghai, Daishan, Qushan, Sijiao and Yangshan, with a total system capacity of 1000 MW.
Core Technologies: Develops multi-terminal flexible DC control & protection and islanded operation strategy, enabling flexible allocation and efficient transmission of wind and solar power.
Project Significance: Solves poor power supply and insufficient renewable energy consumption on islands, offering replicable experience for other islands.





Industrial Microgrid Clusters

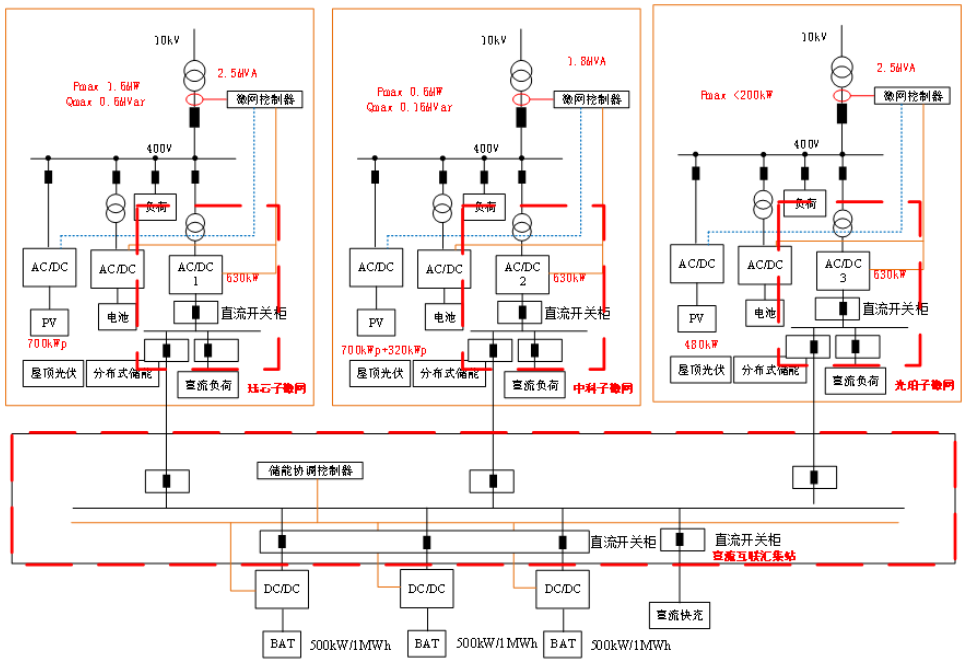
"PV-Storage-DC-Flexibility" Microgrid Cluster in Southern Urban Area of Lishui, Zhejiang

Basic Information

Project Overview & Positioning: Put into operation in December 2025, China's first industrial park microgrid cluster of this type. Equipped with 792 kW PV, 1100 kWh energy storage, **3 industrial sub-systems and 1 shared energy storage station.**

Dual-layer Architecture: Self-balancing of each microgrid & mutual support between MG cluster through DC interconnection are implemented with millisecond-level power support, ensuring self-supply of each micro grid and flexible power dispatch within MG cluster.

Outstanding Operation Results & Values : Power supply reliability reaches 99.999%, and renewable energy in the park is fully consumed with MG cluster.







Outlines

1 Background and Motivation

2 Key Technologies

3 Demonstration Projects

4 Conclusion

Conclusion

- Microgrid Cluster is an emerging technology, and gaining more attention in China.
- More research is required in microgrid cluster, including dynamic reconfiguration and formation, flexible control and operation.
- More R&D projects are expected to make MG clusters in reality.

武漢大學
WUHAN UNIVERSITY

Thanks

Xuzhu Rick Dong
Email: dongxz@whu.edu.cn

Lei Shang
Shanglei@whu.edu.cn