Temporal-Spatial Coordination of Distributed Energy Resources (DERs) in Microgrids

Dr Yan Xu
Cham Tao Soon Professor in Engineering
Director, Center for Power Engineering
Co-Director, SingaporePower Group – NTU Joint Lab
Nanyang Technological University

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

			Timescale
1	REIDS (Renewable Energy Integration Demonstrator – Singapore) Microgrid Demonstration Project		
2	DER Control	Islanded microgrid Grid-connected microgrid	ms ~ seconds
3	DER Operation	Energy dispatch Volt/Var regulation	mins ~ hours
4	Hierarchy Coordination	Volt/Var control Active power balancing	ms ~ hours
5	DER Energy Trading	Centralized trading P2P trading	mins ~ hours
6	DER Planning	Distributed generation Energy storage systems	years ~ decades

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

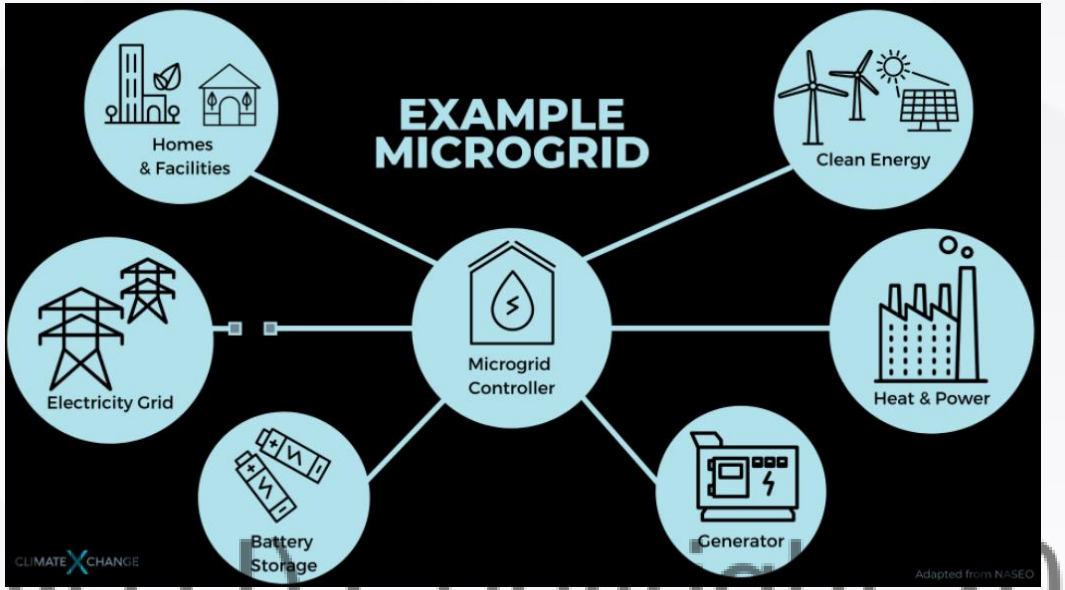
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

- Microgrid Definitions



Picture source: World Economic Forum

1. The U.S. Department of Energy (DOE) defines a microgrid as '*a group of interconnected loads and DERs within clearly defined electrical boundaries that acts as a single controllable entity with respect to the main grid. A microgrid can connect and disconnect from the main grid to enable it to operate in both connected or island-mode*'.
2. The CIGRE C6.22 Working Group defines that '*Microgrids are electricity distribution systems containing loads and DERs, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded*'.
3. N. Hatziargyriou, Microgrids: Architectures and Control, UK: Wiley-IEEE Press, 2014, ISBN: 978-1-118-72068-4. describes the microgrid as '*comprising low-voltage (LV) distribution systems with DERs. Such systems can operate either connected or disconnected from the main grid. The operation of DERs in the network can provide benefits to the overall system performance, if managed and coordinated efficiently*'.

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

- *Renewable Energy Integration Demonstrator – Singapore* (REIDS)

REIDS is a Singapore-based RD&D platform
dedicated to designing, demonstrating and testing solutions
for sustainable multi-activity off-grid communities in Southeast Asia

https://www.ntu.edu.sg/erian/research-focus/flagship-programmes/renewable-energy-integration-demonstrator-singapore

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

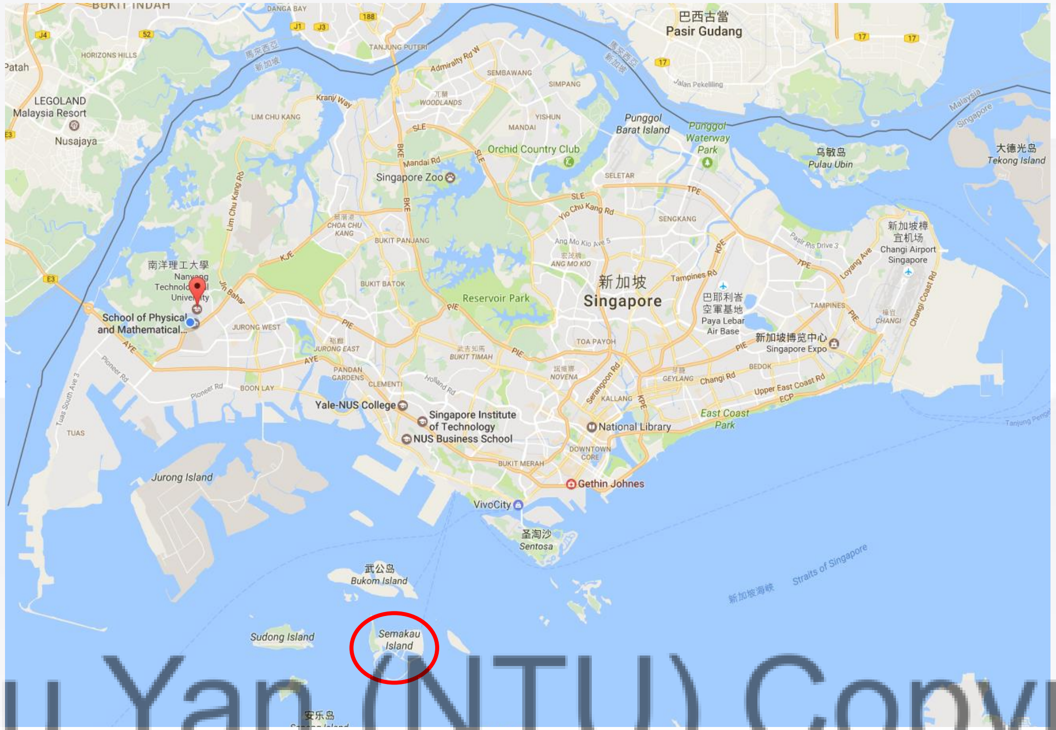
3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG TECHNOLOGICAL UNIVERSITY
SINGAPORE



REIDS Partners

accenture
adaro POWER
Bawah
ClassNK
DLRE
EDF
EMERSON
ENGIE
Evolution Energie
GE
IDSUD ENERGIES
Keppel Offshore & Marine
MEDCOENERGI Power
MERALCO
muRata INNOVATOR IN ELECTRONICS
NORTIS ENERGY
REC
Rolls-Royce
Schneider Electric
SEAS Sustainable Energy Association of Singapore
sembcorp
SPgroup
Trinasolar
VDE RENEWABLES
Vestas

Research Leader

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

Supporting Agencies

EDB singapore
National Environment Agency Safeguard • Nurture • Cherish
Energy Market Authority Smart Energy, Sustainable Future
National Research Foundation

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

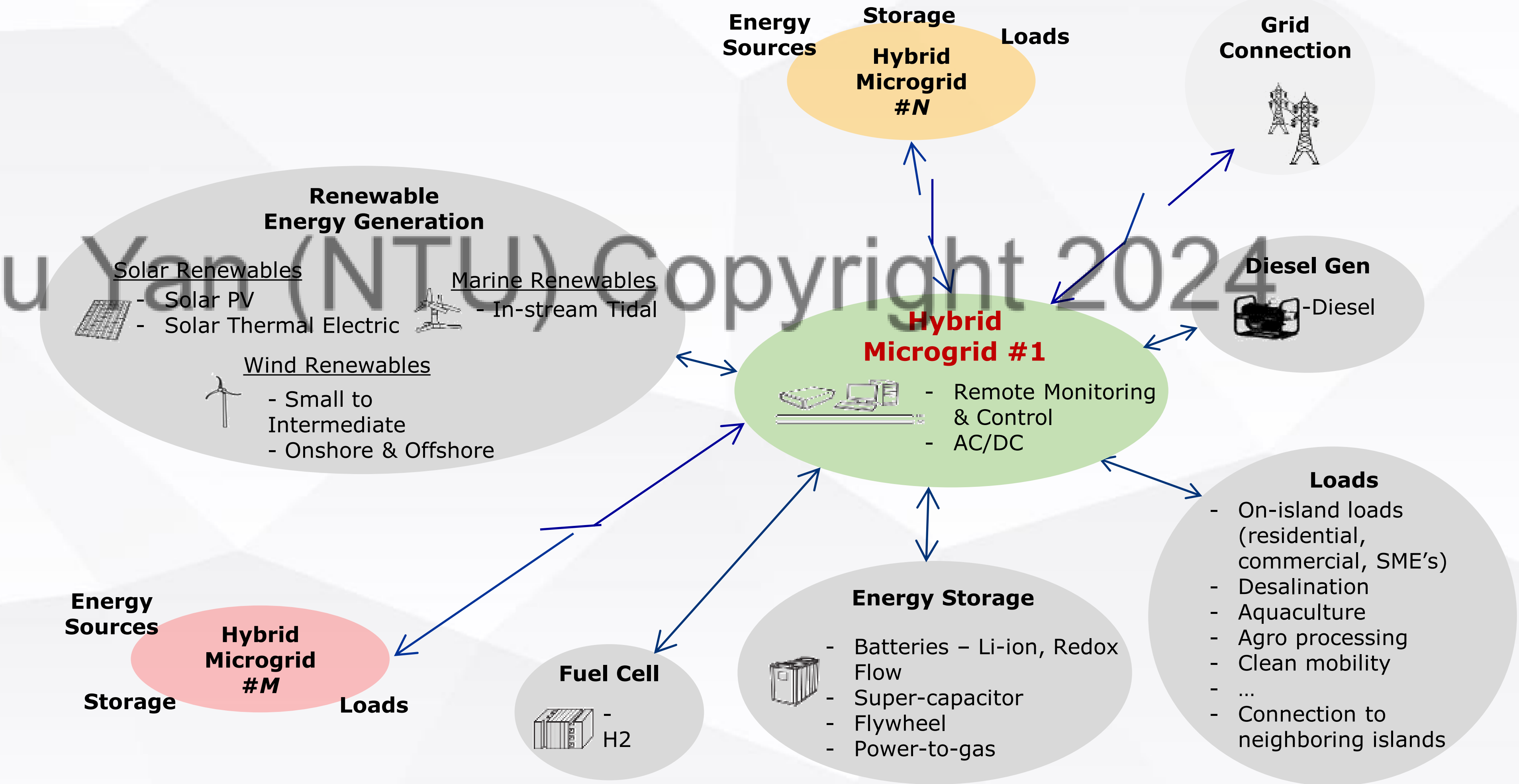
5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

REIDS Roadmap and Framework

Phase I – 4 independent MGs (500kW-1MW each)
Phase II – 4 MGs in a cluster configuration (100kW-250kW each)



Hybrid Microgrid #N
Energy Sources
Storage
Loads

Grid Connection

Renewable Energy Generation

Solar Renewables
- Solar PV
- Solar Thermal Electric

Marine Renewables
- In-stream Tidal

Wind Renewables
- Small to Intermediate
- Onshore & Offshore

Hybrid Microgrid #1
- Remote Monitoring & Control
- AC/DC

Diesel Gen
-Diesel

Loads
- On-island loads (residential, commercial, SME's)
- Desalination
- Aquaculture
- Agro processing
- Clean mobility
- ...
- Connection to neighboring islands

Energy Storage
- Batteries – Li-ion, Redox Flow
- Super-capacitor
- Flywheel
- Power-to-gas

Fuel Cell
- H2

Hybrid Microgrid #M
Energy Sources
Storage
Loads

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

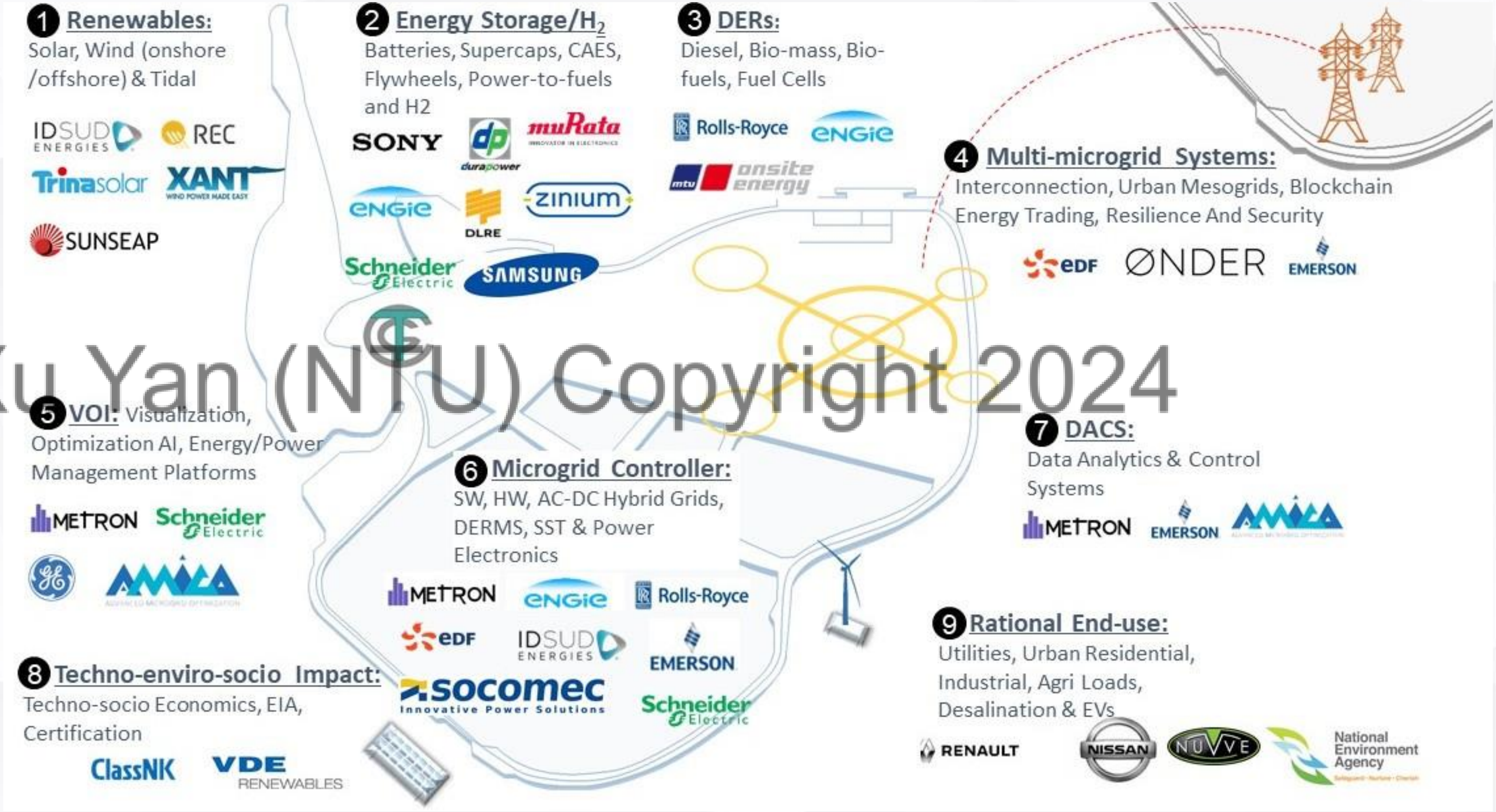
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

Onboard Industry Collaborators



① **Renewables:** Solar, Wind (onshore /offshore) & Tidal

② **Energy Storage/H_2** Batteries, Supercaps, CAES, Flywheels, Power-to-fuels and H2

③ **DERs:** Diesel, Bio-mass, Bio-fuels, Fuel Cells

④ **Multi-microgrid Systems:** Interconnection, Urban Mesogrids, Blockchain Energy Trading, Resilience And Security

⑤ **VOI:** Visualization, Optimization AI, Energy/Power Management Platforms

⑥ **Microgrid Controller:** SW, HW, AC-DC Hybrid Grids, DERMS, SST & Power Electronics

⑦ **DACS:** Data Analytics & Control Systems

⑧ **Techno-enviro-socio Impact:** Techno-socio Economics, EIA, Certification

⑨ **Rational End-use:** Utilities, Urban Residential, Industrial, Agri Loads, Desalination & EVs

http://erian.ntu.edu.sg/REIDS/Pages/AboutREIDS.aspx

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

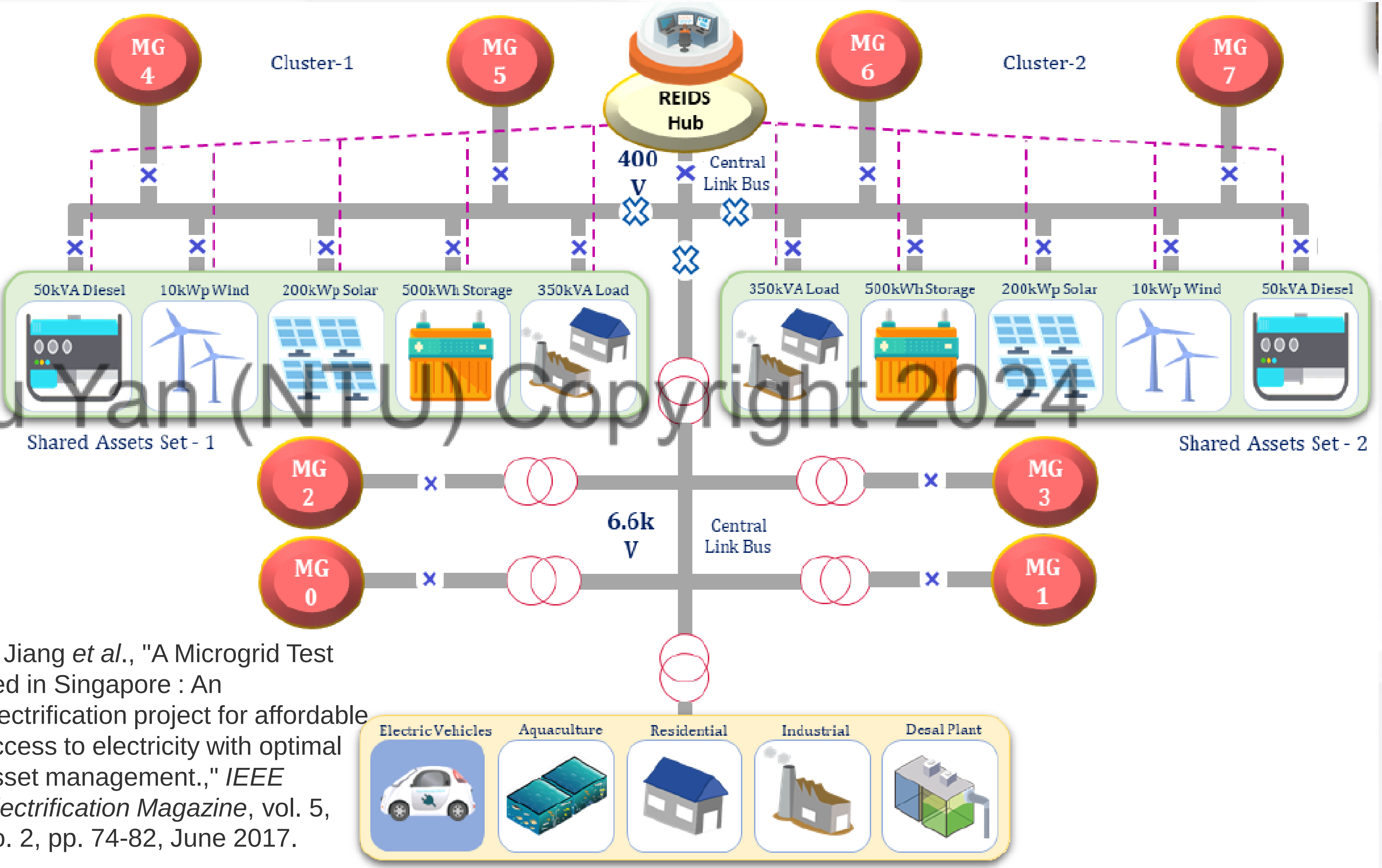
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG TECHNOLOGICAL UNIVERSITY
SINGAPORE

REIDS Electrical Structure



T. Jiang *et al*., "A Microgrid Test bed in Singapore : An electrification project for affordable access to electricity with optimal asset management.," *IEEE Electrification Magazine*, vol. 5, no. 2, pp. 74-82, June 2017.

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

- *Renewable Energy Integration Demonstrator – Singapore* (REIDS)

REIDS Renewable Energy Integration Demonstrator – Singapore

An ERI@N Flagship Project

Interoperable Grid of Grids Testbed

Prasanna I V, prasannaiv@ntu.edu.sg

Research Leader

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE | Energy Research Institute @ NTU

Supporting Agencies

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG TECHNOLOGICAL UNIVERSITY
SINGAPORE

- Onsite pictures

MG0 Test & Commissioning - March 2017

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

- REIDS Electrical Structure

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

- Onsite pictures

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

- Onsite pictures


100kW Wind Turbine


Hydrogen ESS : 2x25kW P2P & 70kVA PCS


HRS: ~20 Vehicles/day


150kVA Gensets


200kWp Solar


Fuel Cell EV: 44kW/70HP

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

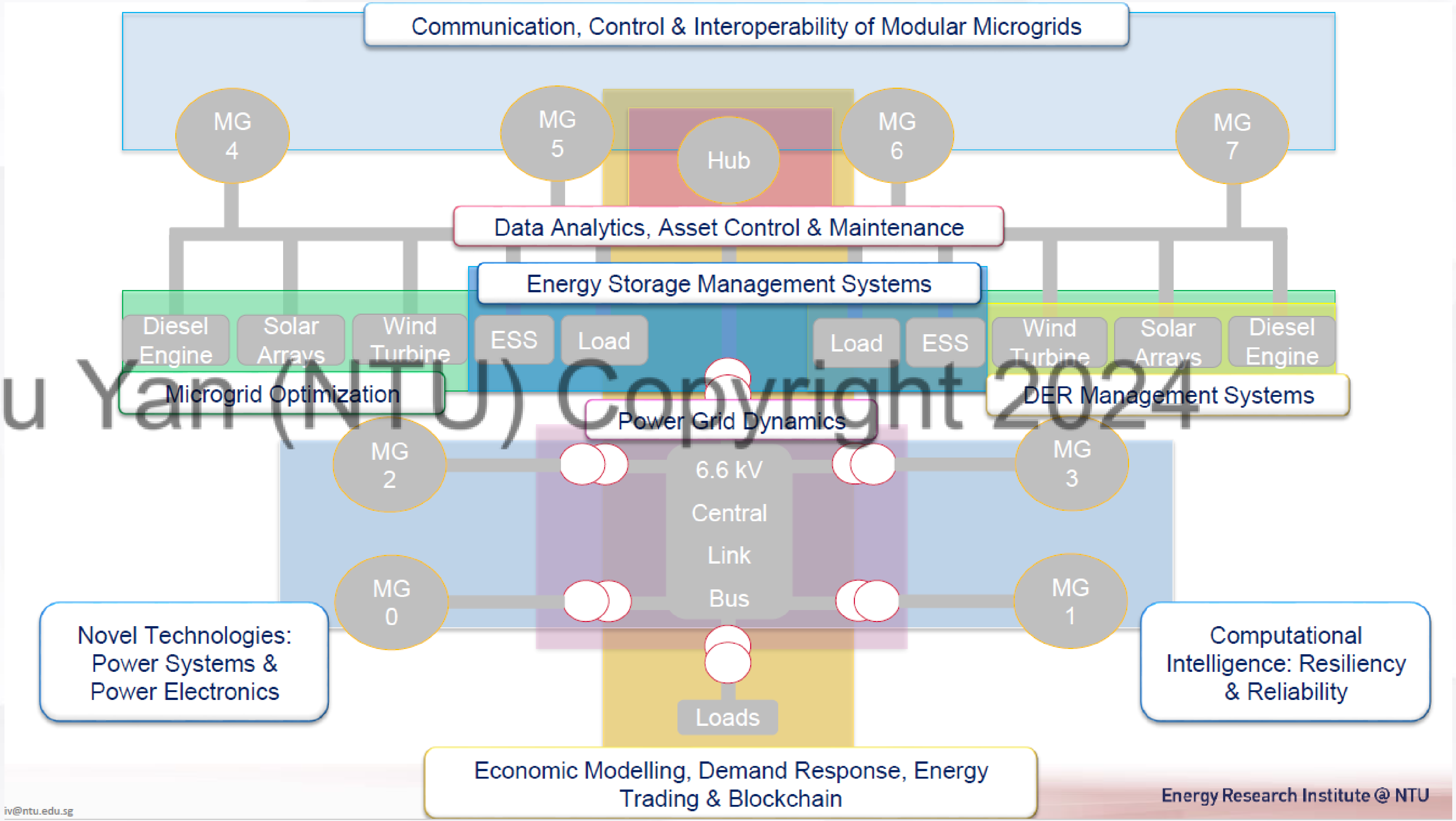
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

REIDS Research Problems



1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

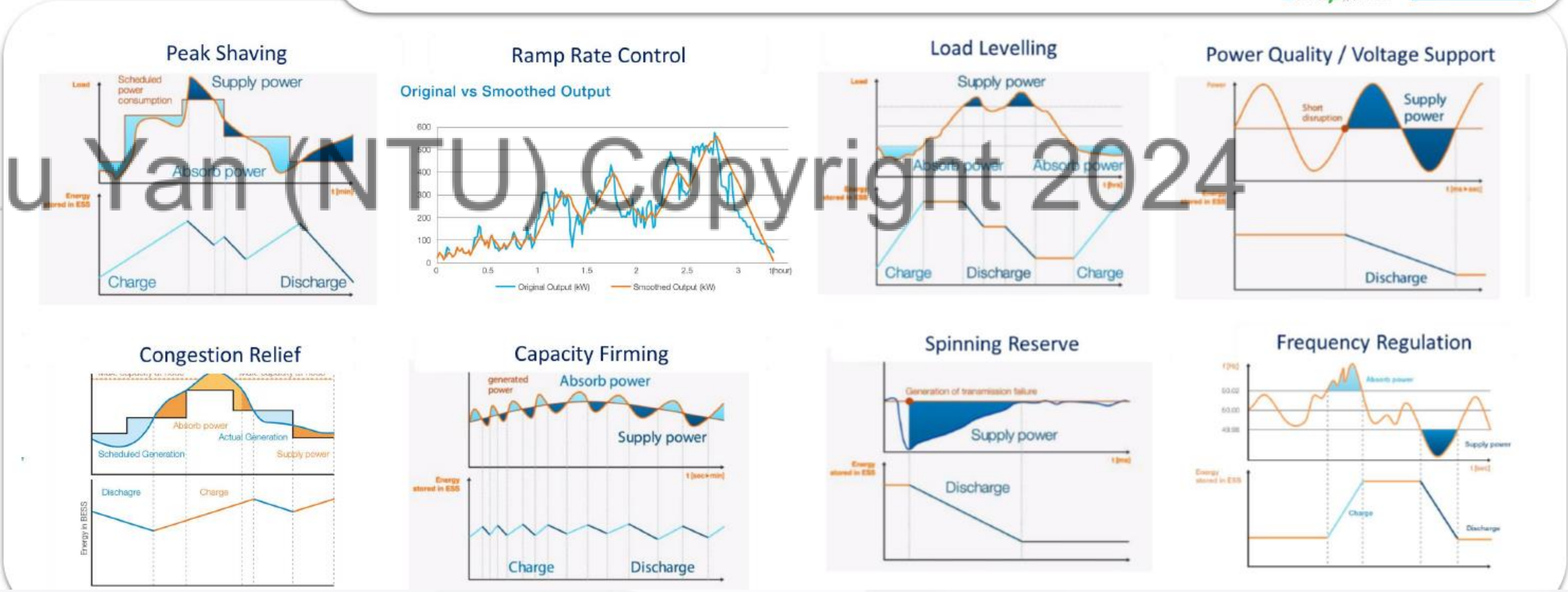
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

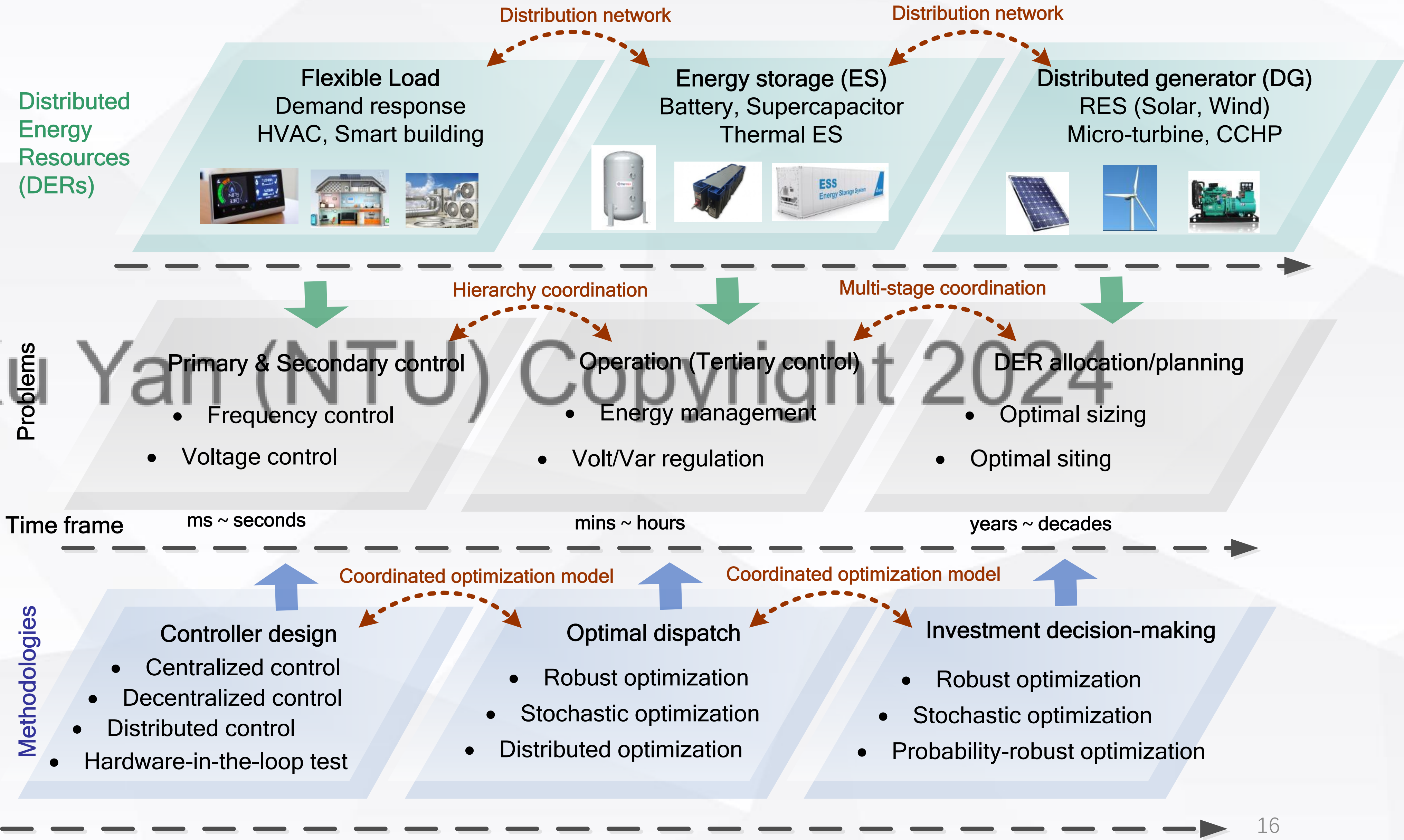
- REIDS Research Problems

Grid Ancillary Services



NANYANG TECHNOLOGICAL UNIVERSITY
SINGAPORE

Our research Framework: system-level coordination of DERs



Distributed Energy Resources (DERs)

Flexible Load
Demand response
HVAC, Smart building

Energy storage (ES)
Battery, Supercapacitor
Thermal ES

Distributed generator (DG)
RES (Solar, Wind)
Micro-turbine, CCHP

Distribution network

Distribution network

Problems

Hierarchy coordination

Multi-stage coordination

Primary & Secondary control
- Frequency control
- Voltage control

Operation (Tertiary control)
- Energy management
- Volt/Var regulation

DER allocation/planning
- Optimal sizing
- Optimal siting

Time frame: ms ~ seconds; mins ~ hours; years ~ decades

Methodologies

Coordinated optimization model

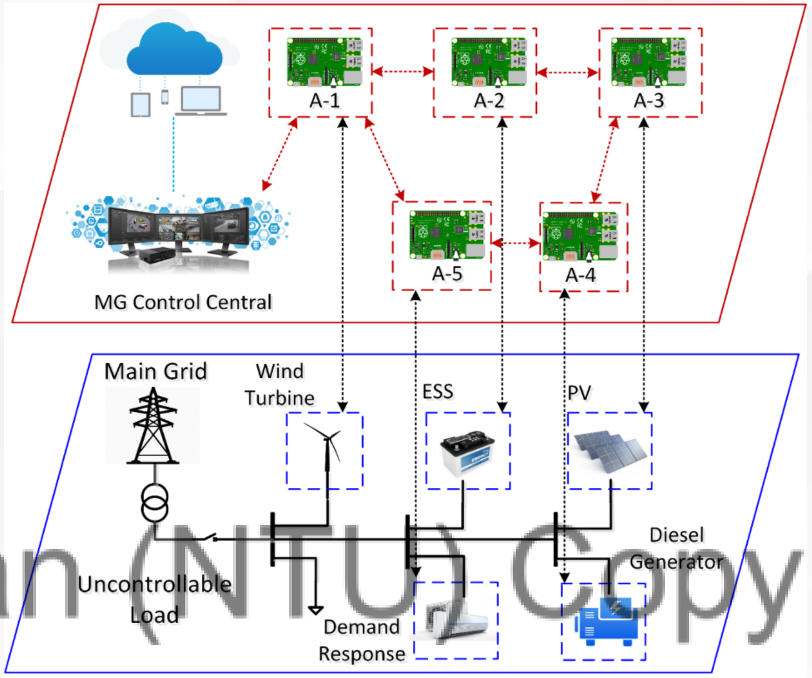
Coordinated optimization model

Controller design
- Centralized control
- Decentralized control
- Distributed control
- Hardware-in-the-loop test

Optimal dispatch
- Robust optimization
- Stochastic optimization
- Distributed optimization

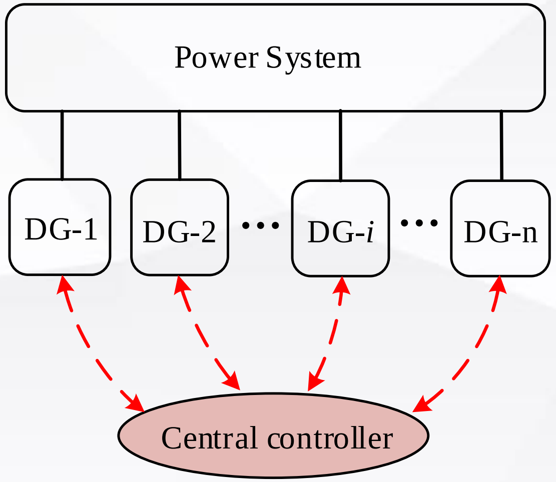
Investment decision-making
- Robust optimization
- Stochastic optimization
- Probability-robust optimization

- Control of DERs in Microgrids

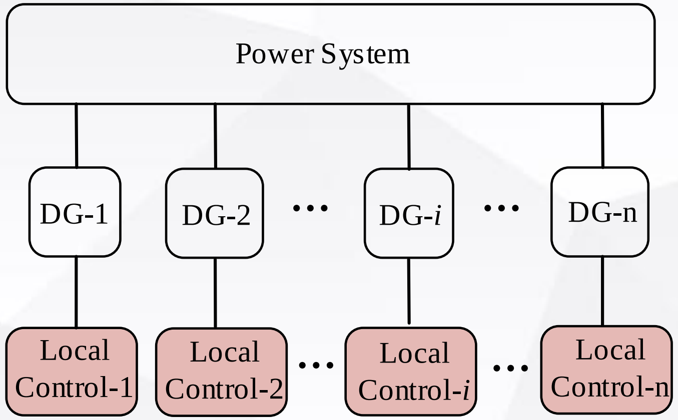


1. Islanded mode:
   - Distributed control (event-triggered, finite-time)
   - Hardware-in-the-Loop (Hil) validation

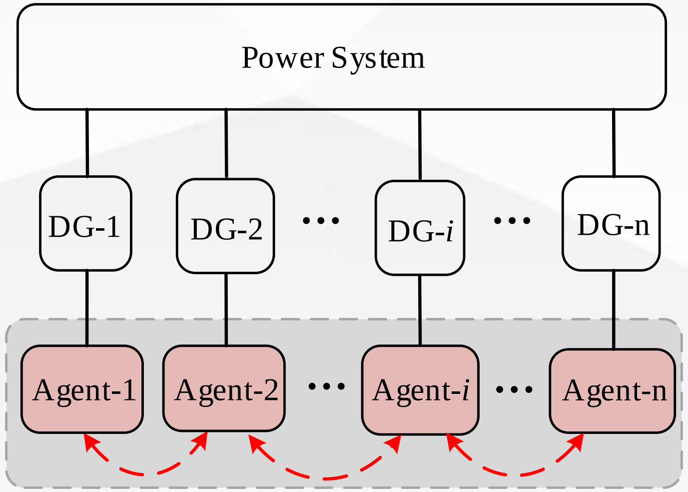
2. Grid-connected mode:
   - DER for *f* support
   - DER for *V* support



(a) Centralized control



(b) Decentralized control



(c) Distributed control

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

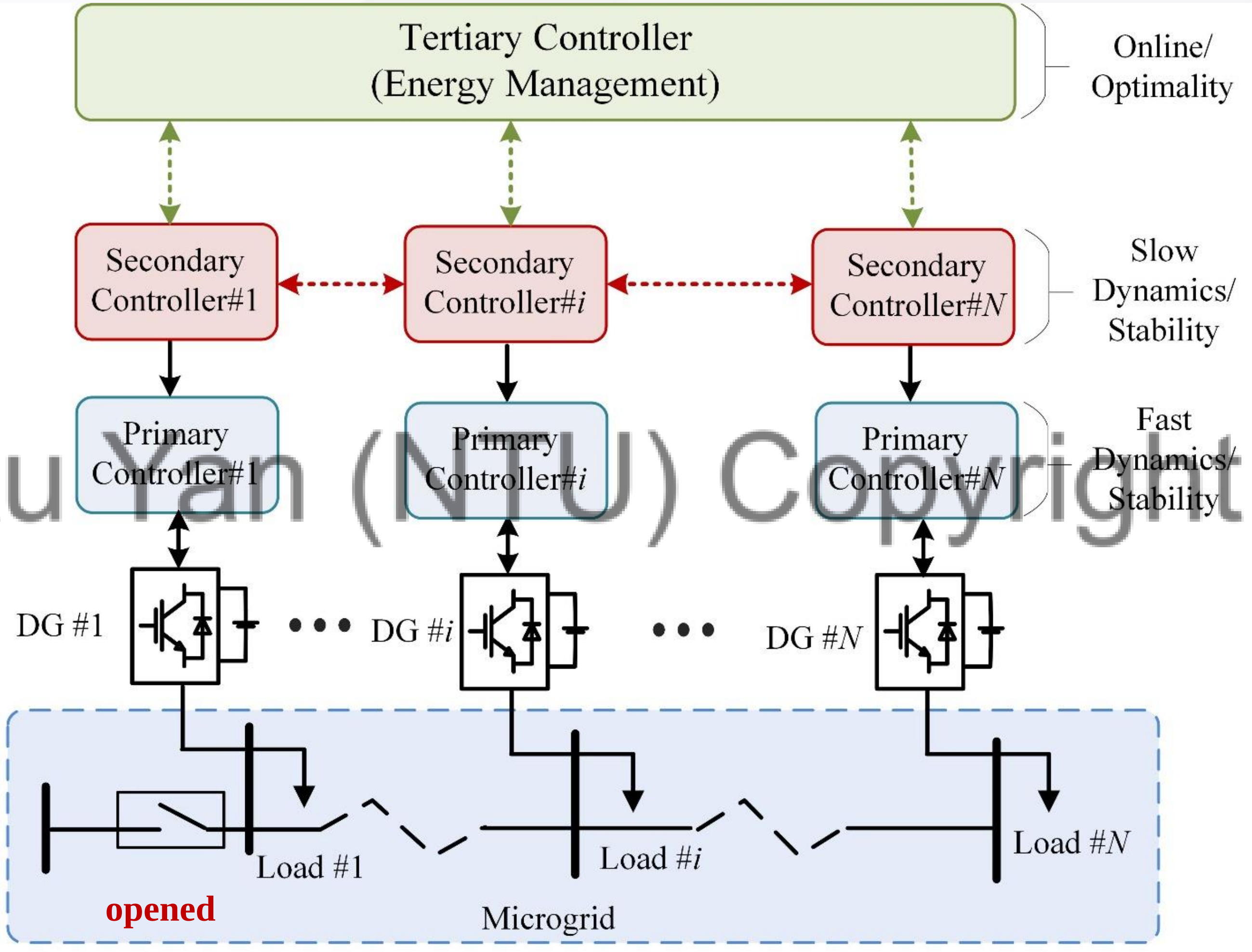
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

Hierarchical control of an islanded microgrid



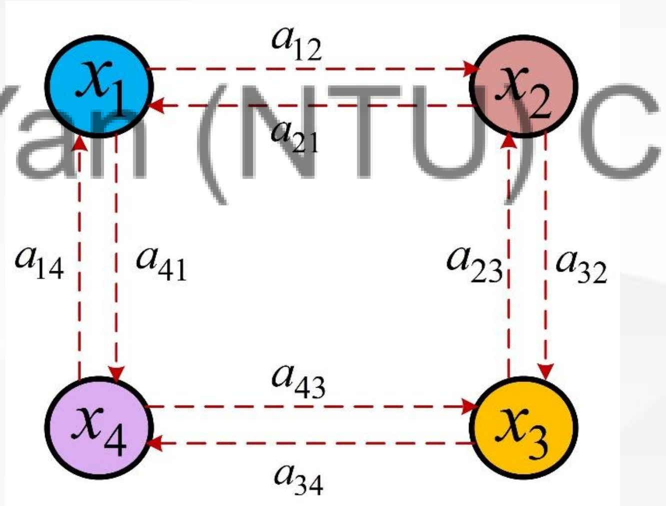
Hierarchical control framework of islanded microgrids

- **Tertiary control (centralized or distributed)**
- Economic dispatch, optimal power flow.
- **Secondary control (centralized or distributed)**
- V/f restoration and accurate power balancing
- **Primary control (decentralized)**
- Inner control loops and droop control
- Local V/f regulation and power sharing

- Distributed Control – Spatial Coordination of DERs

✓ No need for a central controller
✓ One node only communicates with neighbouring nodes
✓ Share communication and computation burden among nodes
✓ Higher resilience, plug-and-play, scalability, data privacy

Example of communication graph



Adjacent matrix of the graph

$$A = \begin{bmatrix} 0 & a_{12} & 0 & a_{14} \\ a_{21} & 0 & a_{23} & 0 \\ 0 & a_{32} & 0 & a_{34} \\ a_{41} & 0 & a_{43} & 0 \end{bmatrix}$$

a) Average consensus control

$$\dot{x}_i(t) = \sum_{j\in N_i} a_{ij}(t)(x_j(t) - x_i(t))$$

$$\lim_{t\to\infty} \left\| x_i(t) - x_j(t) \right\| = 0$$

b) Leader-follower consensus control

$$\dot{x}_i(t) = \sum_{j=1}^{n} a_{ij}(t)(x_j(t) - x_i(t)) + g_i(x_0(t) - x_i(t)).$$

$$\lim_{t\to\infty} \left\| x_i(t) - x_0(t) \right\| = 0$$

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

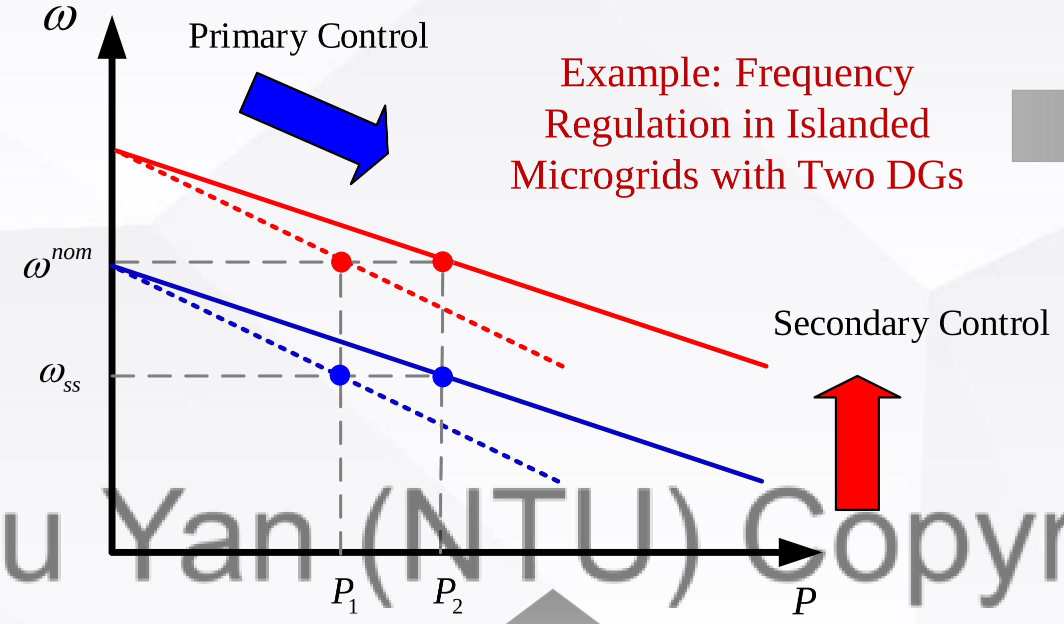
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

Secondary Controller Design – Principle



Example: Frequency Regulation in Islanded Microgrids with Two DGs

Droop control

$$\omega_i = \omega_i^{\text{nom}} - m_i^P P_i$$
$$V_i = V_i^{\text{nom}} - m_i^Q Q_i$$

Taking Derivative

$$\dot{\omega}_i = \dot{\omega}_i^{\text{nom}} - m_i^P \dot{P}_i$$
$$\dot{V}_i = \dot{V}_i^{\text{nom}} - m_i^Q \dot{Q}_i$$

Problem formulation

$$\omega^{\text{nom}} = \int (\dot{\omega}_i + m_i^P \dot{P}_i) dt = \int (u_i^{\omega} + u_i^P) dt$$
$$V^{\text{nom}} = \int (\dot{V}_i + m_i^Q \dot{Q}_i) dt = \int (u_i^V + u_i^Q) dt$$

Apply consensus control rule

$$u_i^{\omega} = \sum_{j=1}^{N} a_{ij} (\omega_j - \omega_i) + g_i (\omega^{ref} - \omega_i)$$
$$u_i^{P} = \sum_{j=1}^{N} a_{ij} (m_j^P P_j - m_i^P P_i)$$
$$u_i^{V} = \sum_{j=1}^{N} a_{ij} (V_j - V_i) + g_i (V^{ref} - V_i)$$
$$u_i^{Q} = \sum_{j=1}^{N} a_{ij} (m_j^Q Q_j - m_i^Q Q_i)$$

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

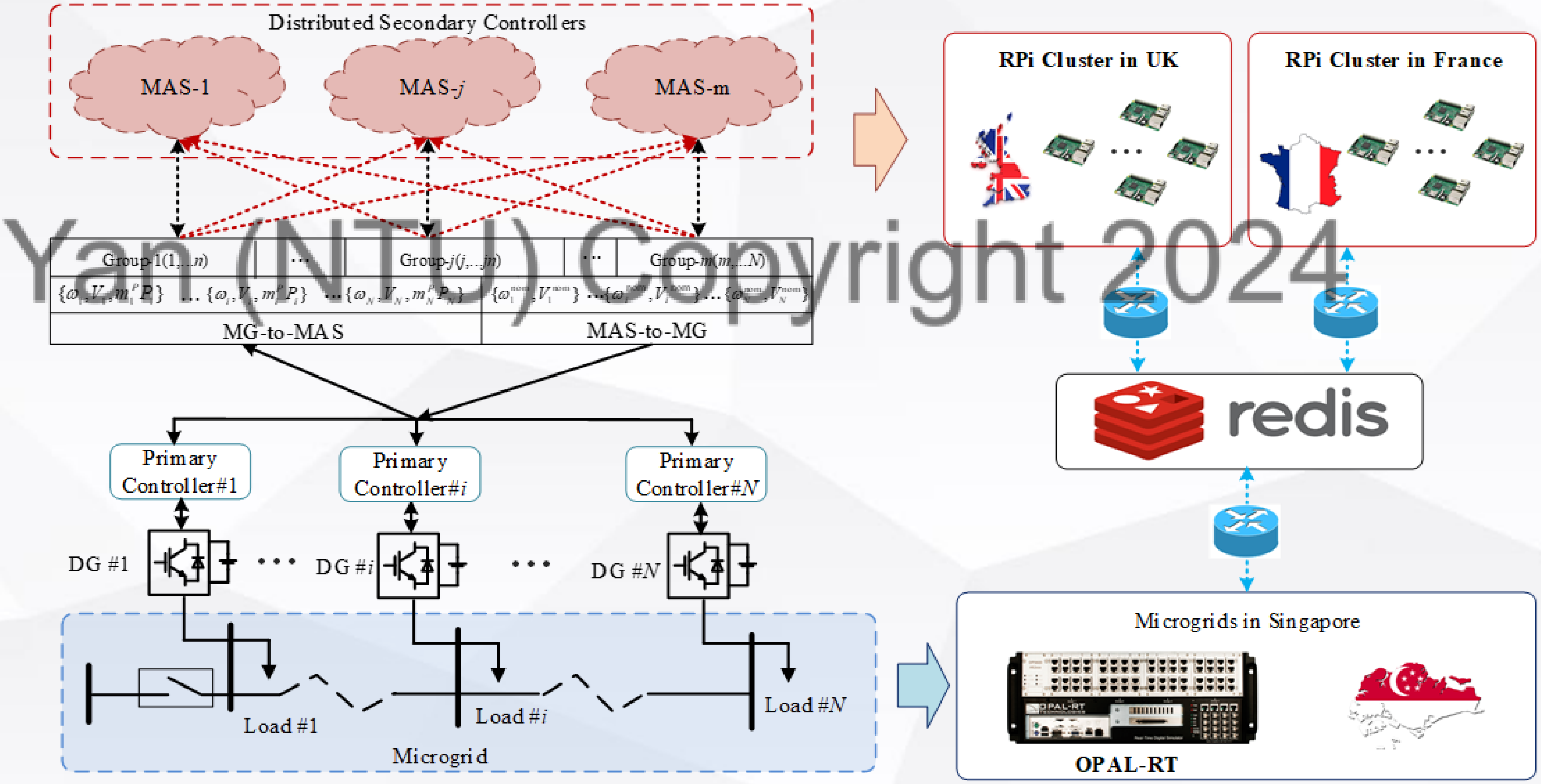
6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

▪ Cross-national hardware-in-the-loop (HiL) testbed

Jointly developed by NTU (Singapore), University of Strathclyde (UK), and G2E Lab (France)

- Microgrids system with OPAL-RT in Singapore.
- Distributed controllers in Raspberry Pi in UK and France.
- Software environment based on gRPC and data exchange via Redis cloud server.



Y. Wang, T. L. Nguyen, M. H. Syed, **Y. Xu***, *et al* "A Distributed Control Scheme of Microgrids in Energy Internet and Its Multi-Site Implementation." *IEEE Transactions on Industrial Informatics*, 2020. – **Web-of-Science Highly Cited Paper**

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

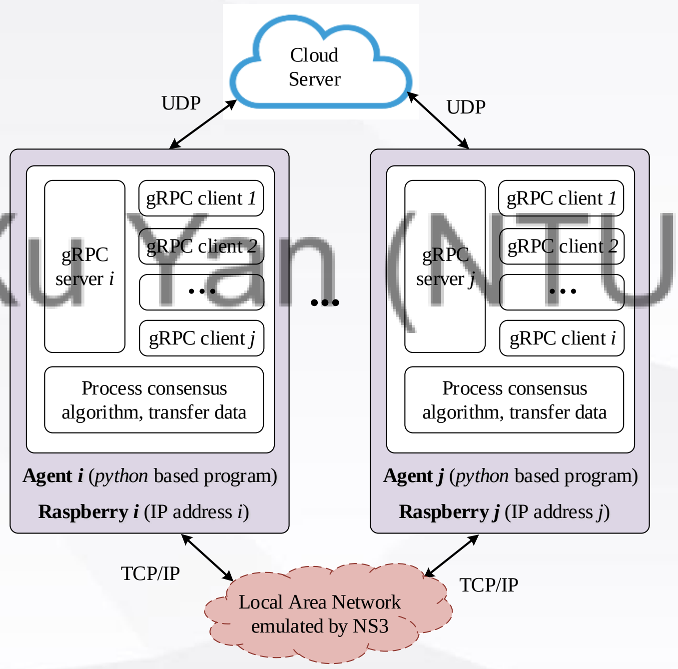
6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

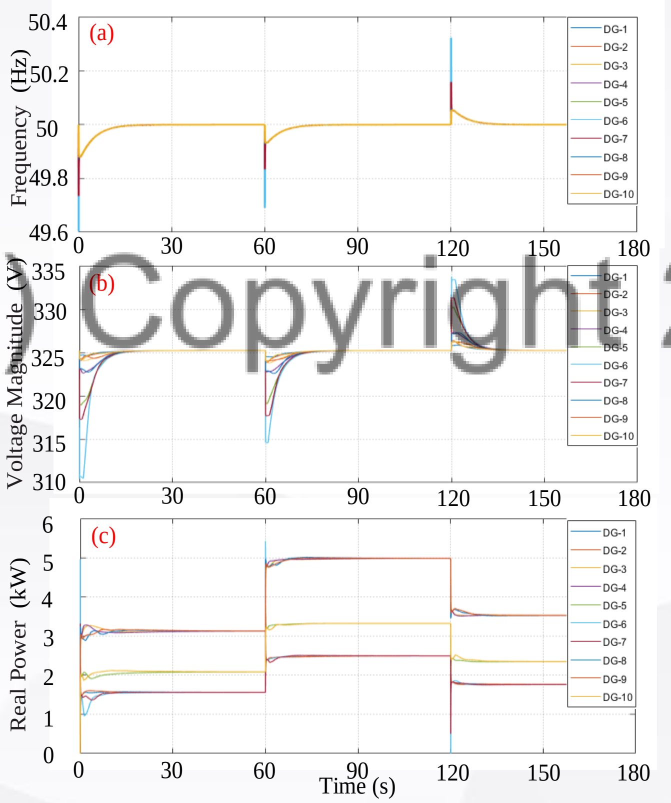
▪ HiL Validation Results – Controller performance

Test system: 10-DG with two controller in UK and France (Each controller for 5 DGs)

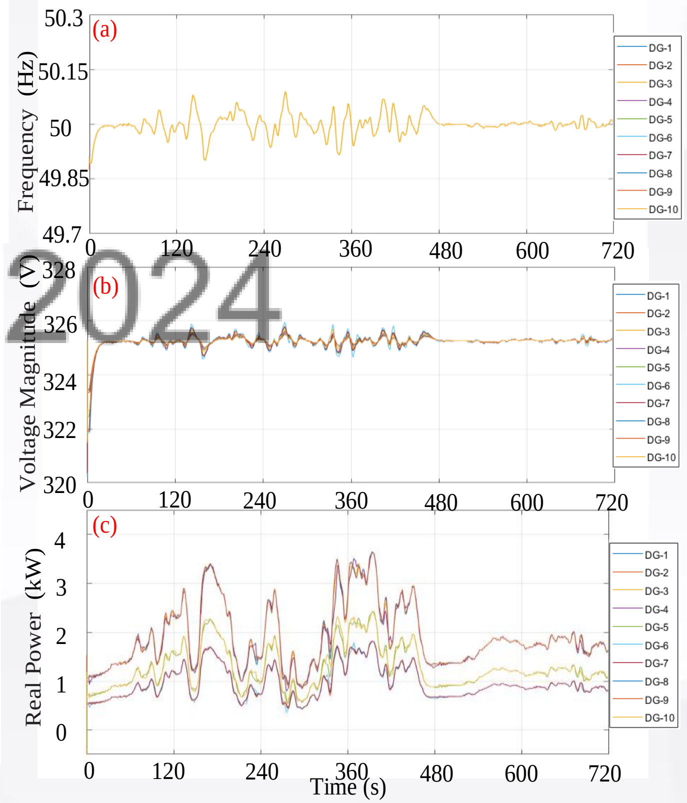
Structure of each agent based on gRPC



a) step load change case



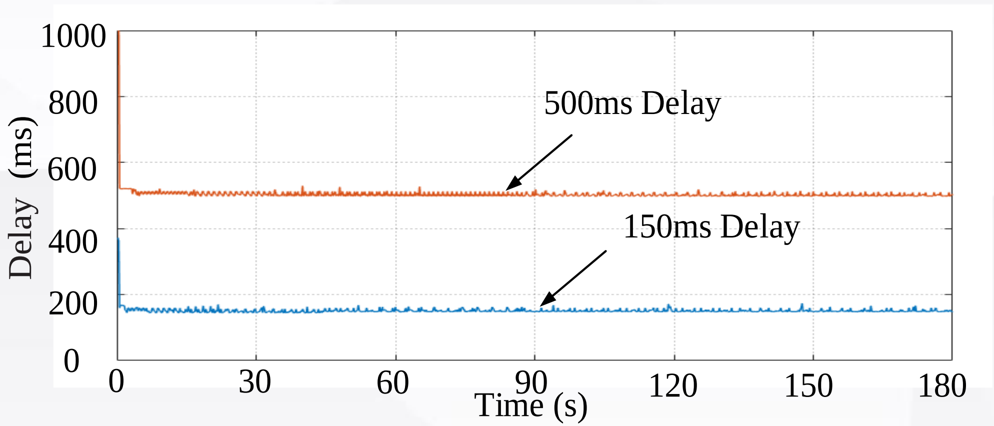
b) Real PV and load profile case



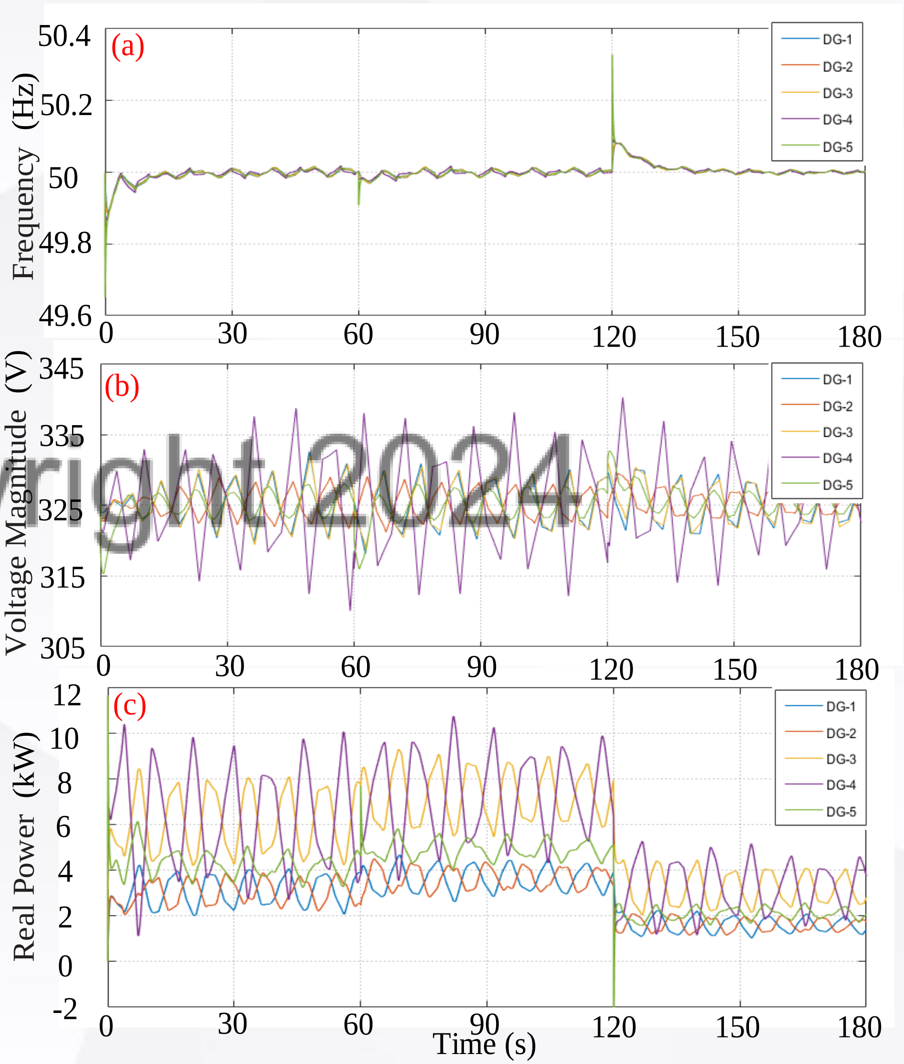
Y. Wang, T. L. Nguyen, M. H. Syed, **Y. Xu*.** "A Distributed Control Scheme of Microgrids in Energy Internet and Its Multi-Site Implementation." ***IEEE Transactions on Industrial Informatics*, 2020.** **– Web-of-Science Highly Cited Paper**

▪ HiL Validation Results – Communication delay

Communication delay emulated by NS3 simulation tools.



Test system: 5-DG MG with one MAS in UK



System oscillation under large delay, which can be mitigated by tuning the control gain.

- ✓ Larger control gain -> converge faster -> withstand smaller delay.
- ✓ Smaller control gain -> converge slower -> withstand larger delay

Y. Wang, T. L. Nguyen, M. H. Syed, **Y. Xu***. "A Distributed Control Scheme of Microgrids in Energy Internet and Its Multi-Site Implementation." ***IEEE Transactions on Industrial Informatics*, 2020.** **– Web-of-Science Highly Cited Paper**

1. REIDS Project

2. Control

1) Islanded mode

2) Grid-tied mode

3. Operation

1) Energy dispatch

2) Volt/Var regulation

4. Hierarchy coordination

5. Trading

1) Centralized trading

2) P2P trading

6. Planning

1) DG planning

2) ESS planning

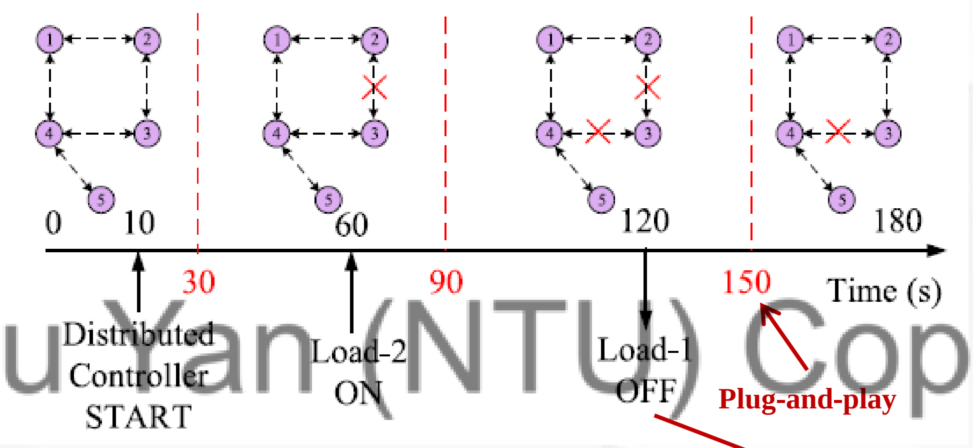
3) PRO algorithm

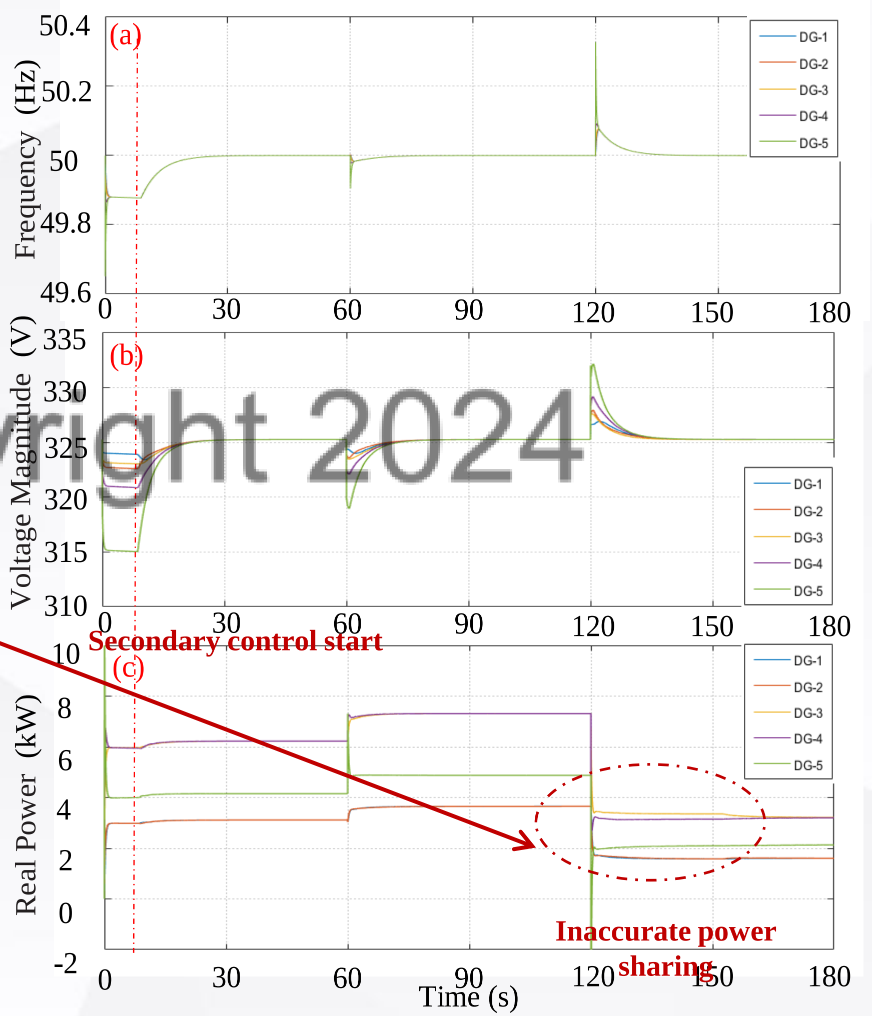
NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

▪ HiL Validation Results – Communication failures

Test system: 5-DG MG with one controller in UK

Communication failures





- ✓ Failure of communication will affect the convergence speed
- ✓ Loss of communication will lead to inaccurate power sharing

Y. Wang, T. L. Nguyen, M. H. Syed, **Y. Xu***. "A Distributed Control Scheme of Microgrids in Energy Internet and Its Multi-Site Implementation." *IEEE Transactions on Industrial Informatics*, 2020. – **Web-of-Science Highly Cited Paper**

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

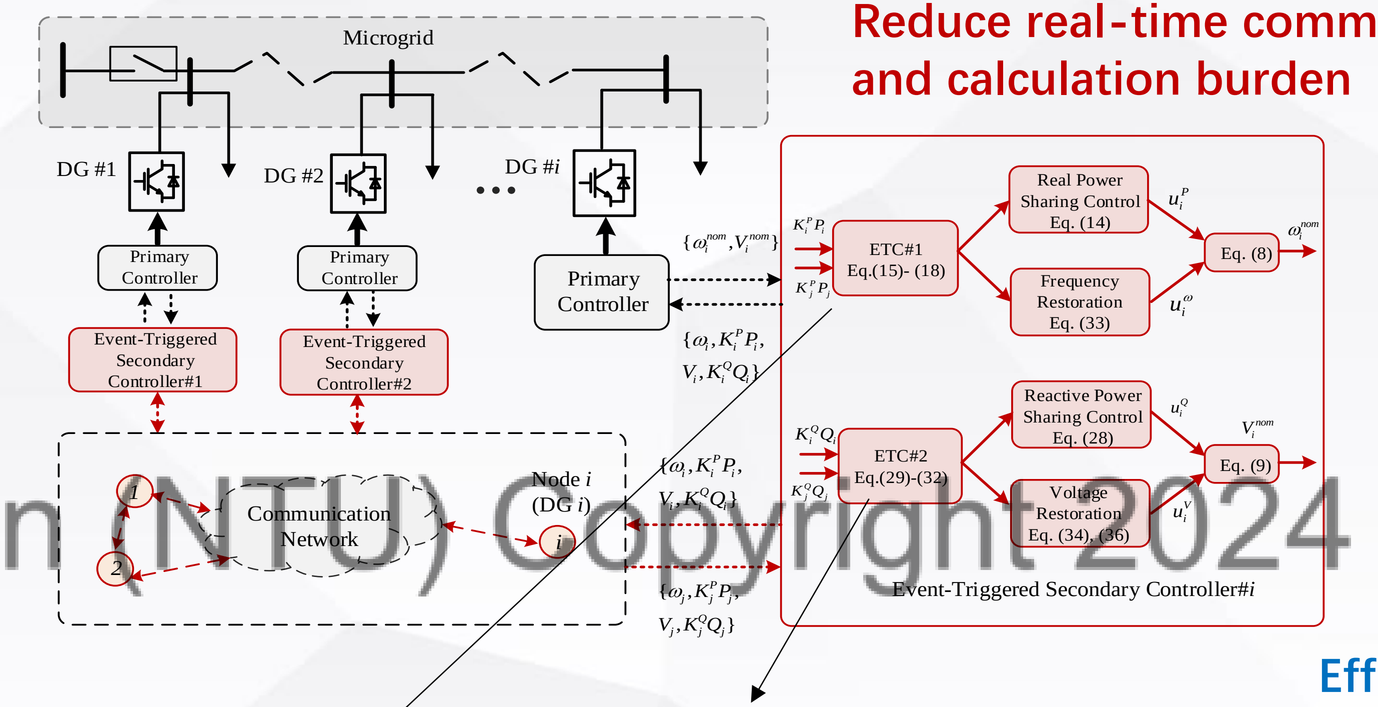
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG TECHNOLOGICAL UNIVERSITY
SINGAPORE

Event-Triggered Distributed Control of Islanded Microgrids



Reduce real-time communication and calculation burden

Event-Trigger Condition for *f* and P:

$$f_i^P(t) = \left\|e_i^P(t)\right\|^2 - \frac{\sigma_i^P \alpha^P (1-\alpha^P d_i)}{d_i}\left\|\delta_i^P(t)\right\|^2$$

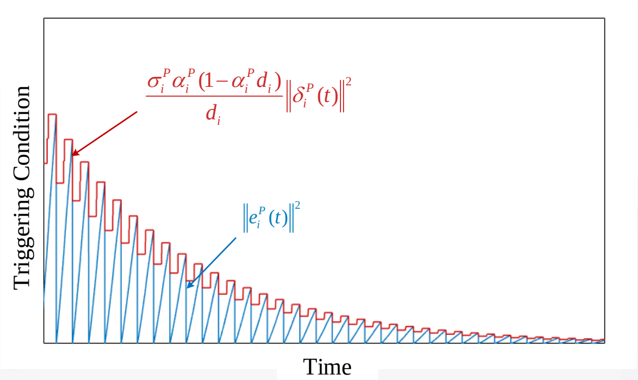
$$t_k^{Pi} = \inf\{t > t_{k-1}^{Pi} \mid f_i^P(t) = 0\}$$

Event-Trigger Condition for V and Q:

$$f_i^Q(t) = \left\|e_i^Q(t)\right\|^2 - \frac{\sigma_i^Q \alpha^Q (1-\alpha^Q d_i)}{d_i}\left\|\delta_i^Q(t)\right\|^2$$

$$t_k^{Qi} = \inf\{t > t_{k-1}^{Qi} \mid f_i^Q(t) = 0\}$$

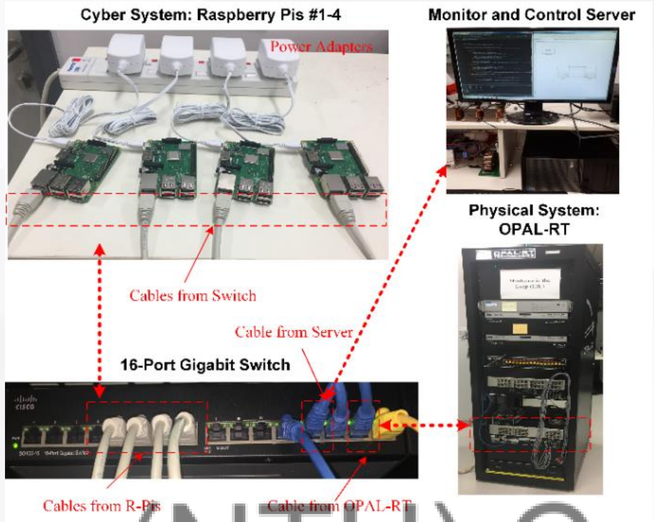
Effects of ETC



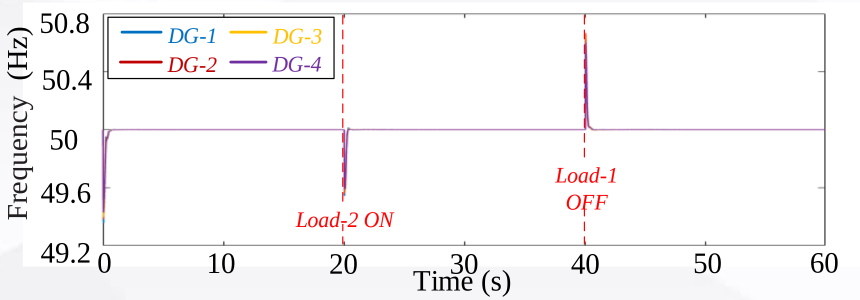
Y. Wang, T. L. Nguyen, **Y. Xu***, et al, “Cyber-Physical Design and Implementation of Distributed Event-Triggered Secondary Control in Islanded Microgrids ,” ***IEEE Trans. Industry Application*, 2019**.

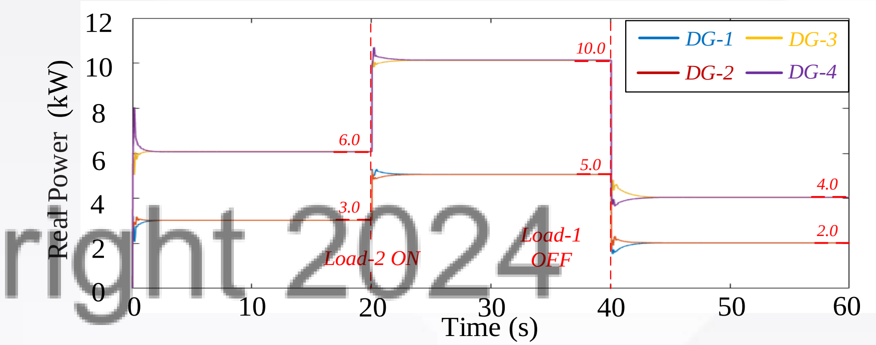
NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

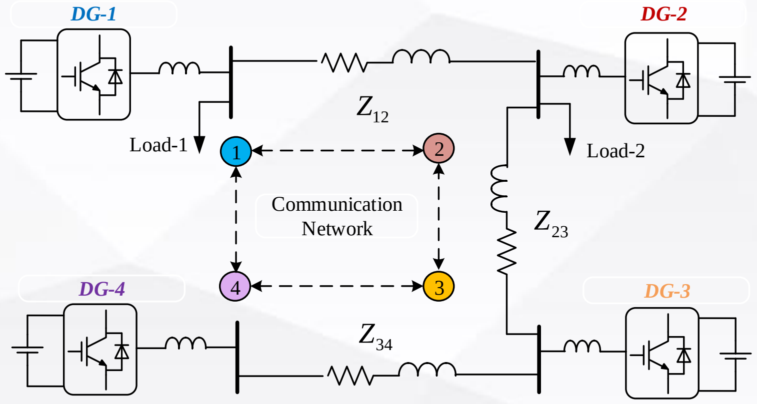
- Controller Hardware-in-the-Loop (CHil) Test



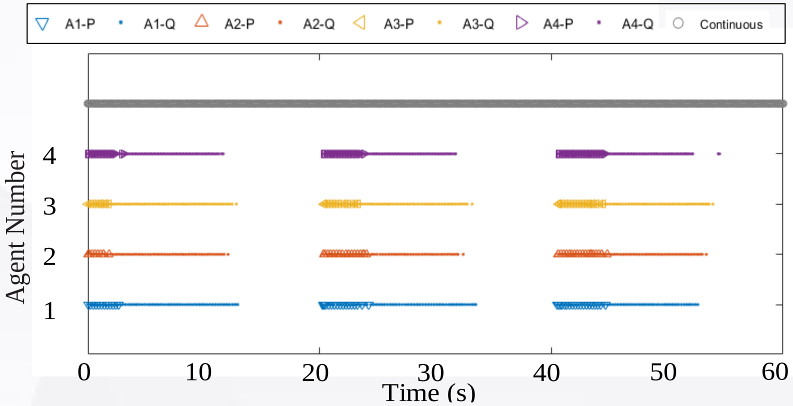
HiL testbed with Raspberry Pi and OPAL-RT







Microgrid topology with four DGs

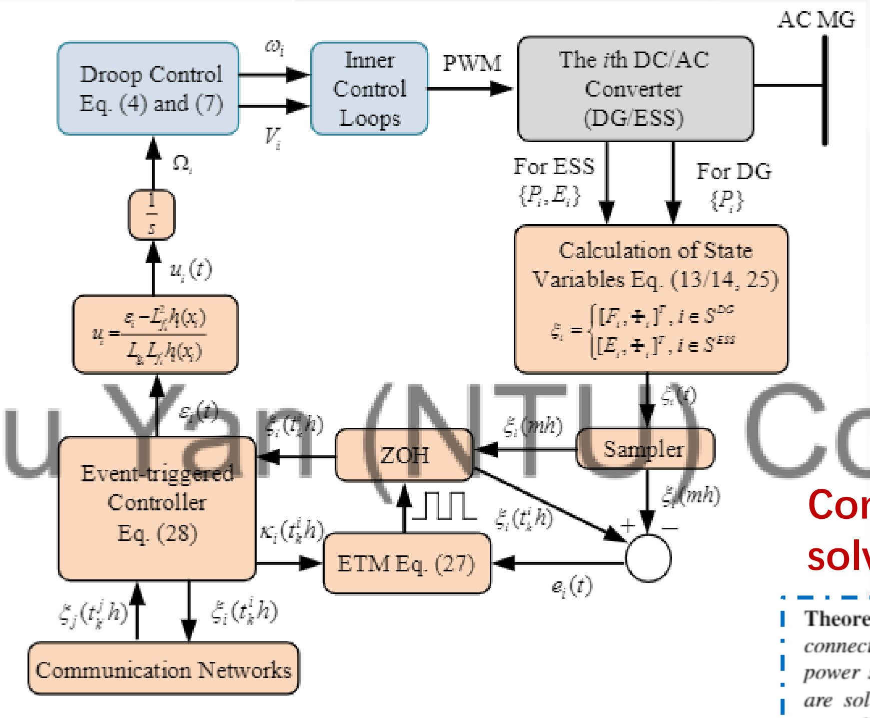


Communication requirement

Y. Wang, T. L. Nguyen, **Y. Xu***, et al, "Cyber-Physical Design and Implementation of Distributed Event-Triggered Secondary Control in Islanded Microgrids ," ***IEEE Trans. Industry Application*, 2019**.

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

▪ Dynamic Event-Triggered Control of Generators and Storages



Unified Control Framework for DGs and ESSs

System Model with DGs and ESSs

$$\dot{F}_i(t) = \Phi_i(t), i \in S^{DG}$$

$$\xi_i(t) = \begin{cases}[F_i(t)\ \Phi_i(t)\ \Gamma_i(t)]^T, i \in S^{DG}, \\ [E_i(t)\ \Phi_i(t)\ \Gamma_i(t)]^T, i \in S^{ESS}.\end{cases}$$

$$\dot{\xi}_i(t) = A\xi_i(t) + B\varepsilon_i(t)$$

$$A = [0\ 1\ 0; 0\ 0\ 1; 0\ 0\ 0]$$

Event-Triggered Controller Design

$$\varepsilon_i(t) = K\sum_{j=1}^{N} a_{ij}[\xi_i(t_k^i h) - \xi_j(t_{k'}^j h)]$$

Control gain K design by solving LMI

Dynamic Event-triggering Mechanism

Theorem 1. *Assume that the communication graph $\mathcal{G}$ is connected. For given γ, δ and h, the proportional active power sharing and energy balancing problems (20) and (21) are solved asymptotically by the distributed event-triggered controller (30) with event-triggered mechanism (28) if there exist matrices $Q > 0$, $P > 0$, $R > 0$, $\Sigma > 0$, K and S such that $\begin{bmatrix} R & S \\ S^T & R \end{bmatrix} > 0$ and $\Psi(\lambda_i) < 0$, where*

$$\Psi(\lambda_i) = \begin{bmatrix} \Psi_{11} & * & * & * & * \\ \Psi_{21}(\lambda_i) & \Psi_{22}(\lambda_i) & * & * & * \\ S^T & \Psi_{32} & \Psi_{33} & * & * \\ \lambda_i K^T B^T P & \delta\lambda_i\Sigma & 0 & \Psi_{44}(\lambda_i) & * \\ \gamma PA & \gamma\lambda_i PBK & 0 & \gamma\lambda_i PBK & \Psi_{55} \end{bmatrix}$$

$$t_{k+1}^i h = \inf_{m\in\mathbb{N}} \{mh > t_k^i h | e_i^T(t)\Sigma e_i(t) \geq \delta\kappa_i^T(t_k^i h)\Sigma\kappa_i(t_k^i h) + \nu_i\beta_i(t)\} \quad (28)$$

where $t_0^i = 0$, $e_i(t) = \xi_i(t_k^i h) - \xi_i(mh)$ $(t \in [mh, mh + h))$ and $\kappa_i(t_k^i h) = \sum_{j=1}^{N} a_{ij}[\xi_i(t_k^i h) - \xi_j(t_{k'}^j h)]$ and $t_{k'}^j = \max_{k\in\mathbb{N}}\{t_k^j | t_k^j h \leq t\}$. The dynamic of $\beta_i(t)$ is given by

$$\dot{\beta}_i(t) = -\beta_i(t) + \kappa_i^T(t_k^i h)W\kappa_i(t_k^i h). \quad (29)$$

The scalar $\delta > 0$ and matrices $\Sigma > 0$ and $W > 0$ will be designed later.

Y. Wang, C. Deng, D. Liu, **Y. Xu***, and J. Dai, “Unified Real Power Sharing of Generator and Storage in Islanded Microgrid via Distributed Dynamic Event-Triggered Control,” ***IEEE Trans. Power Syst., 2021.***

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

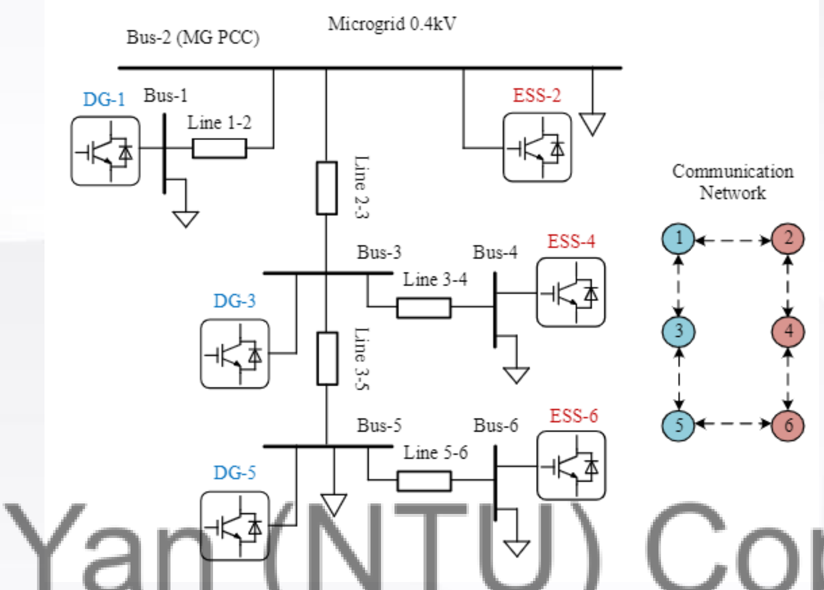
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

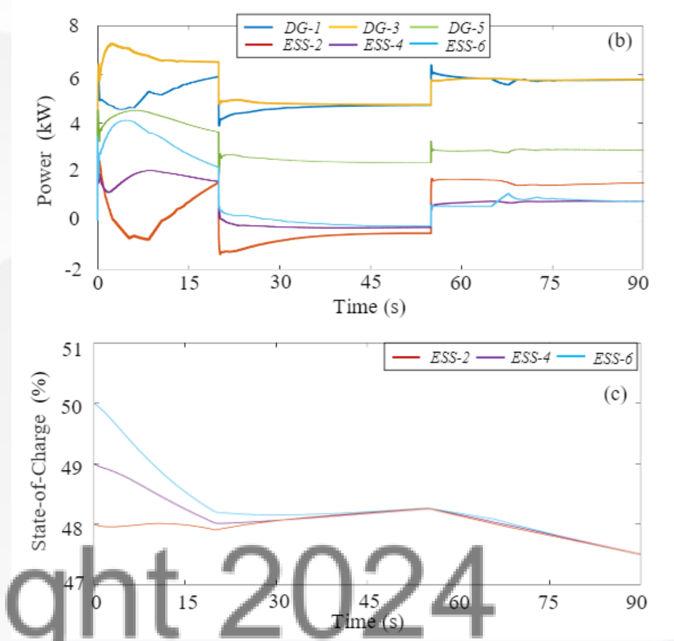
6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

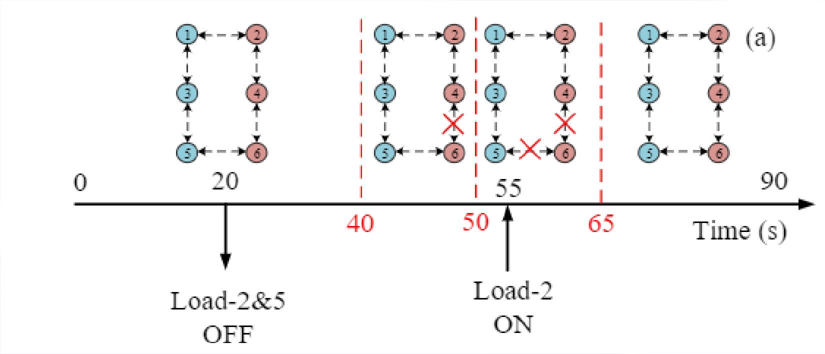
Real-time Simulation Test Results



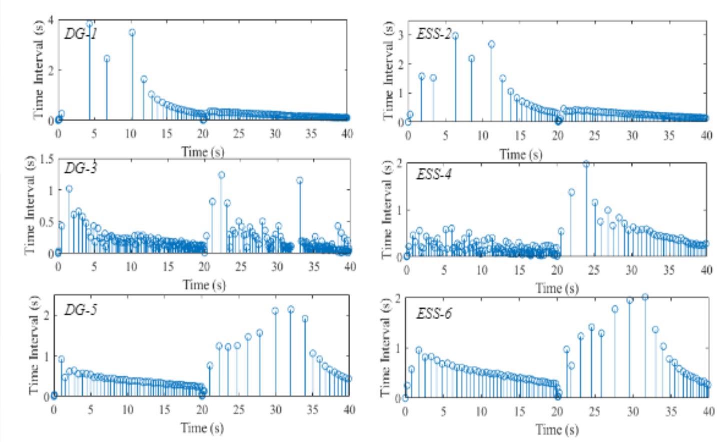
Test Microgrid System



Real-Time Test Results



Time sequence of simulation events



Event-triggered Time Instant

Y. Wang, C. Deng, D. Liu, **Y. Xu***, and J. Dai, "Unified Real Power Sharing of Generator and Storage in Islanded Microgrid via Distributed Dynamic Event-Triggered Control," ***IEEE Trans. Power Syst., 2021.***

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

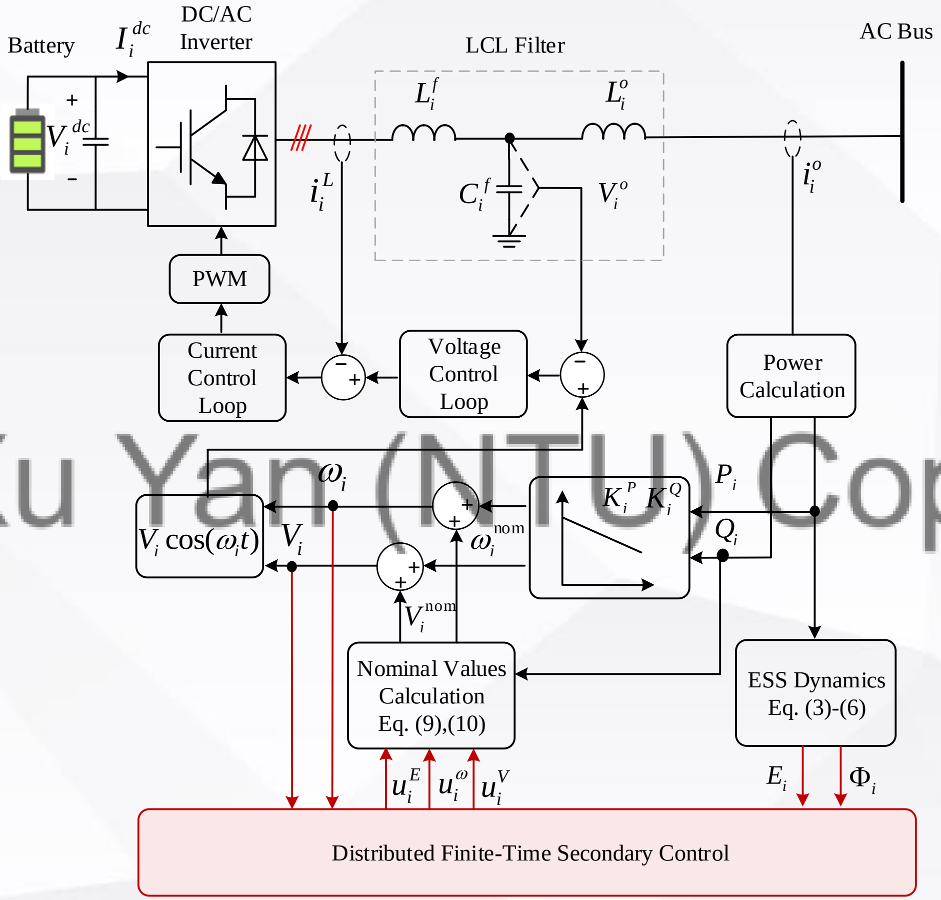
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

▪ Finite-Time Distributed Control of Energy Storage Systems



Control diagram of one ESS unit

Finite-time consensus control law

$$u_i^E = c_1 sig\left(\sum_{j=1}^N a_{ij}(E_j - E_i)\right)^{\alpha_1} + c_2 sig\left(\sum_{j=1}^N a_{ij}(\Phi_j - \Phi_i)\right)^{\alpha_2}$$

$$e_i^\omega = \sum_{j=1}^N a_{ij}(\omega_j - \omega_i) + g_i(\omega^{ref} - \omega_i)$$
$$e_i^V = \sum_{j=1}^N a_{ij}(V_j - V_i) + g_i(V^{ref} - V_i)$$

Control objectives

$$\lim_{t\to T^E}\left|\Phi_i(t) - \Phi_j(t)\right| = 0,\ \lim_{t\to T^E}\left|E_i(t) - E_j(t)\right| = 0$$
$$\Phi_i(t) = \Phi_j(t), E_i(t) = E_j(t)\forall t \geq T^E$$

$$\lim_{t\to T^\omega}\left|\omega_i(t) - \omega^{ref}\right| = 0,\ \omega_i(t) = \omega^{ref}, \forall t \geq T^\omega$$
$$\lim_{t\to T^V}\left|V_i(t) - V^{ref}\right| = 0,\ V_i(t) = V^{ref}, \forall t \geq T^V$$

Y. Wang, T. L. Nguyen, **Y. Xu***, D. Shi, “Distributed control of heterogeneous energy storage systems in islanded microgrids: Finite-time approach and cyber-physical implementation,” ***Int. J. Electrical Power & Energy Systems*, 2020.**

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

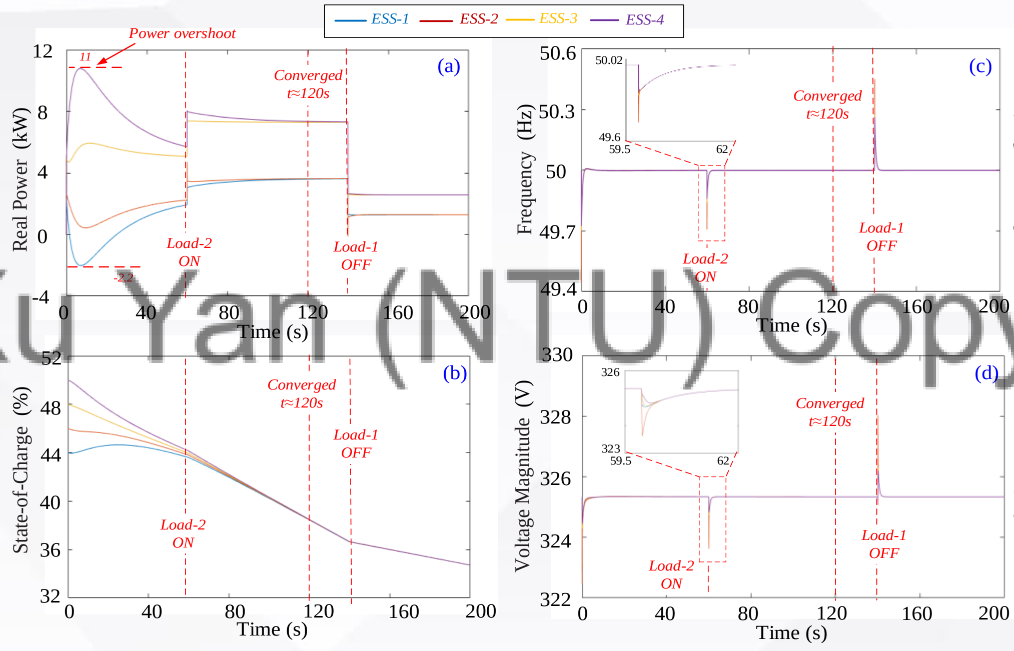
5. Trading
1) Centralized trading
2) P2P trading

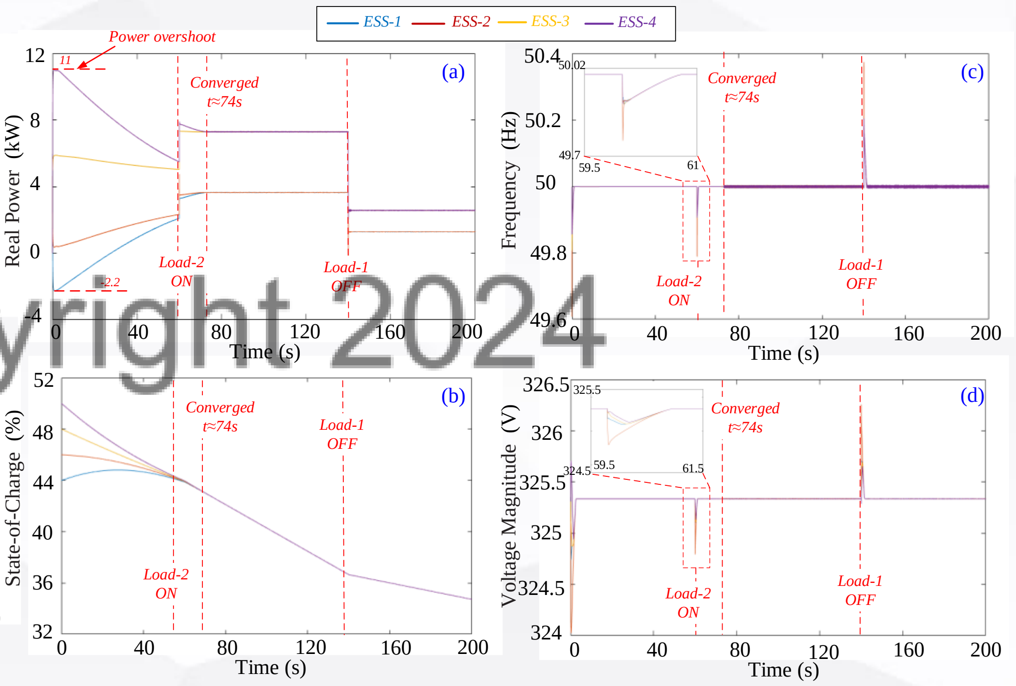
6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG TECHNOLOGICAL UNIVERSITY
SINGAPORE

Finite-Time Distributed Control of Energy Storage Systems

Under the same power overshoot, the proposed controller converges much faster (74s vs 120s)





Linear consensus control

Finite-time consensus control

Y. Wang, T. L. Nguyen, **Y. Xu***, D. Shi, "Distributed control of heterogeneous energy storage systems in islanded microgrids: Finite-time approach and cyber-physical implementation," ***Int. J. Electrical Power & Energy Systems*, 2020.**

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

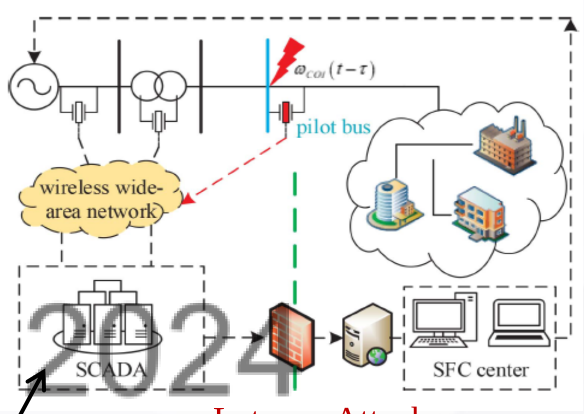
6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG TECHNOLOGICAL UNIVERSITY
SINGAPORE

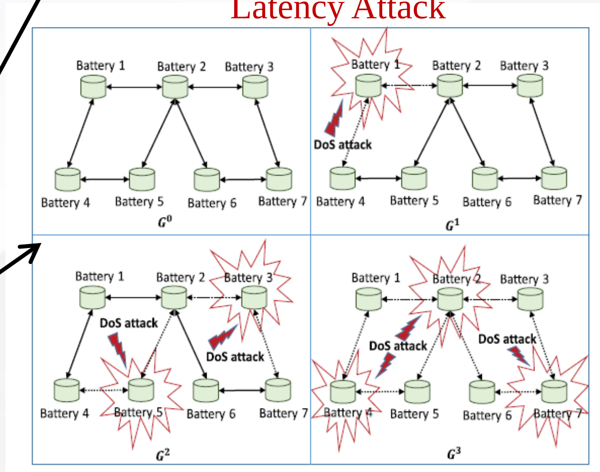
▪ Cyber-Security of Microgrids

A Microgrid might be prone to suffer from cyber-attack due to the huge utilization of information and communication technologies. Regarding the security of CPSs, there are three important aspects to be protected: confidentiality, integrity, and availability.

Security Elements	Definition	Targets	Typical Attack Forms
Confidentiality	Ensure information can only be obtained by authorized users.	Password; Encryption Algorithm	Password Cracking
		Communication Channel	Tapping
Integrity	Maintain the accuracy and consistency of data or information	Electric Quantity	FDIA
		Switching quantity electrical quantity	Topology Tampering Attack
		Clock Signal; Timing Protocol	GPS Synchronous Clock Forgery Attack
Availability	Ensure information can be accessed by authorized parties	Computing; Communication; Storage resources; Communication channels	DoS; Command Delay/Latency Attack



Latency Attack



DoS Attack

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

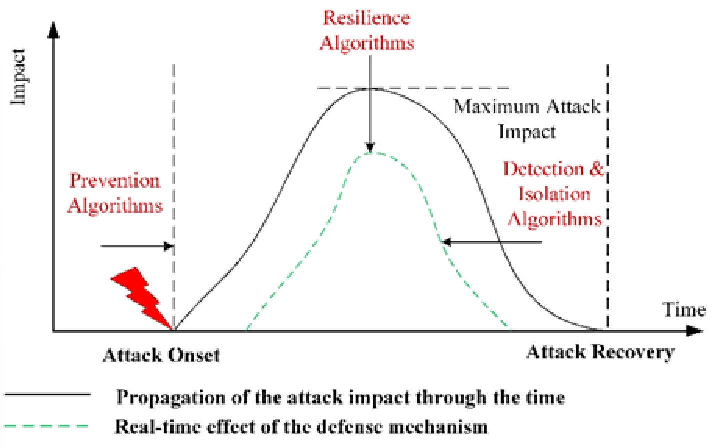
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

Cyber-Resilient Control of Microgrids

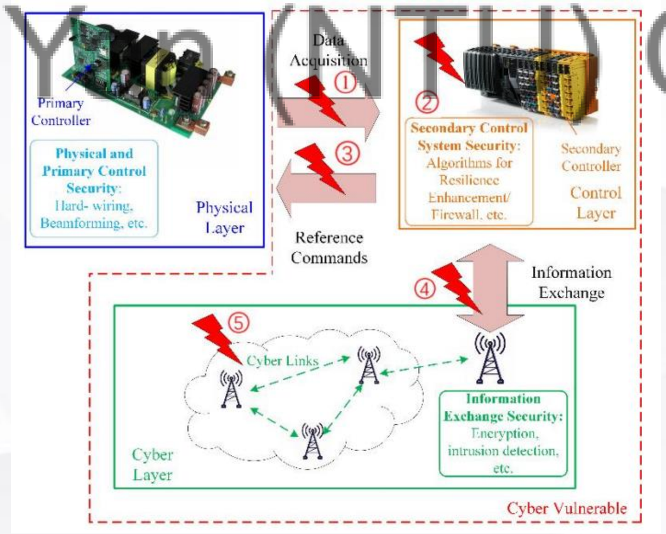


Security of Cyber-Physical System

$$\text{Controller Attack: } u_i^f(t) = \varphi_i(t) u_i(t) + \delta_i(t)$$

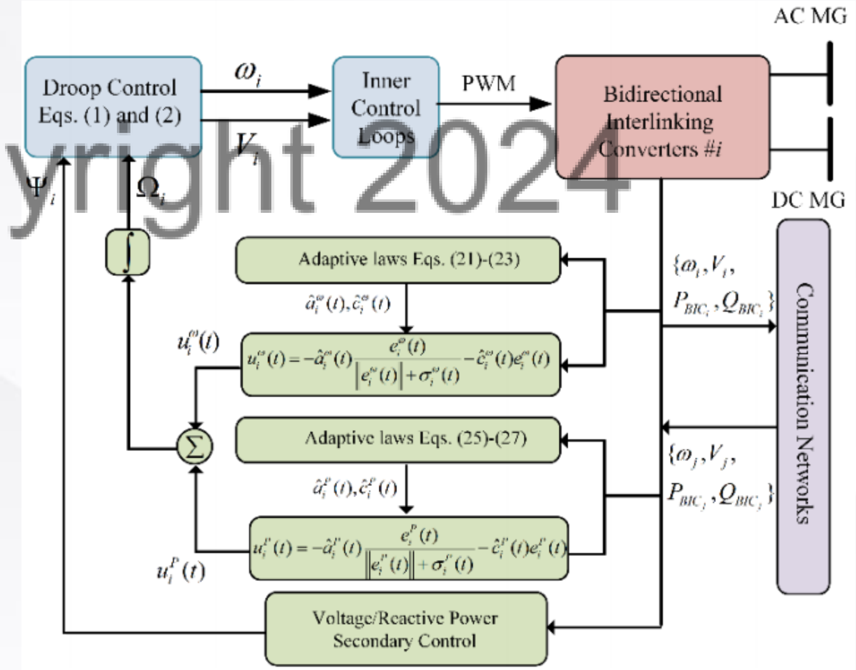
Magnitude manipulation

False data injection



Cyber Vulnerable Process in Microgrid Control

Framework of the Proposed Resilient Controller



Y. Wang, S. Mondal, C. Deng, K. Satpathi, **Y. Xu*** and S. Dasgupta, "Cyber-Resilient Cooperative Control of Bidirectional Interlinking Converters in Networked AC/DC Microgrids," ***IEEE Trans. Industrial Electronics*, 2021.**

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

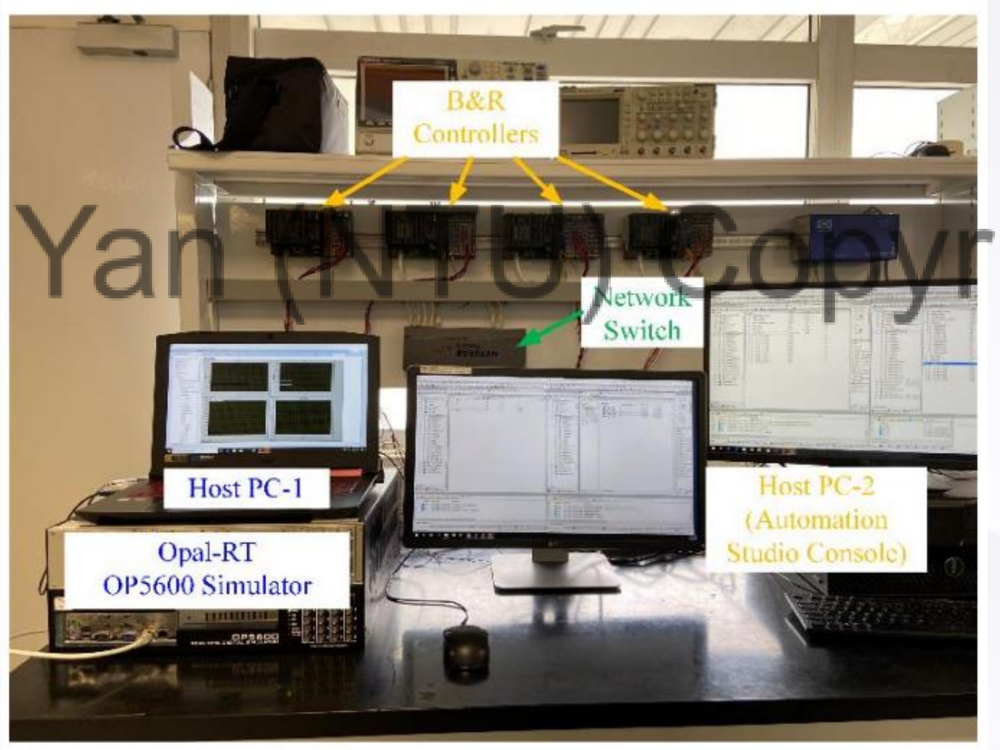
6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

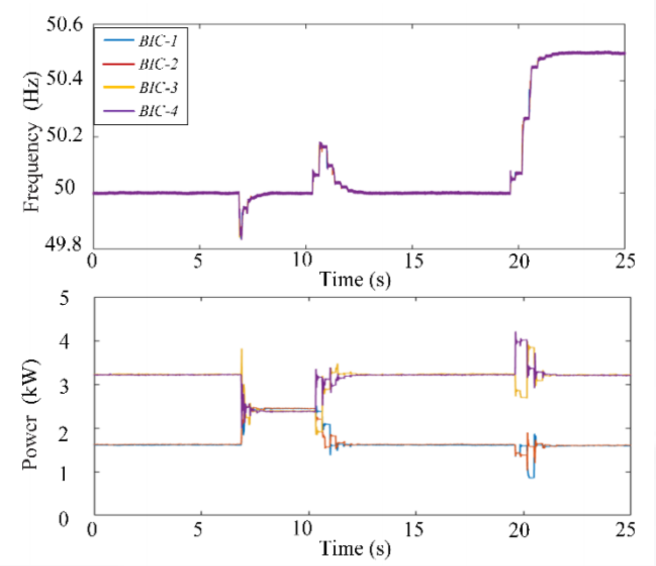
▪ Experimental Test Results

❑ **MAS-MG Platform**

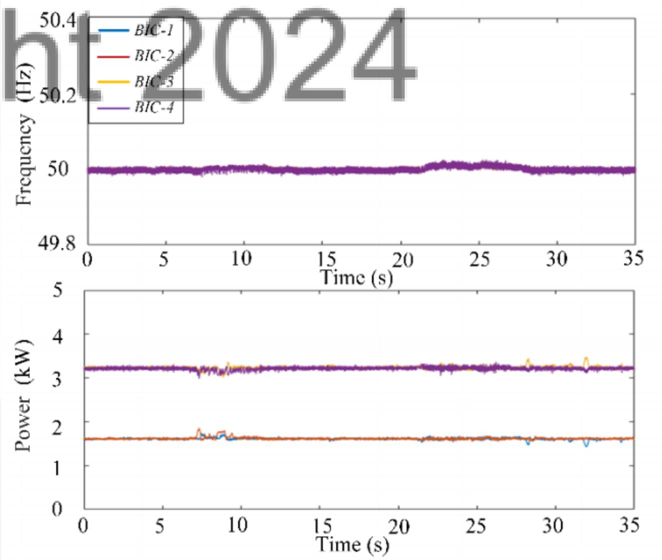
- Multi-agent system with B&R programable logic controllers and network switch
- Enhance the cyber-resilience of the secondary controllers under false data injection attacks.



Experimental Platform of MAS-MG



Original Controllers subject to Cyber Attacks



Performance of Cyber-Resilient Control

Y. Wang, S. Mondal, C. Deng, K. Satpathi, **Y. Xu*** and S. Dasgupta, "Cyber-Resilient Cooperative Control of Bidirectional Interlinking Converters in Networked AC/DC Microgrids," ***IEEE Trans. Industrial Electronics*, 2021.**

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

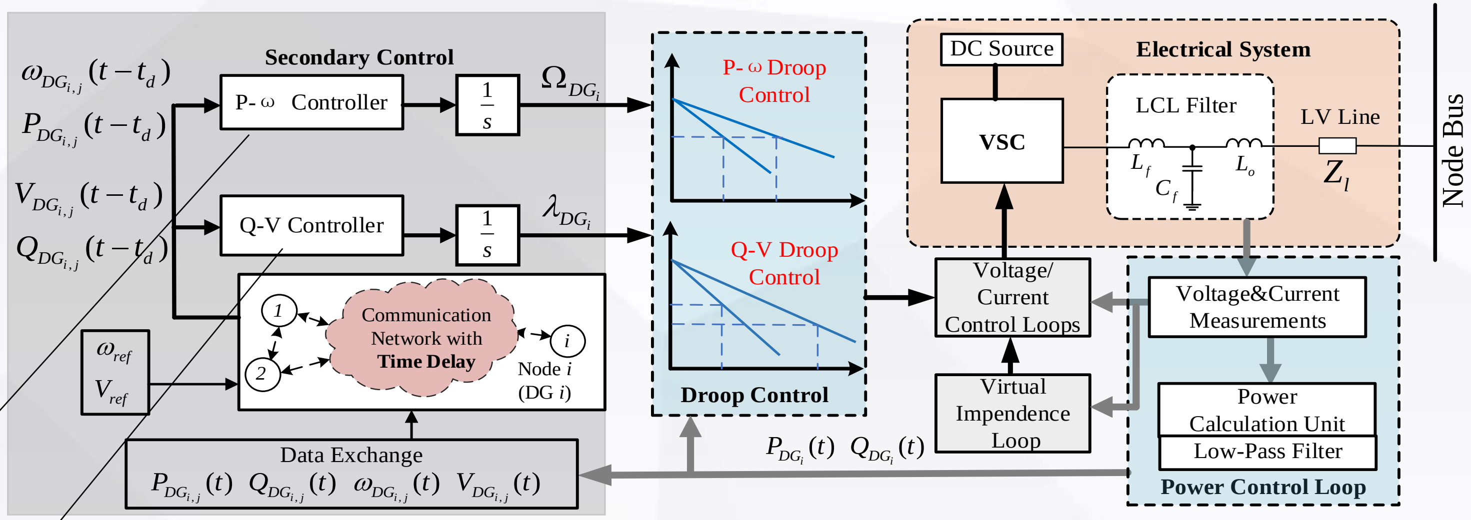
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG TECHNOLOGICAL UNIVERSITY
SINGAPORE

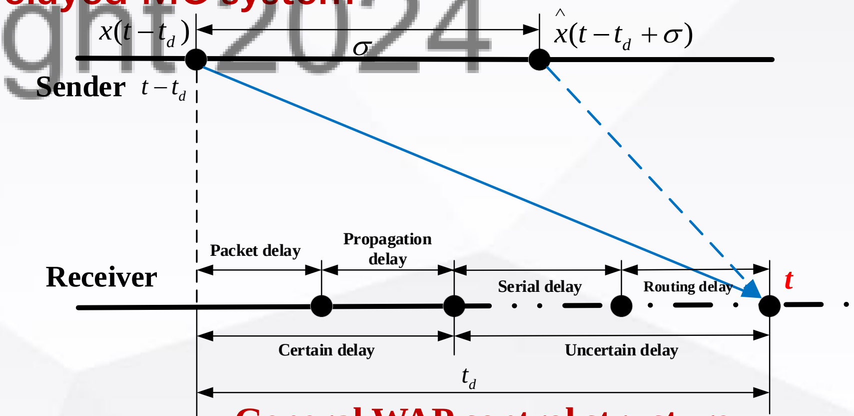
Weight-Average-Prediction Control and Stability Analysis



Control diagram of Time-delayed MG system

$$\dot{\Omega}(t) = -c_\omega * L\left[\omega(t-t_d)+\sigma\dot{\omega}(t-t_d)\right]+c_\omega * G*(I*\omega_{ref}-\omega(t-t_d))$$
$$-c_p * L * k_p\left[P(t-t_d)+\sigma\dot{P}(t-t_d)\right]$$
$$\dot{\lambda}(t) = -c_v * L*\left[v_{od}(t-t_d)+\sigma\dot{v}_{od}(t-t_d)\right]+c_v*G*(I*V_{ref}-v_{od}(t-t_d))$$
$$-c_q * L * k_q\left[Q(t-t_d)+\sigma\dot{Q}(t-t_d)\right]$$

Weight-average-prediction control law



General WAP control structure

$$\Delta\dot{X}_{MG}(t)=A_{MG_1}\Delta X_{MG}(t)+A_{MG_2}\Delta X_{MG}(t-t_d)+A_{MG_3}\Delta\dot{X}_{MG}(t-t_d)$$

Time-delayed MG small-signal model under WAP control

W. Yao, Y. Wang, , **Y. Xu***, C. Deng, and Q. Wu, "Distributed Weight-Average-Prediction Control and Stability Analysis for an Islanded Microgrid with Communication Time Delay," ***IEEE Trans. Power Syst.*, 2021.**

1. REIDS Project

2. Control

1) Islanded mode

2) Grid-tied mode

3. Operation

1) Energy dispatch

2) Volt/Var regulation

4. Hierarchy coordination

5. Trading

1) Centralized trading

2) P2P trading

6. Planning

1) DG planning

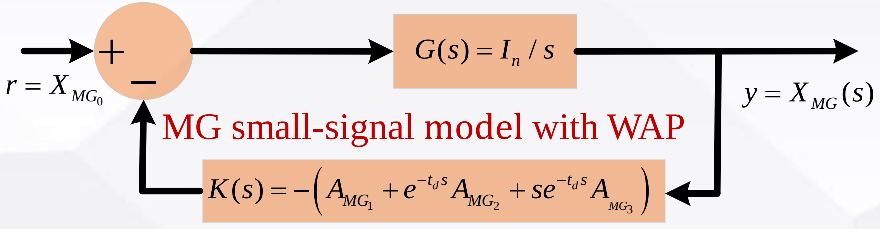
2) ESS planning

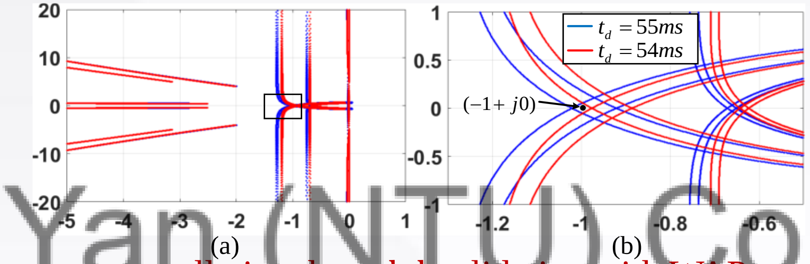
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

Weight-Average-Prediction Control and Stability Analysis

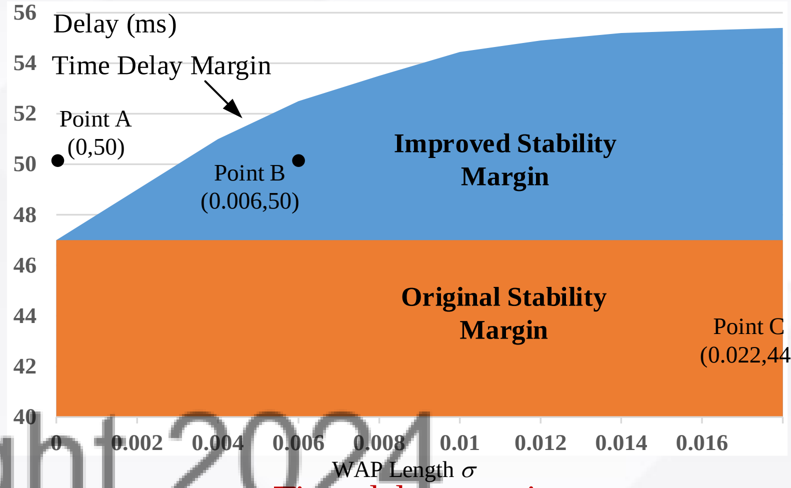
Analysis for fixed time delay (generalized Nyquist stability criterion)





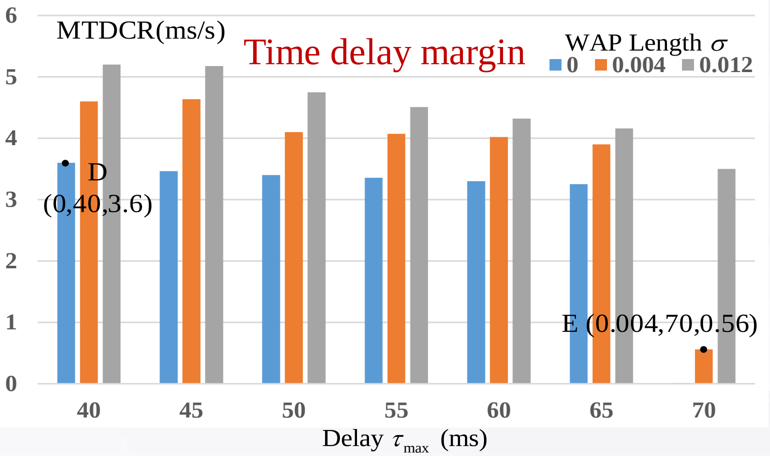
(a) (b)

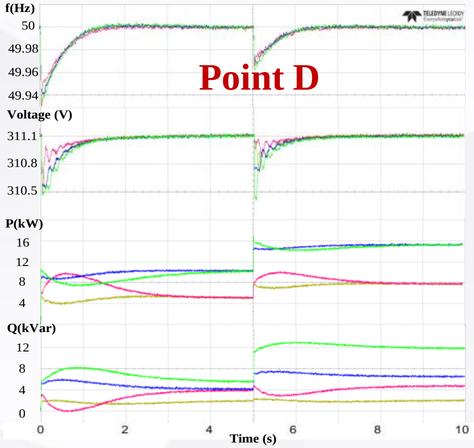
small-signal model validation with WAP

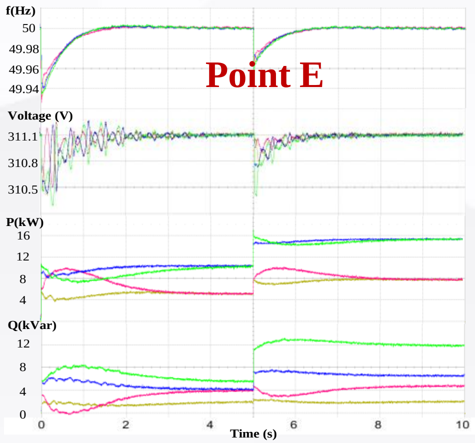


Time delay margin

Analysis for time-varying delay (Lyapunov-Krasovskii function and LMIs)







W. Yao, Y. Wang, , **Y. Xu***, C. Deng, and Q. Wu, "Distributed Weight-Average-Prediction Control and Stability Analysis for an Islanded Microgrid with Communication Time Delay," ***IEEE Trans. Power Syst., 2021.***

1. REIDS Project

2. Control

1) Islanded mode

2) Grid-tied mode

3. Operation

1) Energy dispatch

2) Volt/Var regulation

4. Hierarchy coordination

5. Trading

1) Centralized trading

2) P2P trading

6. Planning

1) DG planning

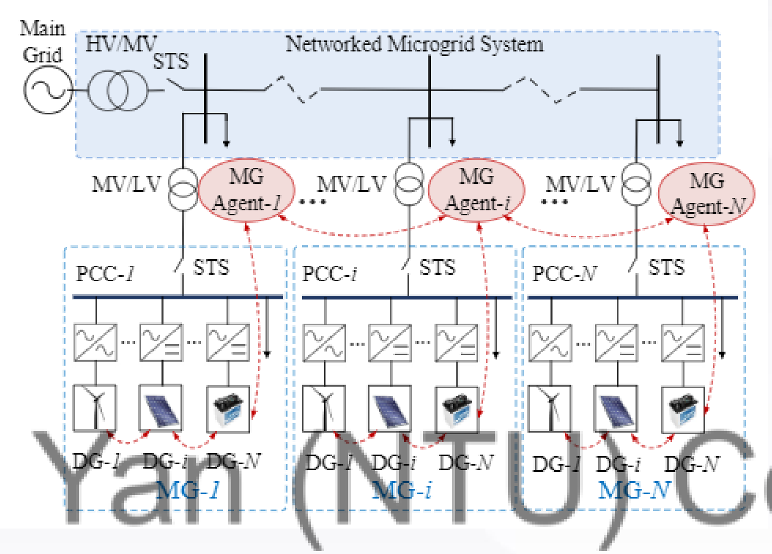
2) ESS planning

3) PRO algorithm

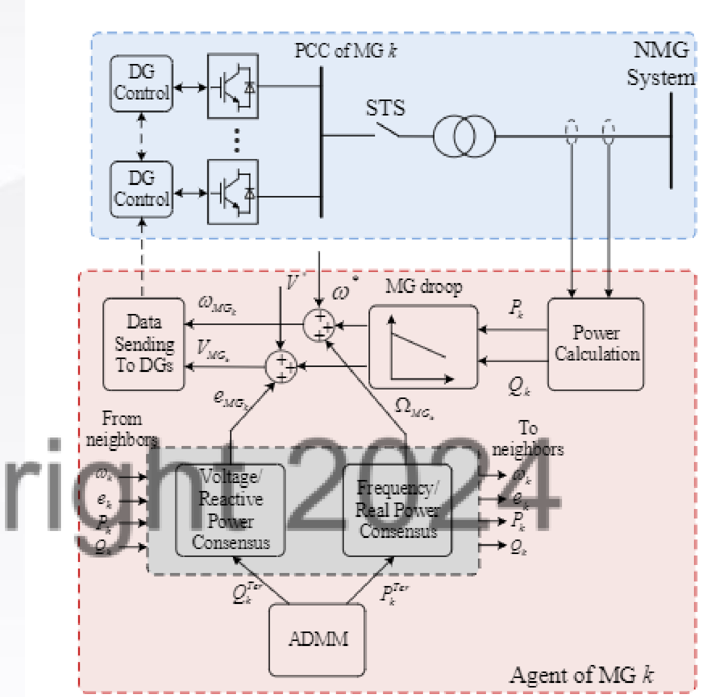
NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

Multi-Layer Multi-Agent Control of Networked Microgrids

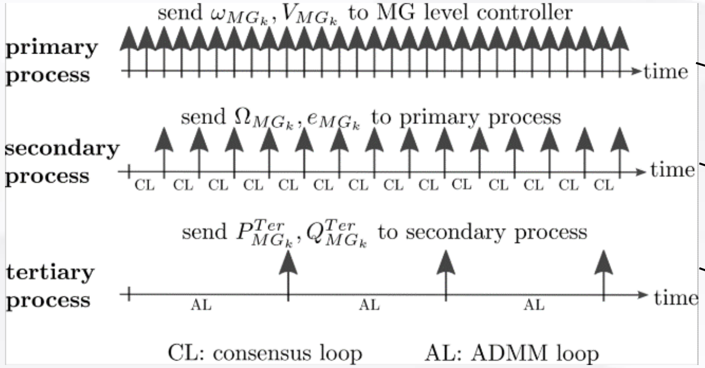
Structure of the Networked Microgrid System



Control System of each Agent



Timescale Coordination of Control Layers



Droop Control Loop：local measurement and signal from secondary control

Consensus Control Loop：local measurement, neighbouring signal, and signal from tertiary control

ADMM Loop：local measurement and neighbouring signal

Y. Wang, T.L. Nguyen, **Y. Xu***, Q.T. Tran, and R. Caire, “Peer-to-Peer Control for Networked Microgrids: Multi-Layer and Multi-Agent Architecture Design,” ***IEEE Trans. Smart Grid*, 2020.**

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

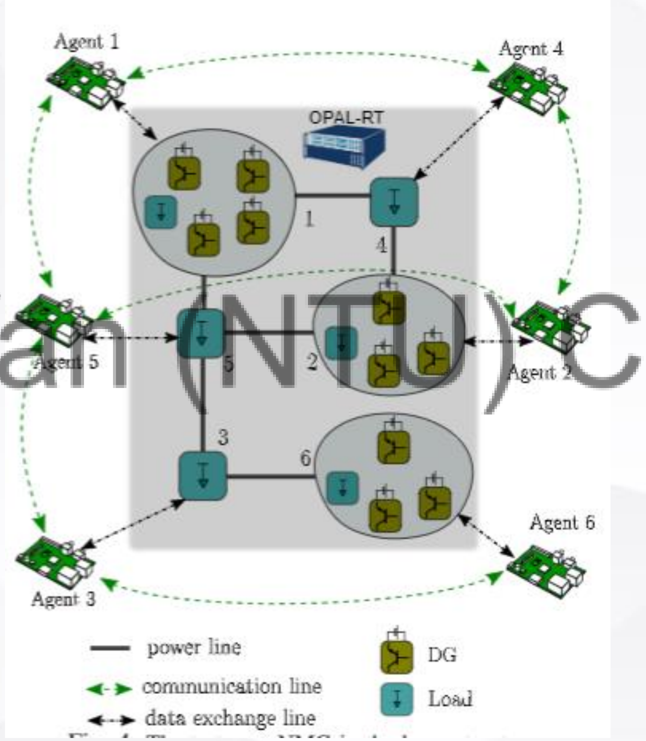
5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

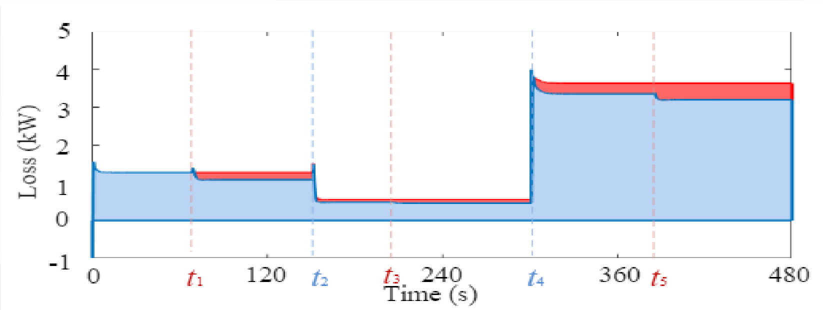
▪ Controller HIL Test Results

❑ **The proposed method realize frequency/voltage regulation, real power sharing and network loss minimization.**

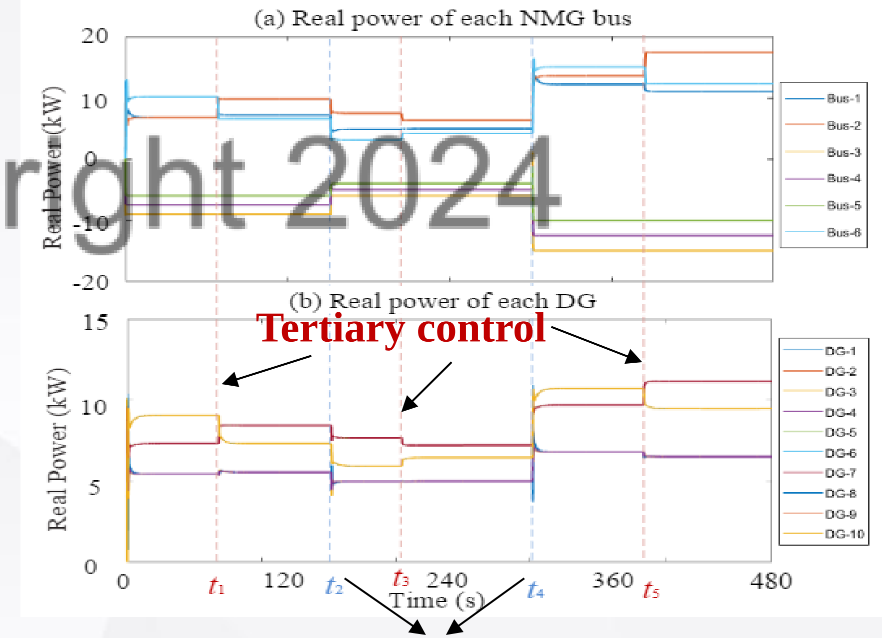


Structure of the controller HIL test system

System network loss minimization



Real power among buses and DGs



Tertiary control

Load change

Performance of Cyber-Resilient Control

Y. Wang, T.L. Nguyen, **Y. Xu***, Q.T. Tran, and R. Caire, "Peer-to-Peer Control for Networked Microgrids: Multi-Layer and Multi-Agent Architecture Design," ***IEEE Trans. Smart Grid* , 2020.**

Grid-connected mode of Microgrids (DER support)

Voltage control support:

mitigate voltage deviation

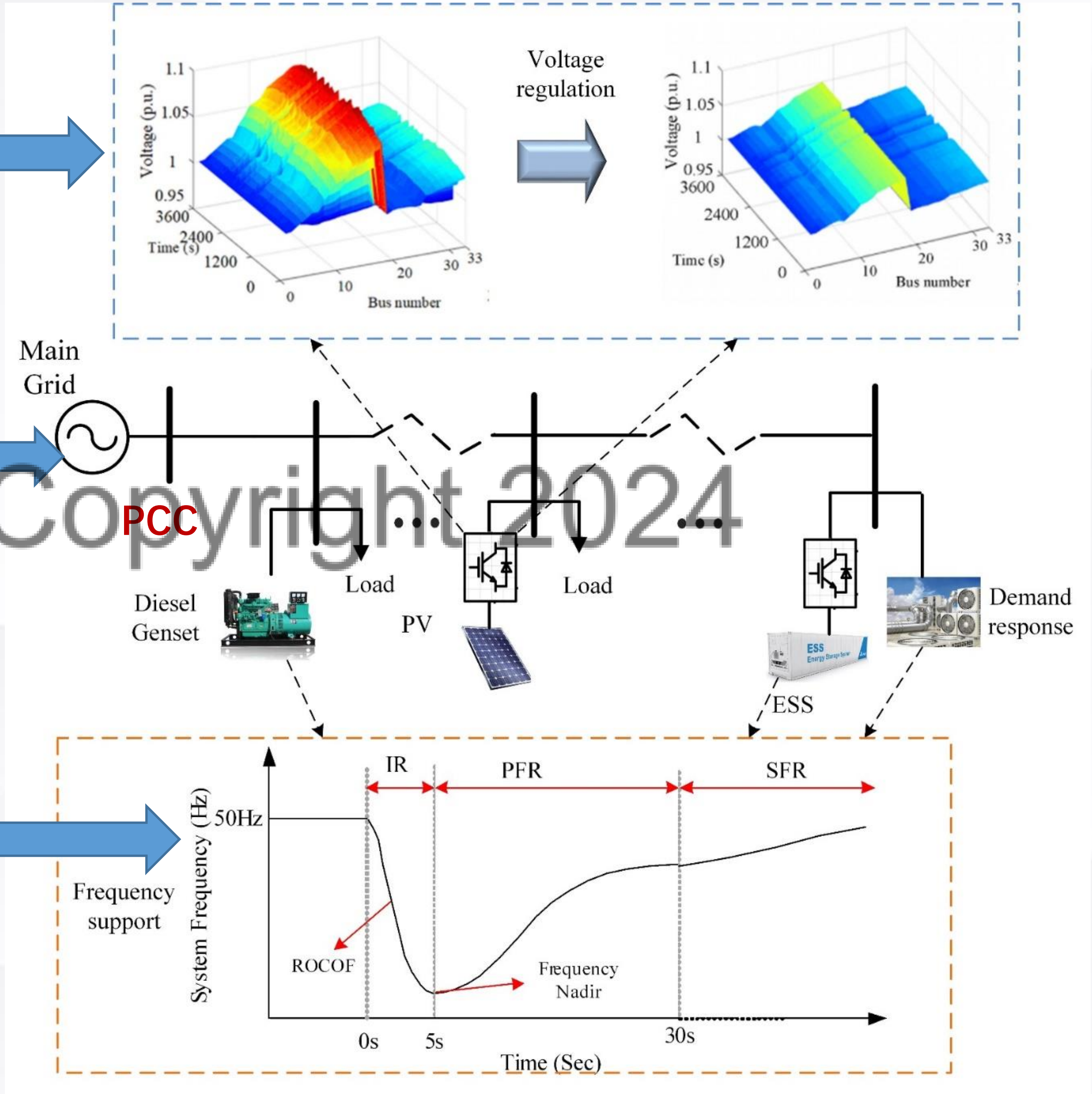
(seconds to minutes)

Frequency and voltage are dominated by the main grid through point of coupling connection (PCC).

Frequency control support:

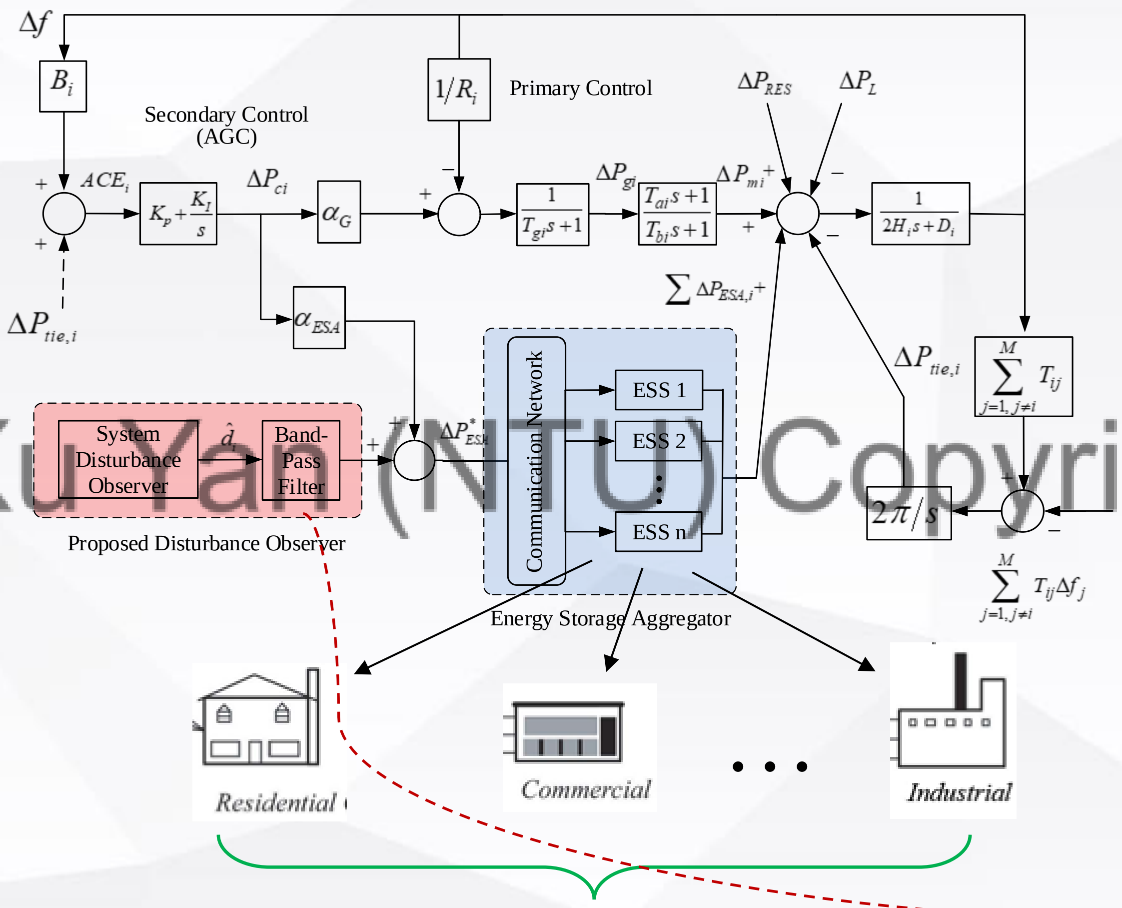
mitigate frequency variation

(ms to seconds)



▪ Frequency Support from Aggregated Small-Scale Energy Storage Units

Proposed load frequency control (LFC) framework



Widespread small-scale ES units, large in number but small in capacity (kWh)

Frequency dynamic model

$$\Delta\dot{f}_i(t) = -\frac{D_i}{2H_i}\Delta f_i(t) + \frac{1}{2H_i}\left(\Delta P_{mi}(t) - \Delta P_{L,i}(t) + \Delta P_{RES,i}(t) - \Delta P_{tie,i}(t) + \boxed{\Delta P_{ESA,i}(t)}\right)$$

$$\Delta\dot{P}_{mi}(t) = -\frac{1}{T_{bi}}\Delta P_{mi}(t) + \frac{1}{T_{bi}}\Delta P_{gi}(t) + \frac{T_{ai}}{T_{bi}}\Delta\dot{P}_{gi}(t)$$

$$\Delta\dot{P}_{gi}(t) = -\frac{1}{T_{gi}}\Delta P_{gi}(t) + \frac{1}{T_{gi}}\Delta P_{ci}(t) - \frac{1}{R_iT_{gi}}\Delta f_i(t)$$

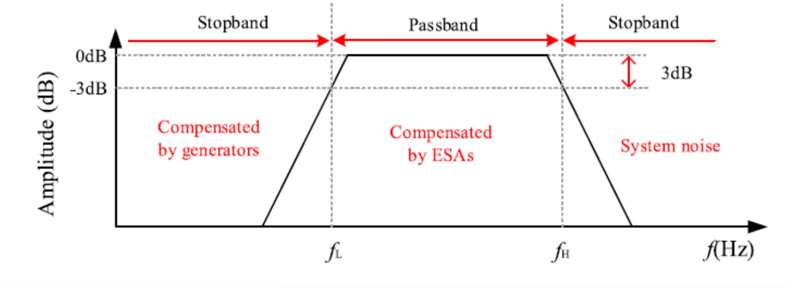
$$\Delta\dot{P}_{tie,i}(t) = 2\pi\cdot\left[\sum_{j=1,j\neq i}^{M} T_{ij}(\Delta f_i(t) - \Delta f_j(t))\right]$$

Tie-line power flow

$$ACE_i(t) = B_i\Delta f_i(t) + \Delta P_{tie,i}(t)$$

$$\Delta P_{ci}(t) = -K_P ACE_i(t) - K_I\int ACE_i(t)$$

Secondary control



Y. Wang, **Y. Xu***, Y. Tang, et al "Aggregated Energy Storage for Power System Frequency Control: A Finite-Time Consensus Approach," ***IEEE Trans. Smart Grid*, May 2018.**

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

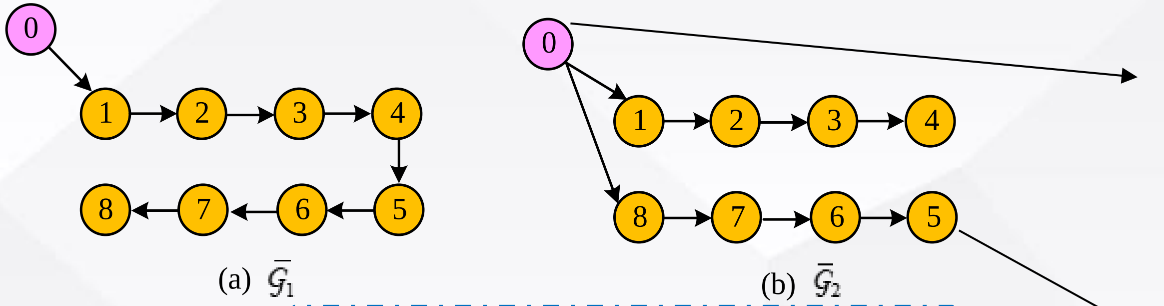
5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG TECHNOLOGICAL UNIVERSITY
SINGAPORE

Frequency Support from Aggregated Energy Storage

Communication topologies of ESSs



Leader model

$$\begin{cases}\dot{e}_0(t)=K_{ESS}\,p_0(t)\\ p_0(t)=\dfrac{P^{*}_{ESA}(t)}{P^{\max}_{ESA}}\end{cases}$$

LFC power reference

ESS model (follower)

$$\begin{cases}\dot{e}_i(t)=K_{ESS}\,p_i(t)\\ \dot{p}_i(t)=u_i(t)\end{cases},\qquad i=1,2...,N.$$

Matrices to describe graph

Adjacent Matrix

$$\boldsymbol{A}=[aij]\qquad a_{ij}=\begin{cases}1, & \text{if } (v_i,v_j)\in\mathcal{E}\\ 0, & \text{otherwise.}\end{cases}$$

Pinning Matrix

$$\boldsymbol{G}=\mathrm{diag}\{gi\}\quad g_i=\begin{cases}1, & \text{if } \exists\,(v_i,v_0)\\ 0, & \text{otherwise.}\end{cases}$$

Proposed Control Protocol: achieve LFC power reference with consensus SOC in finite time

$$u_i(t)=\sum_{j=1}^{N}a_{ij}(sig(e_i(t)-e_j(t))^{\alpha})-g_i(sig(e_i(t)-e_0(t))^{\alpha})$$

Consensus SOC

$$-\gamma\sum_{j=1}^{N}a_{ij}(sig(p_i(t)-p_j(t))^{\beta})-g_i(sig(p_i(t)-p_0(t))^{\beta})$$

LFC power reference

$$\lim_{t\to T_0}\left\|e_i(t)-e_0(t)\right\|=0,\ \ \lim_{t\to T_0}\left\|p_i(t)-p_0(t)\right\|=0$$

$$e_i(t)=e_0(t),\quad p_i(t)=p_0(t),\ \ \forall t\ge T_0,\ \ i=1,2,...N.$$

1. REIDS Project

2. Control

1) Islanded mode

2) Grid-tied mode

3. Operation

1) Energy dispatch

2) Volt/Var regulation

4. Hierarchy coordination

5. Trading

1) Centralized trading

2) P2P trading

6. Planning

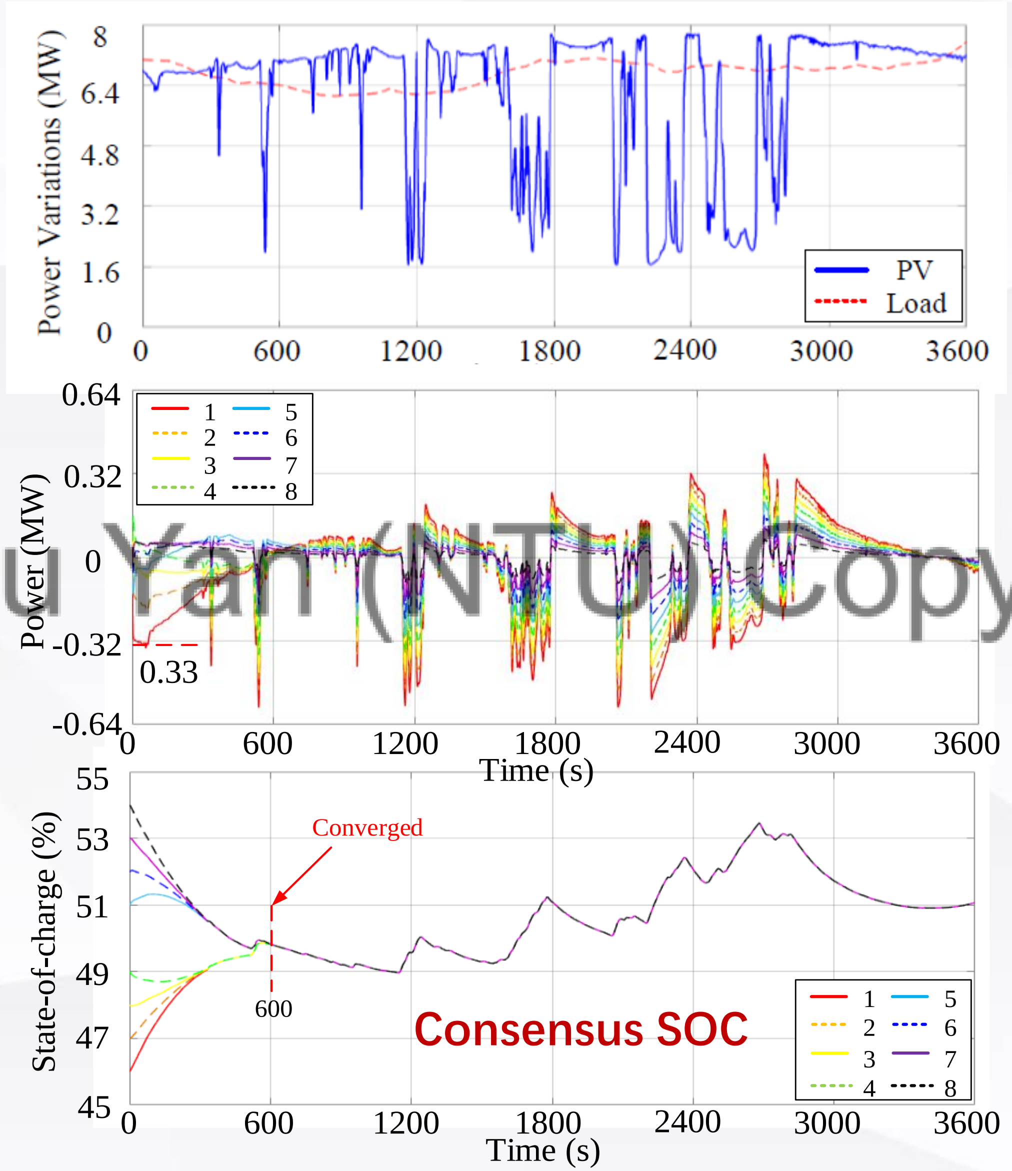
1) DG planning

2) ESS planning

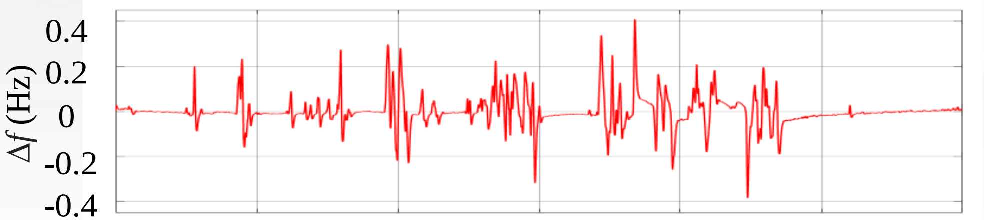
3) PRO algorithm

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

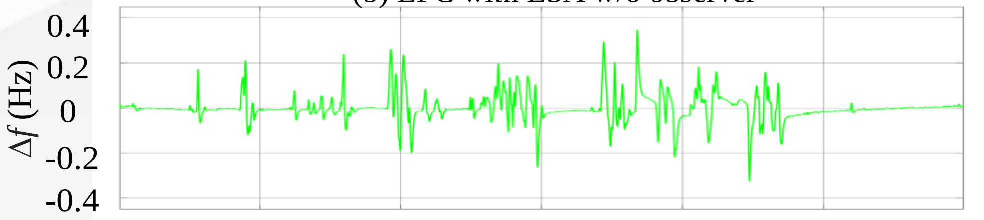
Simulation Results



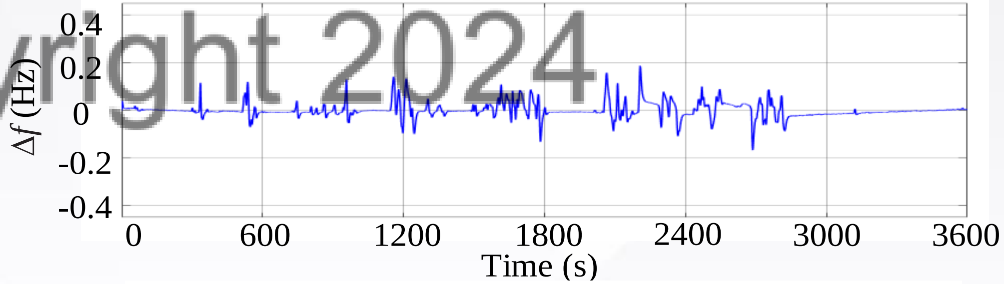
(a) Conventional LFC scheme



(b) LFC with ESA w/o observer



(c) Proposed control scheme



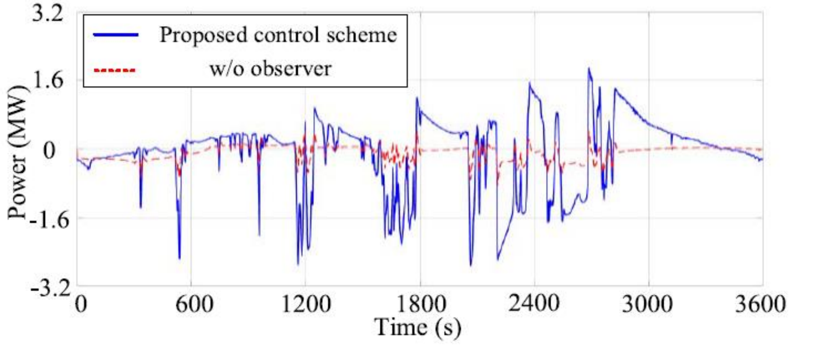
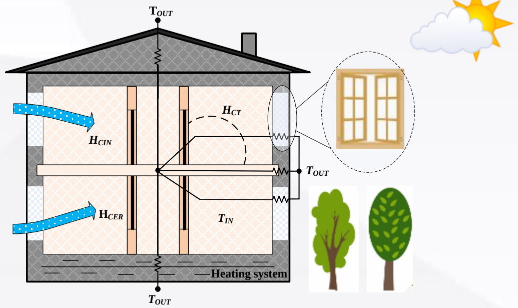


Fig. 11. Total power output of the ESA with and without the proposed disturbance observer.

Thermostatically Controlled Loads (TCLs) for frequency support



Temperature dynamics of TCL:

$$C_{th}\frac{dT_i(t)}{dt}=\frac{T_a(t)-T_i(t)}{R_{th}}-\eta\bar{P}\alpha_i(t),\ \ i\in\mathcal{G}.$$

Heat exchange with the ambient

Thermal energy from VFAC

Assume power state αi is a continuous variable from 0 to 1.

Comfort zone of TCL:

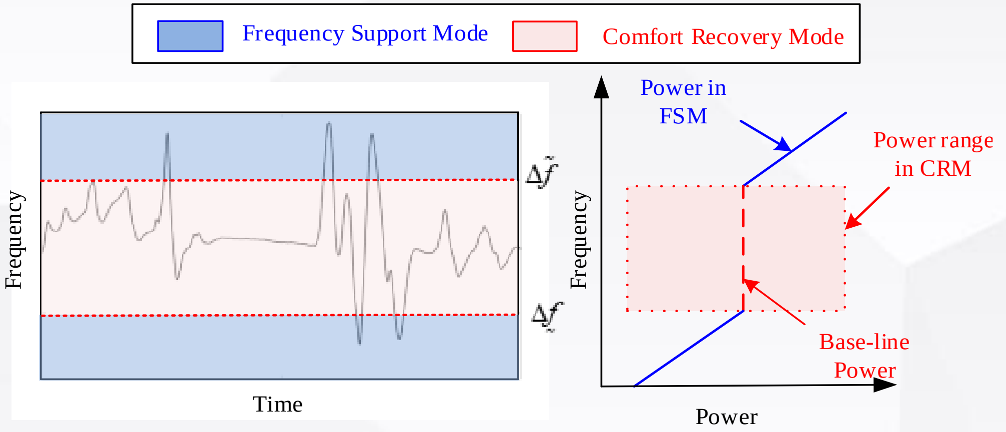
$$\beta_i(t)=\frac{T_i(t)-T_s+\Delta T}{2\Delta T},\ \ i\in\mathcal{G}$$

Comfort state βi is an index from 0 to 1.

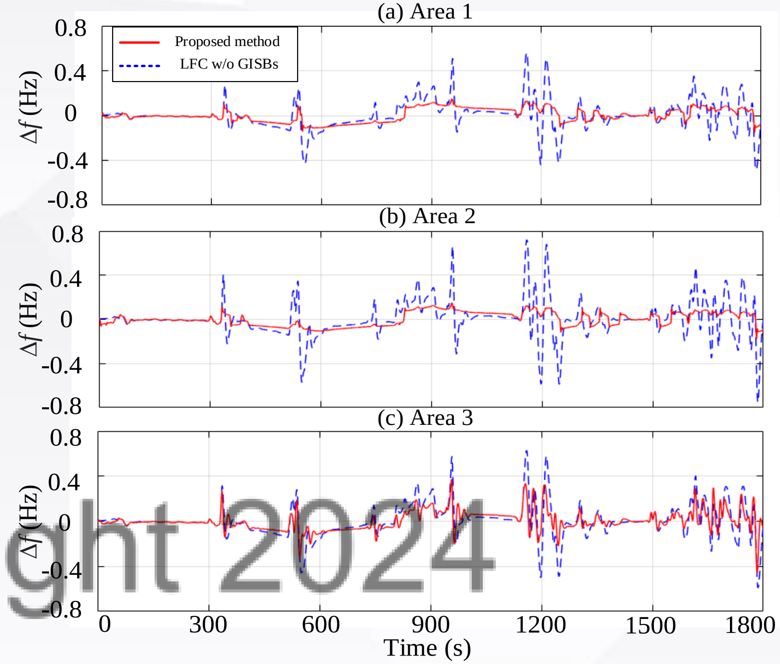
State-space model of TCL:

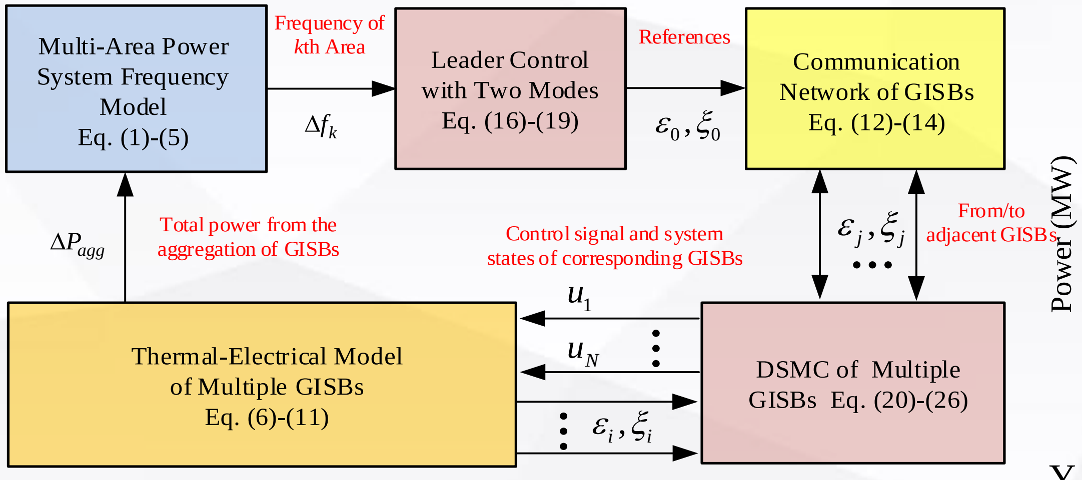
$$\underbrace{\begin{bmatrix}\frac{d\alpha_i(t)}{dt}\\ \frac{d\beta_i(t)}{dt}\end{bmatrix}}_{\dot{x}_i}=\underbrace{\begin{bmatrix}0 & 0\\ -\frac{2\Delta T}{C_{th}R_{th}} & -\frac{\eta\bar{P}}{C_{th}}\end{bmatrix}}_{A}\underset{x_i}{\begin{bmatrix}\alpha_i\\ \beta_i\end{bmatrix}}+\underset{B}{\begin{bmatrix}1\\ 0\end{bmatrix}}u_i+\underbrace{\begin{bmatrix}0\\ \frac{T_a(t)-T_s+\Delta T}{C_{th}R_{th}}\end{bmatrix}}_{W}$$

Thermostatically Controlled Loads (TCLs) for frequency support



Leader control mode: *f* support mode and comfort recover mode





Multi-Area Power System Frequency Model Eq. (1)-(5)

Frequency of *k*th Area

Δf_k

Leader Control with Two Modes Eq. (16)-(19)

References

ε_0, ξ_0

Communication Network of GISBs Eq. (12)-(14)

ΔP_{agg}

Total power from the aggregation of GISBs

Control signal and system states of corresponding GISBs

ε_j, ξ_j …

From/to adjacent GISBs

u_1

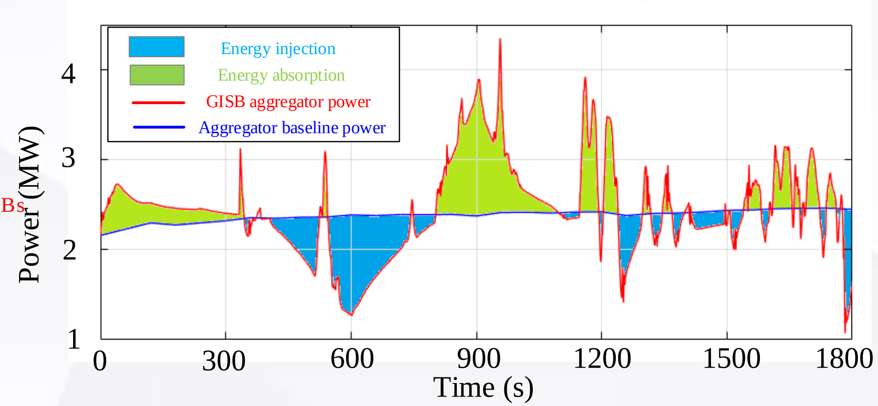
u_N

Thermal-Electrical Model of Multiple GISBs Eq. (6)-(11)

ε_i, ξ_i

DSMC of Multiple GISBs Eq. (20)-(26)

Leader-follower consensus controller



Y. Wang, **Y. Xu**, and Y. Tang, "Distributed Aggregation Control of Grid-Interactive Smart Buildings for Power System Frequency Support," ***Applied Energy*, 2019.**

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

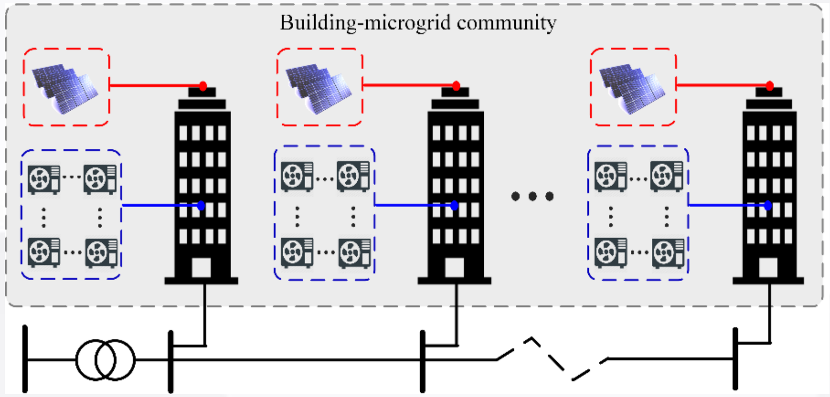
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

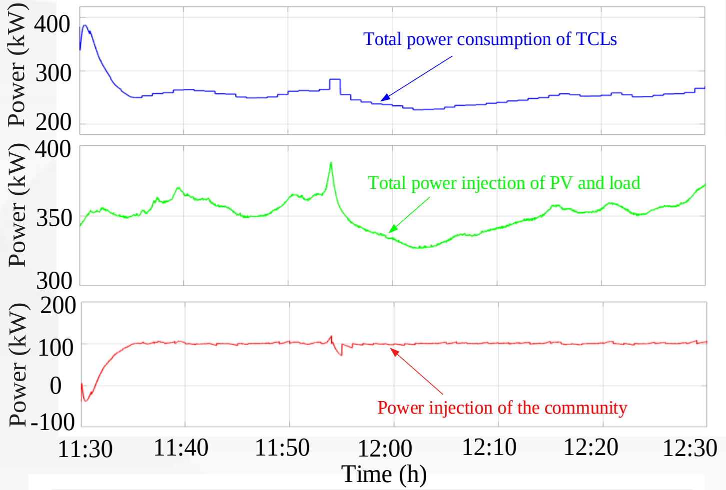
6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

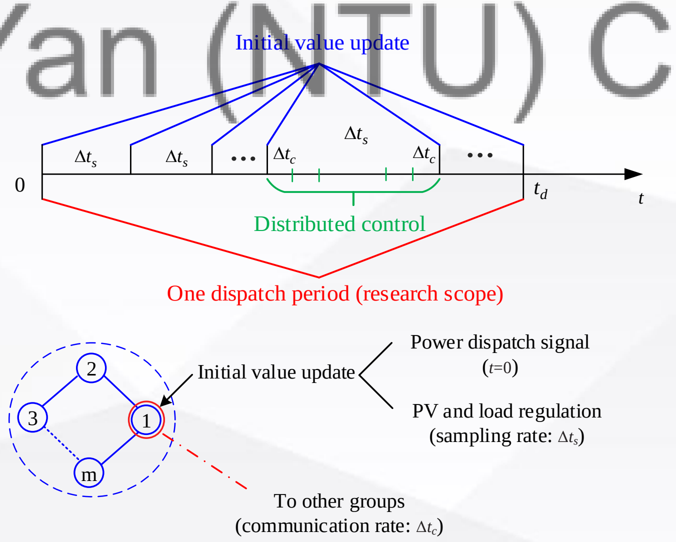
NANYANG TECHNOLOGICAL UNIVERSITY
SINGAPORE

▪ Ancillary Service Support from Smart Building Community

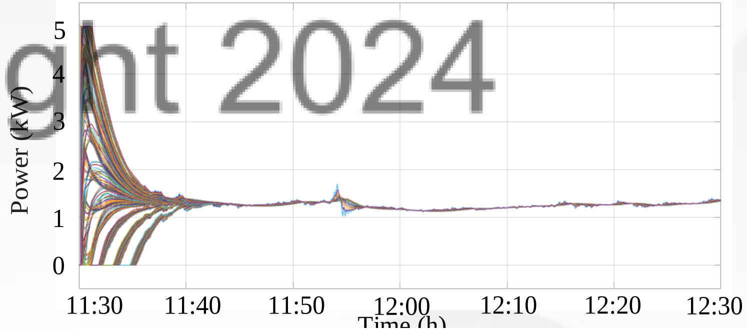


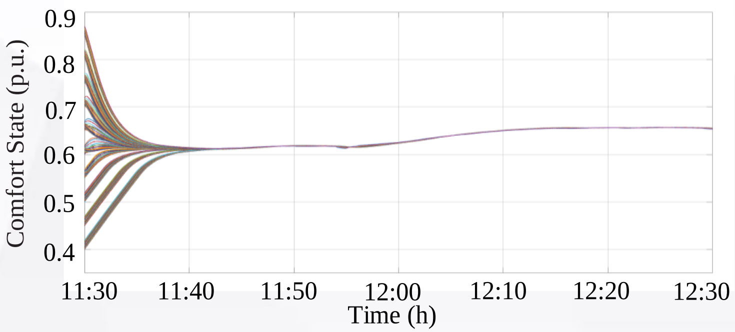
Smart building community: TCLs+PVs





Initial value updating scheme

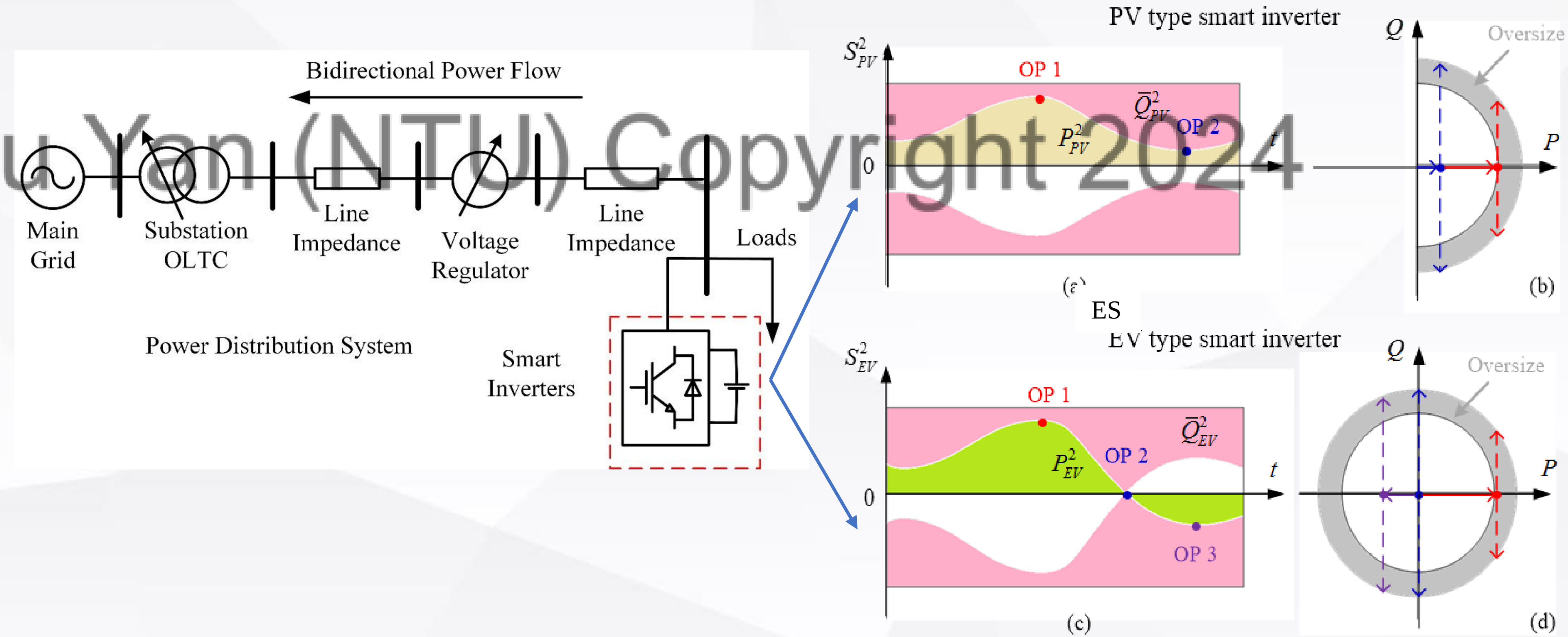




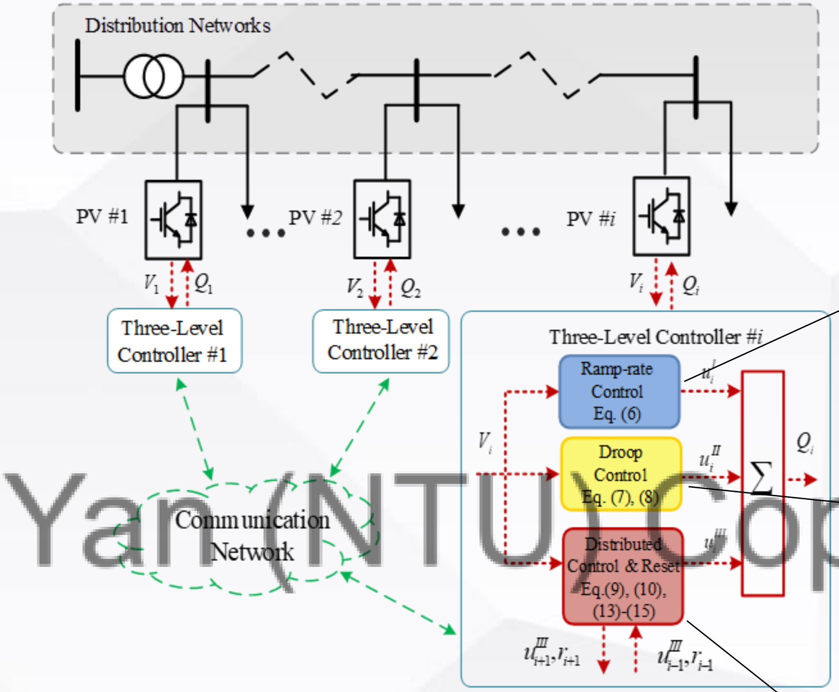
Y. Wang, Y. Tang, **Y. Xu***, et al, “A Distributed Control Scheme of Thermostatically Controlled Loads for Building-Microgrid Community,” ***IEEE Trans. Sustainable Energy*, 2019**.

- Real-time Voltage/Var Control (VVC) Support from DERs

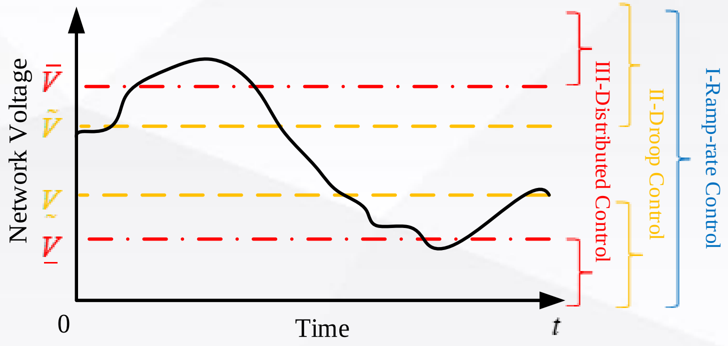
- **Existing Challenges:** High PV penetration level, massive EV charging.
- **Voltage quality issues:** Voltage rise, drop and fast fluctuations.
- **Potential solutions:** inverter-assisted voltage/var support



Real-Time Coordinated Voltage/Var Control Controller



VVC operational range



Controller design:

Level I: Ramp-rate Control -> smooth voltage fluctuation

$$u_i^I(t) = K_i^I\left[V_i(t) - \frac{\sum_{j=t-\omega}^{t} V_i(j)}{T(t)-T(t-\omega)}\right]$$

Level II: Droop Control -> immediate voltage support

$$u_i^{II}(t) = \begin{cases} K_i^{II}(V_i(t)-\tilde{V}), & V_i(t) > \tilde{V} \\ 0, & \underset{\sim}{V} \le V_i(t) \le \tilde{V} \\ K_i^{II}(V_i(t)-\underset{\sim}{V}), & V_i(t) < \underset{\sim}{V} \end{cases}$$

Level III: Distributed Control -> voltage regulation to acceptable range

$$\dot{u}_i^{III}(t) = G_i^{III}\left[\sum_{i=1}^{N} a_{ij}(u_j^{III}(t)-u_i^{III}(t))\right] + e(t)$$

$$e(t) = \begin{cases} K_i^{III}(V_i(t)-\bar{V}), & V_i > \bar{V} \\ 0, & \underline{V} \le V_i \le \bar{V} \\ K_i^{III}(V_i(t)-\underline{V}), & V_i < \underline{V} \end{cases}$$

Dynamic consensus

Y. Wang, M. H. Syed, E. Guillo-Sansano, **Y. Xu***, and G. Burt "Inverter-Based Voltage Control of Distribution Networks: A Three-Level Coordinated Method and Power Hardware-in-the-Loop Validation," ***IEEE Transactions on Sustainable Energy*, 2019**.

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

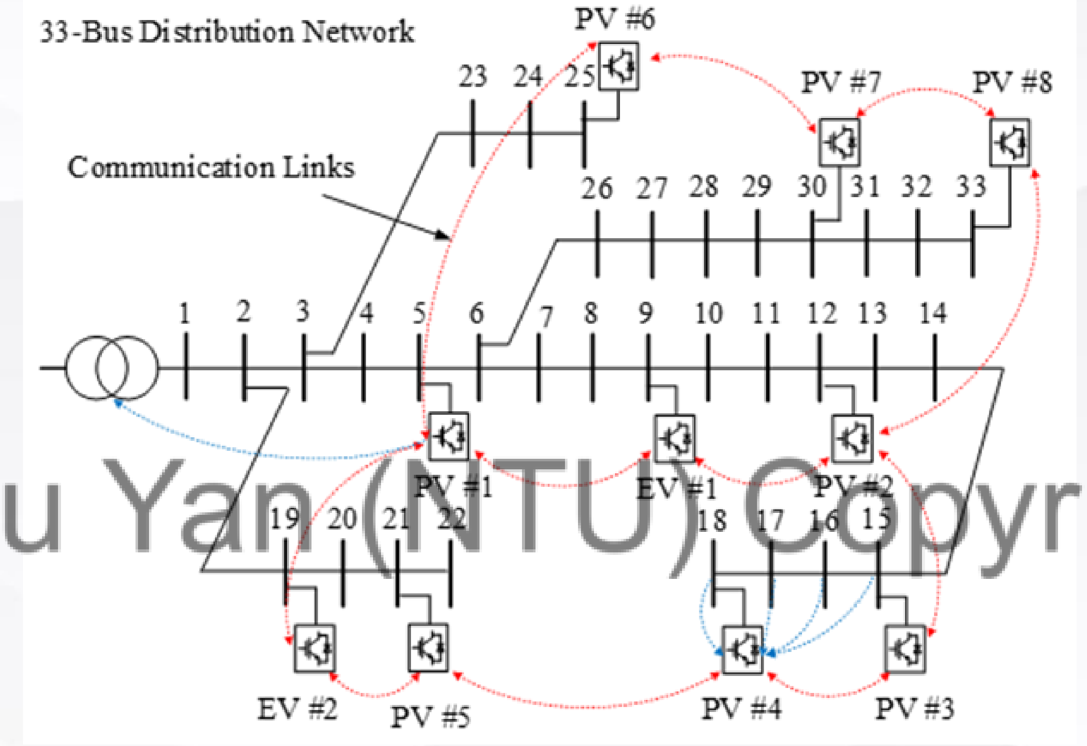
3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

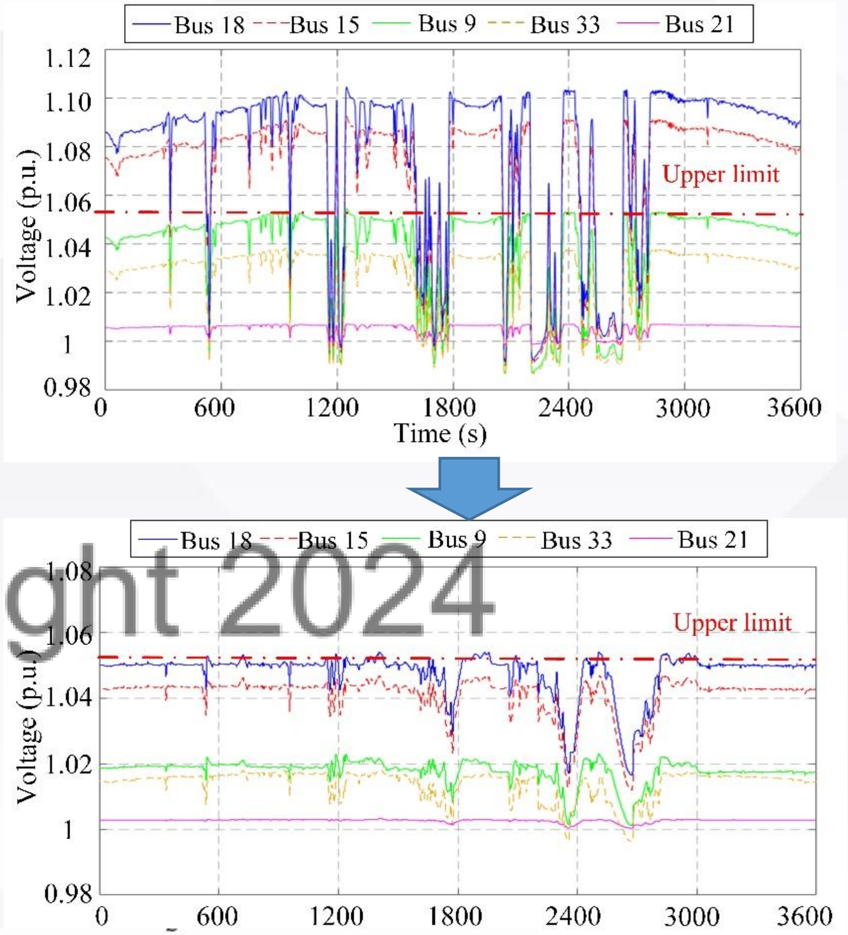
5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

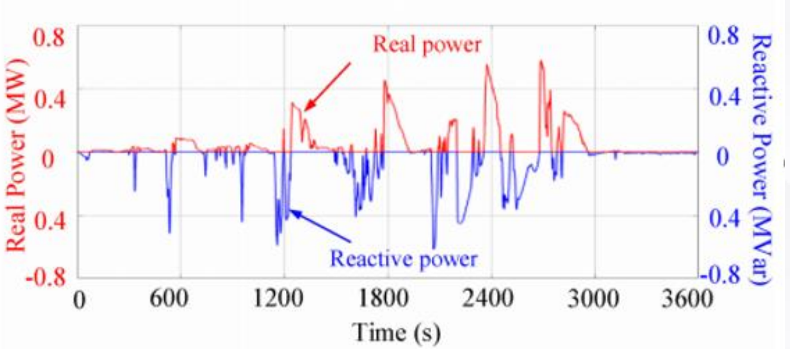
- Simulation Tests

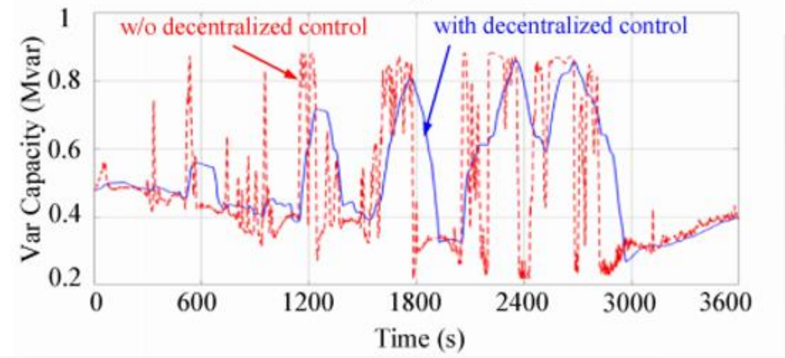


Real-time voltage/var control from inverters

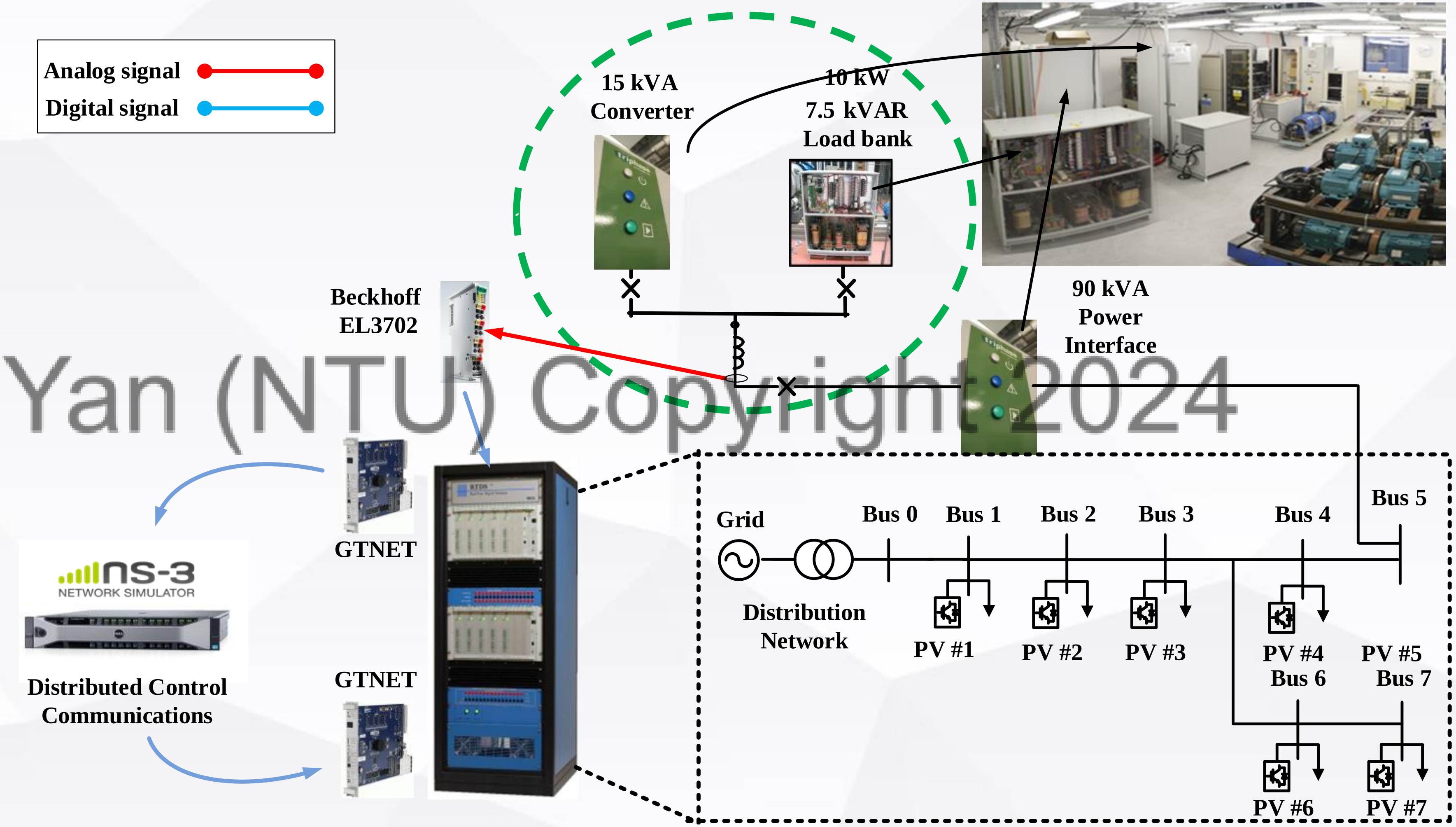


Effectiveness of ramp-rate control





- Power Hardware-in-the-Loop (PHiL) Test



Y. Wang, M. H. Syed, E. Guillo-Sansano, **Y. Xu***, and G. Burt "Inverter-Based Voltage Control of Distribution Networks: A Three-Level Coordinated Method and Power Hardware-in-the-Loop Validation," ***IEEE Transactions on Sustainable Energy*, 2019**.

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

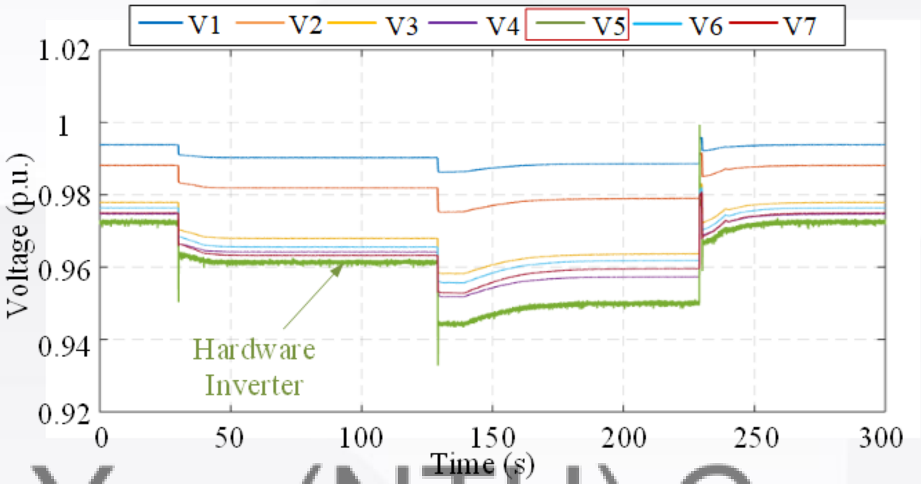
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

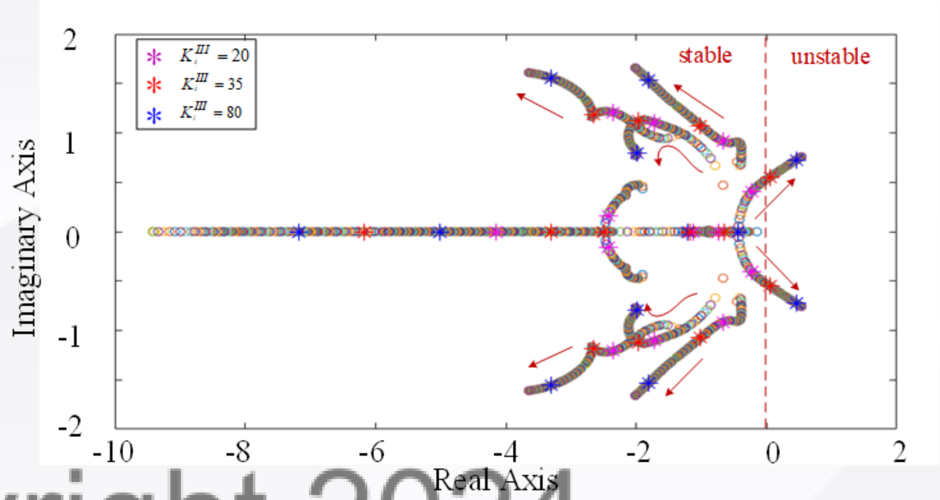
6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

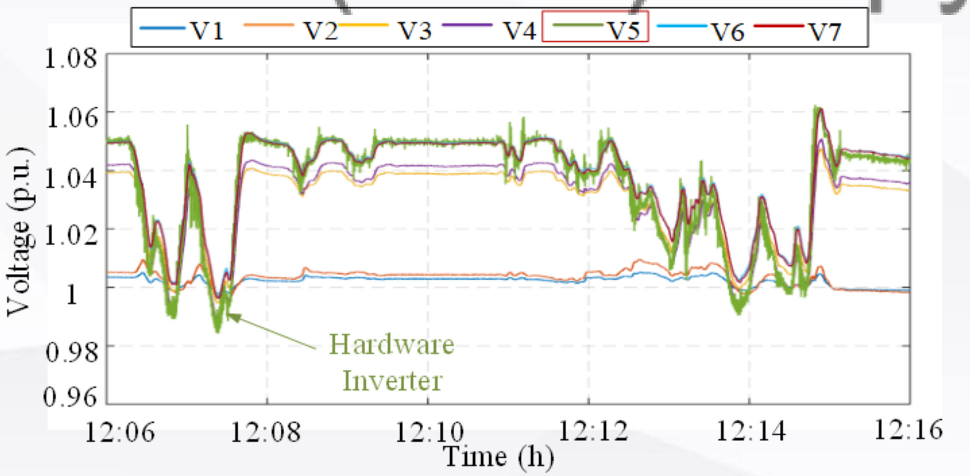
Power HiL Results and Eigenvalues

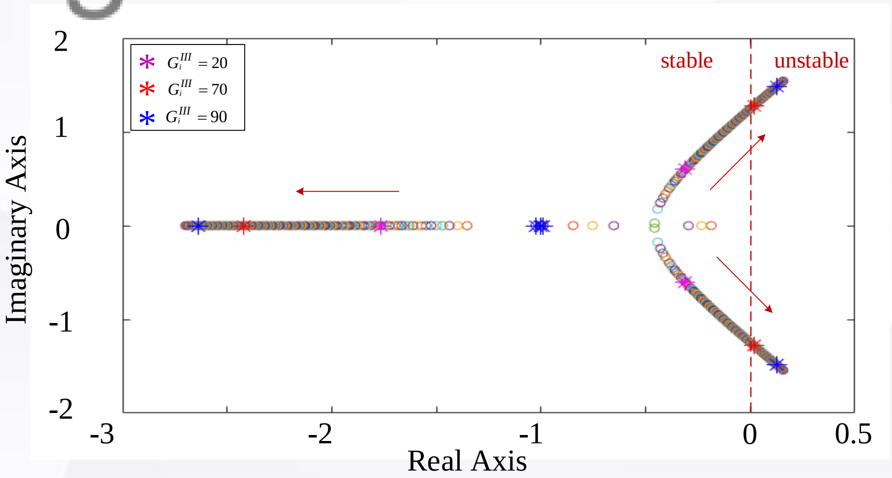


Voltage profiles under step load changes



Trace of eigenvalues under different control gains

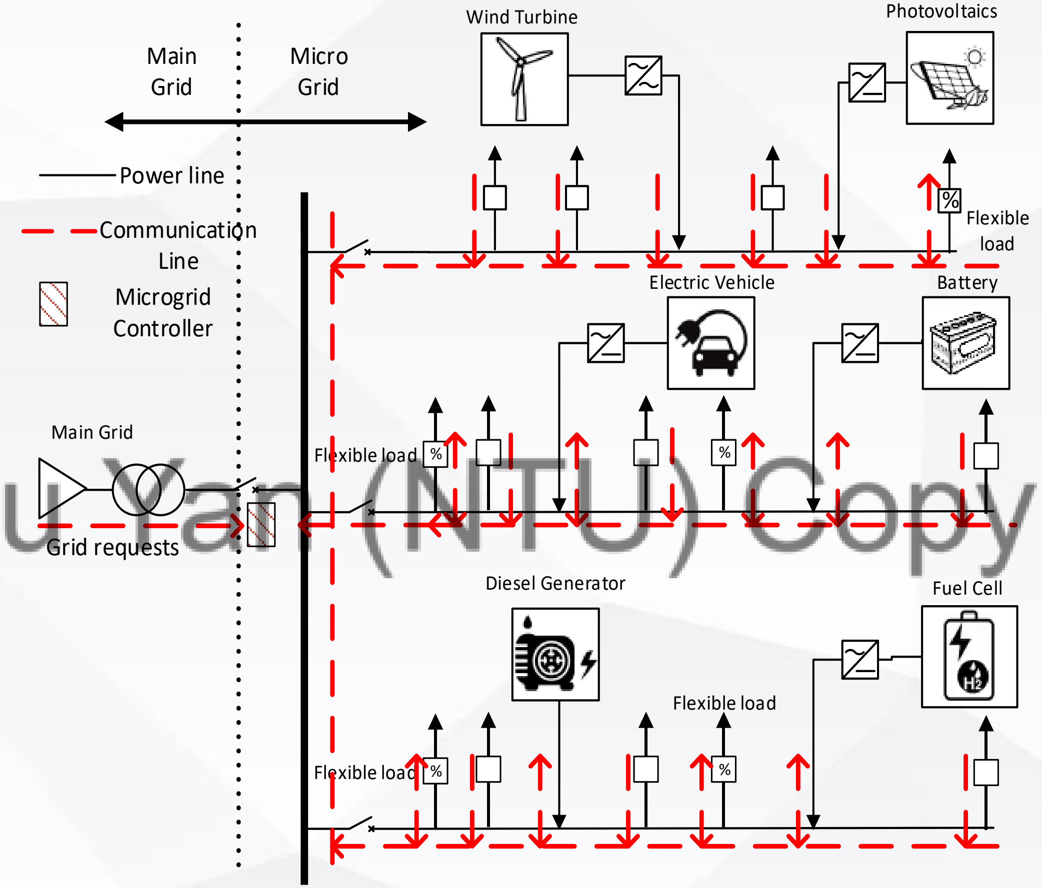




Voltage profiles under real PV and load data

Y. Wang, M. H. Syed, E. Guillo-Sansano, **Y. Xu***, and G. Burt "Inverter-Based Voltage Control of Distribution Networks: A Three-Level Coordinated Method and Power Hardware-in-the-Loop Validation," ***IEEE Transactions on Sustainable Energy*, 2019**.

- Operation of DER - Energy Dispatch & Volt/Var Regulation in Microgrid



- Control variables:

1) Micro-turbine
2) Energy storage
3) Demand response
4) Capacitor banks
5) On-load tap changers
6) PV inverters

Active power resource

Reactive power resource

- Parameters:

1) Load demand
2) Wind and PV output
3) Electricity price
4) Network parameters (R,X,B)

Uncertain

- Network model:

1) Linearized Dist-Flow
2) Second-order cone programming (SOCP) model

- State variables:

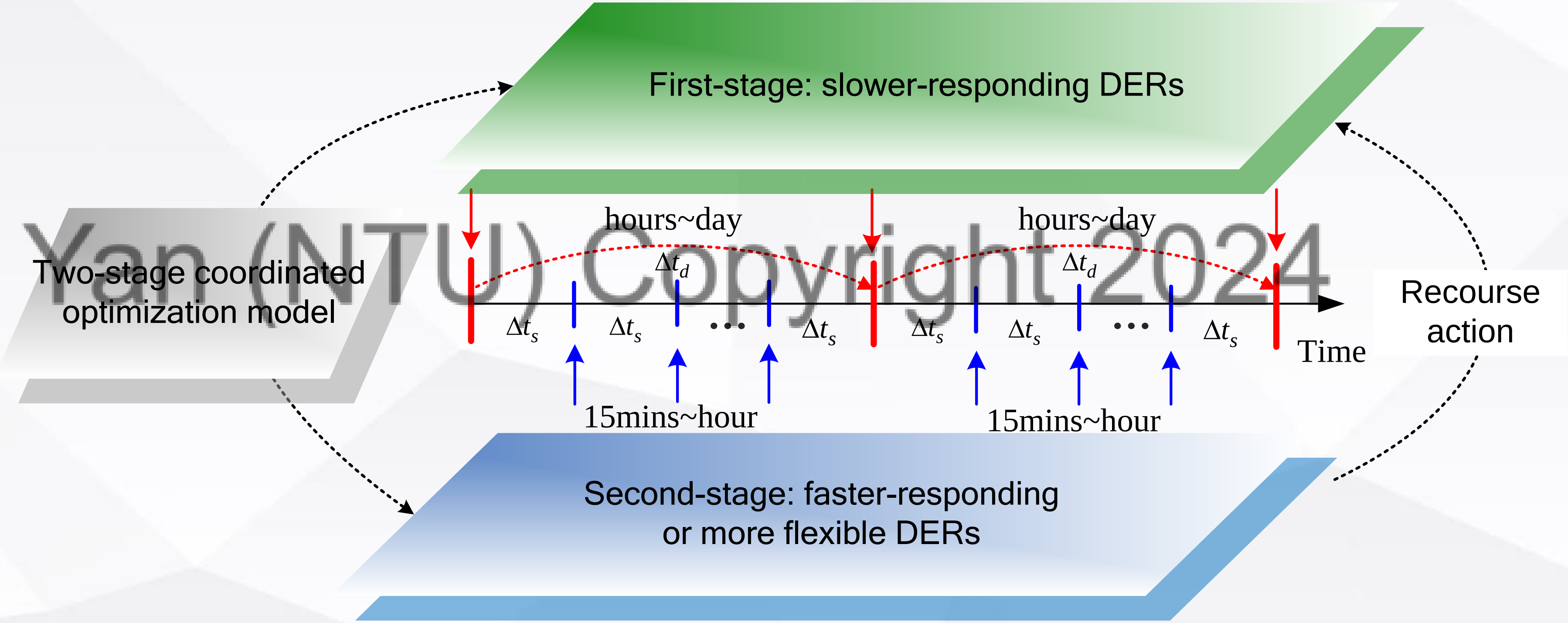
1) Bus voltage
2) Branch power flow
3) Power exchange with main grid

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

Two-stage coordinated operation – Temporal Coordination of DERs

Principle: coordinate different DERs in different timescales against uncertainty.

- **First-stage:** slower-responding DER in longer timescale.
- **Second-stage**: faster-responding or more flexible DER in shorter timescale.



- **Frist-stage decisions** are implemented before uncertainty realizes and will be fixed in the second-stage.
- **Second-stage decisions** will be re-optimized and implemented after uncertainty realizes, therefore it is a recourse action to the first-stage decision.

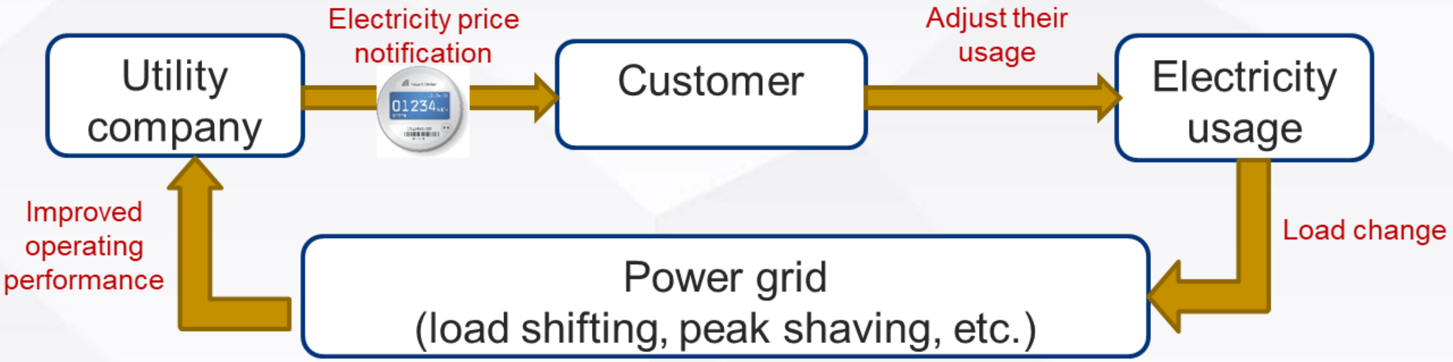
- Optimization Methods

Method	Stochastic Programming	Robust Optimization (RO)
Uncertainty Modeling	Probabilistic scenarios based on probability distribution function (PDF)	Uncertainty set with bounds and budgets
Inputs	Point prediction	Interval prediction
Model	Optimize under expectation $\min\limits_{x\in F}\{f(x)+E[Q(x,\xi)]\}$	Optimize under worst case $\min\limits_{\boldsymbol{x}}\left(\boldsymbol{c}^T\boldsymbol{x}+\max\limits_{\boldsymbol{d}\in\mathcal{D}}\min\limits_{\boldsymbol{y}\in\Omega(\boldsymbol{x},\boldsymbol{d})}\boldsymbol{b}^T\boldsymbol{y}\right)$
Advantages	• Simpler formulation and solution process	• No need for PDF • Fully robust within the uncertainty sets
Disadvantages	• Need for PDF • Probabilistic robustness	• Complex formulation and solution process • May be conservative

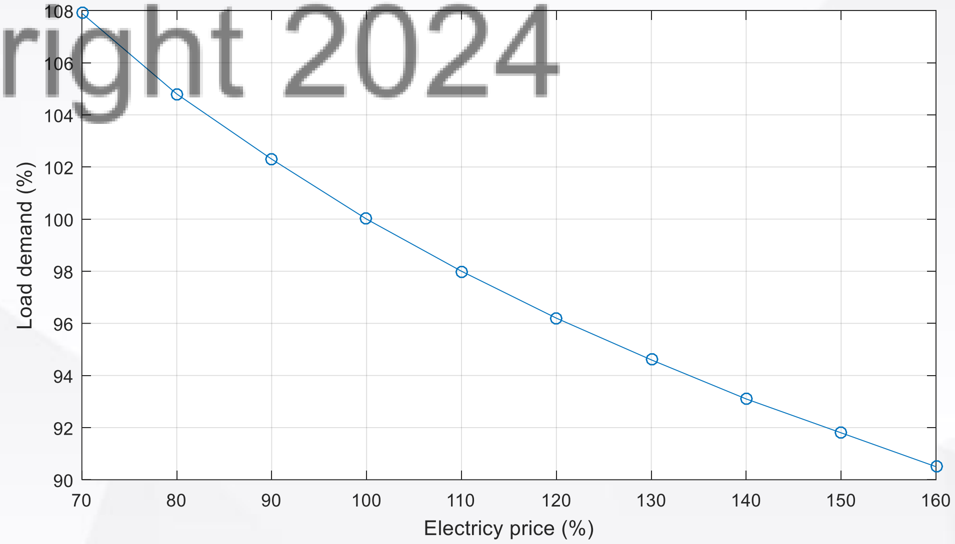
- Robustly Coordinated Energy Management

Day-ahead Price-based Demand Response & Hourly-ahead Microturbine

Price-based Demand Response (PBDR)



Level	Price Rate (%)	Load Rate (%)
1	70	107.9
2	80	104.8
3	90	102.3
4	100	100.0
5	110	98.0
6	120	96.2
7	130	94.6
8	140	93.1
9	150	91.8
10	160	90.5



$$P_t^D = A\,{Pr_t}^{\varepsilon}$$

where ε is **price elasticity** of electric demand, and A is a constant value modeling the relationship between the price and load demand. E.g., the price elasticity of load is -0.38 for Australian power systems.

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

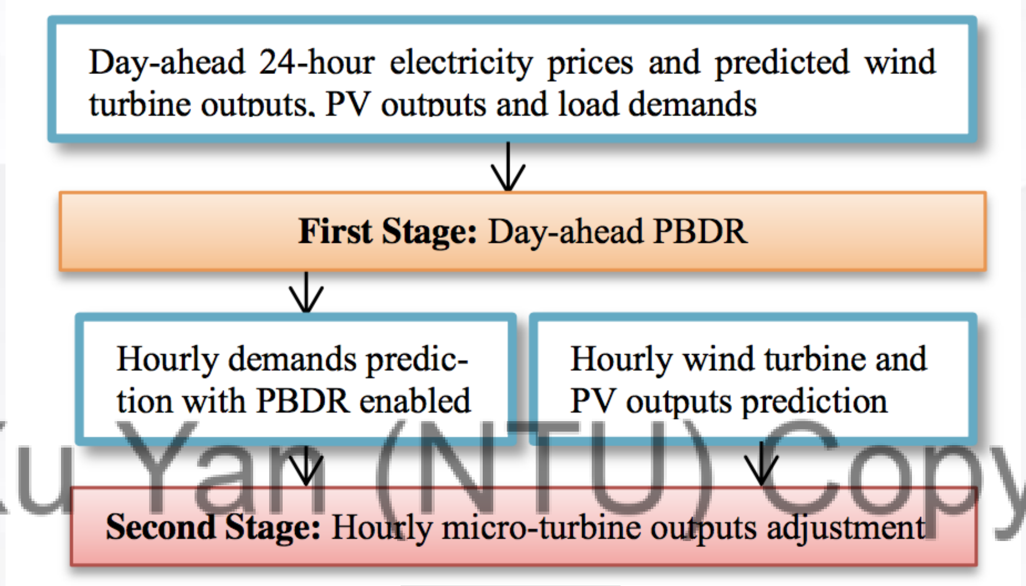
6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

- Robustly Coordinated Energy Management

Day-ahead Price-based Demand Response & Hourly-ahead Microturbine

Two-Stage Operation Framework



Day-ahead 24-hour electricity prices and predicted wind turbine outputs, PV outputs and load demands

First Stage: Day-ahead PBDR

Hourly demands prediction with PBDR enabled

Hourly wind turbine and PV outputs prediction

Second Stage: Hourly micro-turbine outputs adjustment

Two-Stage Robust Optimization (TSRO) model

$$\min_{x} c^T x + \max_{u} \min_{y} d^T y + e^T u$$

s.t.

$$Ax \geq \text{b}$$

$$y \in O(x,u) = \{Fx + Gy \leq v, Hx + Iy + Ju = w\}$$

$$u \in U$$

Objective function

$$\min_{\alpha} -C_{rev}^{pr} + \max_{R_{WT},R_{PV},R_D^{unc}} \min_{P_{MT},V,P,Q} C_{MT} + C_{WT} + C_{PV} + C_{grid} - C_{rev}^{unc}.$$

Uncertainty modeling –uncertainty set

$$U_{WT} = \{R_{WT,n,t} \in \mathbb{R}^{n_{wt}}: \mu_{WT,l} \leq \frac{\sum_{n \in N_{WT}} \sum_{t \in T} R_{WT,n,t}}{\sum_{n \in N_{WT}} \sum_{t \in T} R_{WT,n,t}^{pr}} \leq \mu_{WT,u}, \; R_{WT,n,t}^{low} \leq R_{WT,n,t} \leq R_{WT,n,t}^{up}, \forall n,t\},$$

$$U_{PV} = \{R_{PV,n,t} \in \mathbb{R}^{n_{pv}}: \mu_{PV,l} \leq \frac{\sum_{n \in N_{PV}} \sum_{t \in T} R_{PV,n,t}}{\sum_{n \in N_{PV}} \sum_{t \in T} R_{PV,n,t}^{pr}} \leq \mu_{PV,u}, \; R_{PV,n,t}^{low} \leq R_{PV,n,t} \leq R_{PV,n,t}^{up}, \forall n,t\},$$

$$U_{LD} = \{P_D^{unc} \in \mathbb{R}^{n_{ld}}: \mu_{LD,l} \leq 1 + \frac{1}{n_i n_t} \sum_{i \in N_D} \sum_{t \in T} \sum_{j \in J} \alpha_{j,t} R_{D,i,j,t}^{unc} \leq \mu_{LD,u}, \; R_{D,i,j,t}^{low} \leq 1 + R_{D,i,j,t}^{unc} \leq R_{D,i,j,t}^{up}, \forall i,j,t\}.$$

C. Zhang, **Y. Xu**, Z. Y. Dong, "Robust Coordination of Distributed Generation and Price-Based Demand Response in Microgrids," ***IEEE Trans. Smart Grid*, 2018.** **Web-of-Science Highly Cited Paper**

- Robustly Coordinated Energy Management

Day-ahead Price-based Demand Response & Hourly-ahead Microturbine

Modelling for Price-based DR

$$C_{rev} = C_{rev}^{pr} + C_{rev}^{unc} \quad (9)$$

$$C_{rev}^{pr} = \sum_{t\in T}\sum_{i\in N_D} P_{D,i,t}^{pr} \sum_{j\in J} \alpha_{j,t}\, L_j Pr_j \quad (10)$$

$$C_{rev}^{unc} = \sum_{t\in T}\sum_{i\in N_D} P_{D,i,t}^{pr} \sum_{j\in J} \alpha_{j,t}\, L_j Pr_j R_{D,i,j,t}^{unc} \quad (11)$$

$$\alpha_{j,t} \in \{0,1\}, \forall j,t \quad (12)$$

$$\sum_{j\in J} \alpha_{j,t} = 1, \forall t \quad (13)$$

$$\sum_{t\in T}\sum_{i\in N_D} P_{D,i,t}^{pr} \sum_{j\in J} \alpha_{j,t} L_{j,t}\, Pr_{j,t} \le \sum_{t\in T}\sum_{i\in N_D} P_{D,i,t}^{pr} Pr_{0,t} \quad (14)$$

$$\sum_{t\in T}\sum_{i\in N_D} P_{D,i,t}^{pr} \sum_{j\in J} \alpha_{j,t} L_{j,t} \ge \sum_{t\in T}\sum_{i\in N_D} P_{D,i,t}^{pr} \quad (15)$$

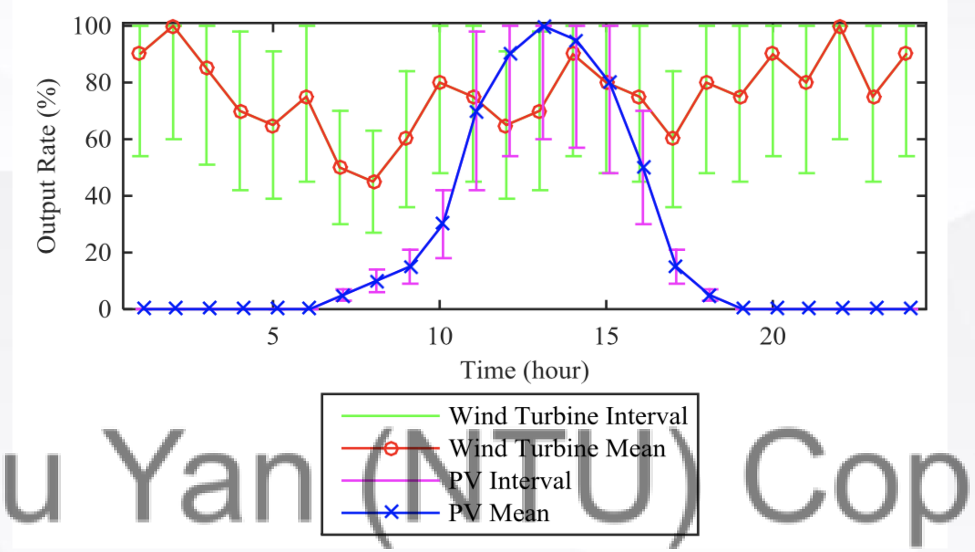
- Considering the characteristics of the uncertain load demands, in (9), the revenue from the demands is split into two parts i.e. the predicted revenue based on the predicted load demands and the uncertain revenue difference from the predicted one.
- Constraints (10) and (11) support the calculation functions of these two revenue items respectively.
- Constraint (12) denotes the decision variable for each PBDR level is binary.
- Constraint (13) guarantees that only one PBDR level decision can be carried out for each hour.
- Constraint (14) and (15) guarantees the bills for the customers cannot increase and the energy which the customers can use cannot decrease. These mean that the proposed PBDR does not reduce the customers’ economic benefits.

C. Zhang, **Y. Xu**, Z. Y. Dong, "Robust Coordination of Distributed Generation and Price-Based Demand Response in Microgrids," ***IEEE Trans. Smart Grid*, 2018.** **Web-of-Science Highly Cited Paper**

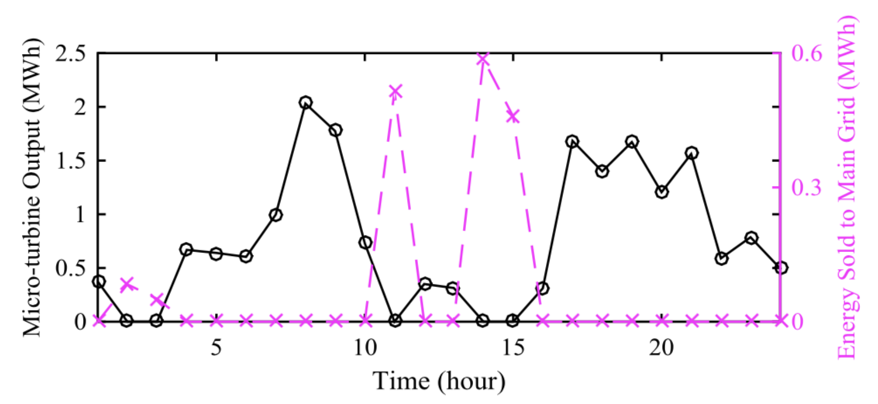
- Robustly Coordinated Energy Management

Day-ahead Price-based Demand Response & Hourly-ahead Microturbine

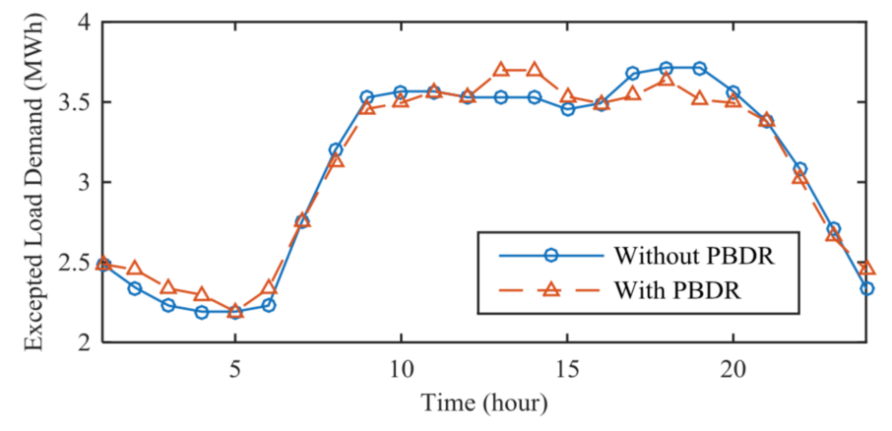
Day-ahead Interval Prediction

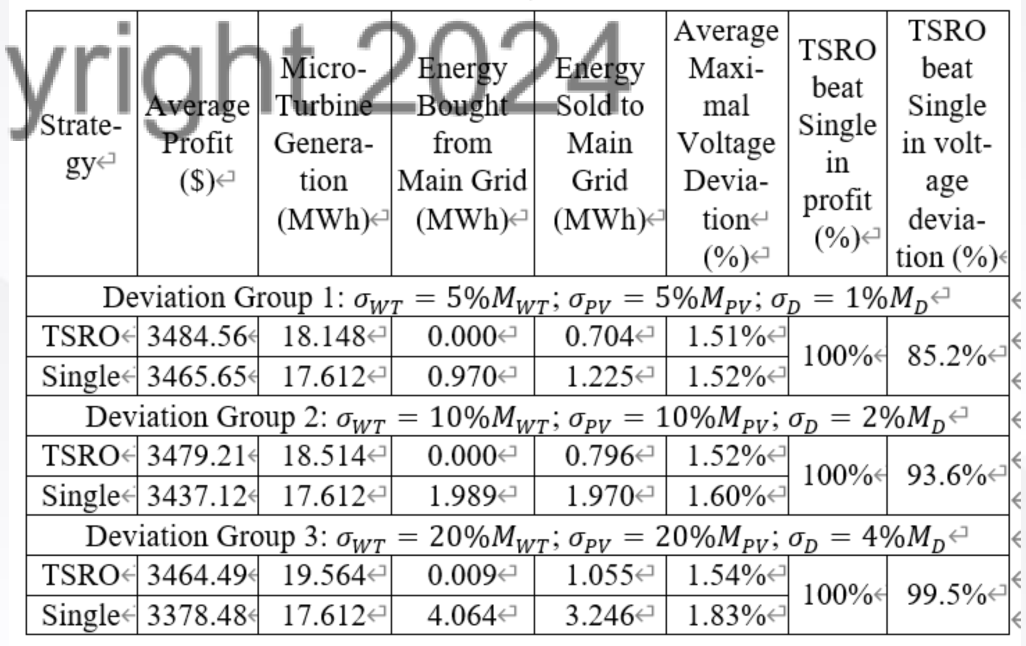


Hourly Microturbine Dispatch



Day-ahead PBDR Decision





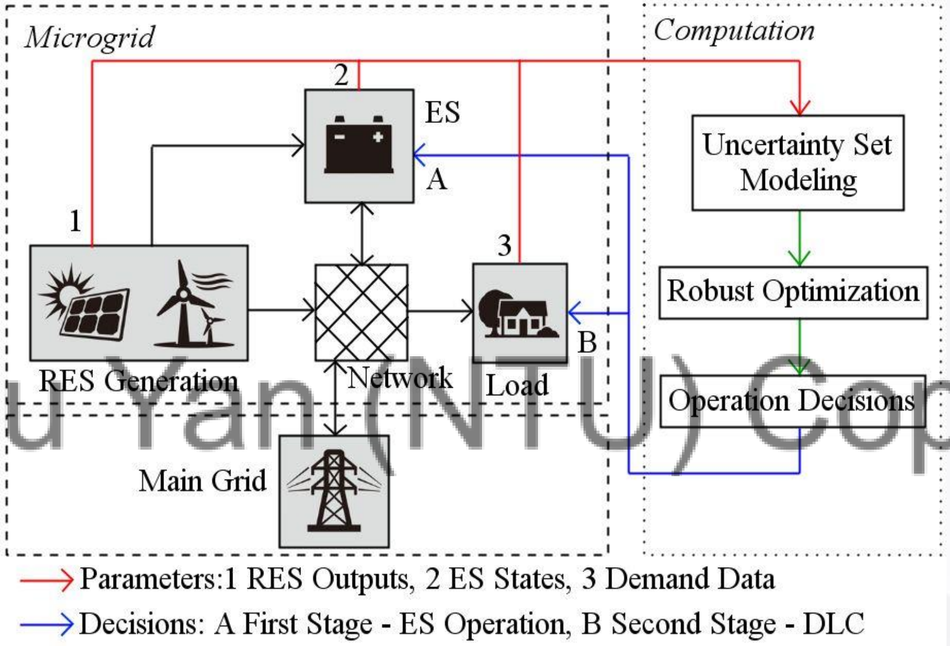
Strategy	Average Profit ($)	Micro-Turbine Generation (MWh)	Energy Bought from Main Grid (MWh)	Energy Sold to Main Grid (MWh)	Average Maximal Voltage Deviation (%)	TSRO beat Single in profit (%)	TSRO beat Single in voltage deviation (%)
Deviation Group 1: $\sigma_{WT} = 5\%M_{WT}$; $\sigma_{PV} = 5\%M_{PV}$; $\sigma_D = 1\%M_D$							
TSRO	3484.56	18.148	0.000	0.704	1.51%	100%	85.2%
Single	3465.65	17.612	0.970	1.225	1.52%		
Deviation Group 2: $\sigma_{WT} = 10\%M_{WT}$; $\sigma_{PV} = 10\%M_{PV}$; $\sigma_D = 2\%M_D$							
TSRO	3479.21	18.514	0.000	0.796	1.52%	100%	93.6%
Single	3437.12	17.612	1.989	1.970	1.60%		
Deviation Group 3: $\sigma_{WT} = 20\%M_{WT}$; $\sigma_{PV} = 20\%M_{PV}$; $\sigma_D = 4\%M_D$							
TSRO	3464.49	19.564	0.009	1.055	1.54%	100%	99.5%
Single	3378.48	17.612	4.064	3.246	1.83%		

C. Zhang, **Y. Xu**, Z. Y. Dong, "Robust Coordination of Distributed Generation and Price-Based Demand Response in Microgrids," ***IEEE Trans. Smart Grid*, 2018.** **Web-of-Science Highly Cited Paper**

▪ Robustly Coordinated Energy Management

Hourly-ahead energy storage & 15min-ahead direct load control (DLC)

Two-stage coordination framework



Two-stage robust optimization model

$$\min_{\alpha_{dis},\alpha_{ch}} C_{ES} + \max_{P_{WT},P_{PV}} \min_{K_{DLC},V,P,Q\in O} C_{WT} + C_{PV} + C_{grid} - C_{rev}.$$

ESS economic model

$$C_{ES,dis}E_{dis} + C_{ES,ch}E_{ch} = C_{ES,OM}E_{stored}.$$

$$E_{stored} = \eta_{dis}E_{dis} = \eta_{ch}E_{ch}, \eta_{dis} > 1, \eta_{ch} < 1.$$

$$\frac{C_{ES,dis}}{\eta_{dis}} + \frac{C_{ES,ch}}{\eta_{ch}} = C_{ES,OM}.$$

ESS operation model

$$P_{ES,dis,m} = P_{dis,m}^{max} \sum_{j\in J_{dis}} \alpha_{dis,m,j} L_{dis,m,j}.$$

$$P_{ES,ch,m} = P_{ch,m}^{max} \sum_{j\in J_{ch}} \alpha_{ch,m,j} L_{ch,m,j}.$$

C. Zhang, **Y. Xu**, Z. Y. Dong, "Robust Operation of Microgrids via Two-Stage Coordinated Energy Storage and Direct Load Control," ***IEEE Trans. Power Syst., 2017.***

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

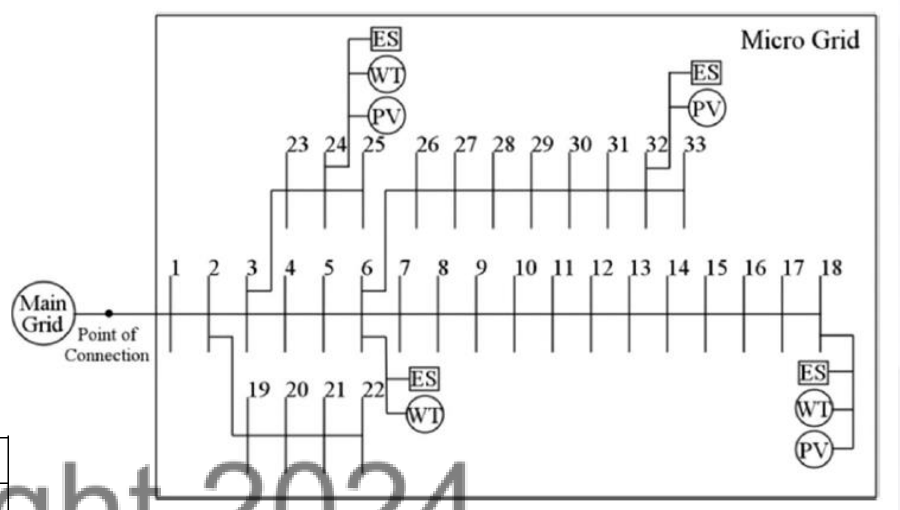
6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

▪ Robustly Coordinated Energy Management

Hourly-ahead energy storage & 15min-ahead direct load control (DLC)

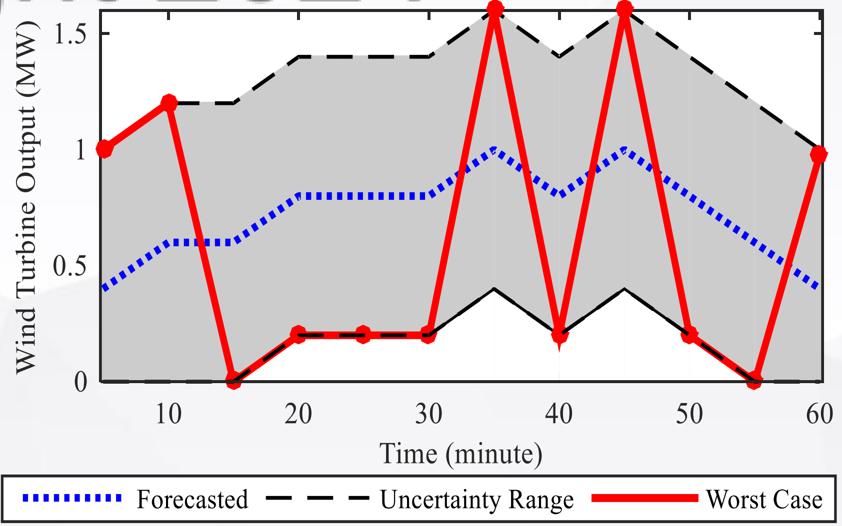
UNCERTAINTY BUDGET SETS UNDER TESTS

Test No	1	2	3	4	5	6
$\mu_{WT,l}$	95%	90%	85%	80%	75%	70%
$\mu_{WT,u}$	105%	110%	115%	120%	125%	130%
$\mu_{PV,l}$	97.5%	95%	92.5%	90%	87.5%	85%
$\mu_{PV,u}$	102.5%	105%	107.5%	110%	112.5%	115%



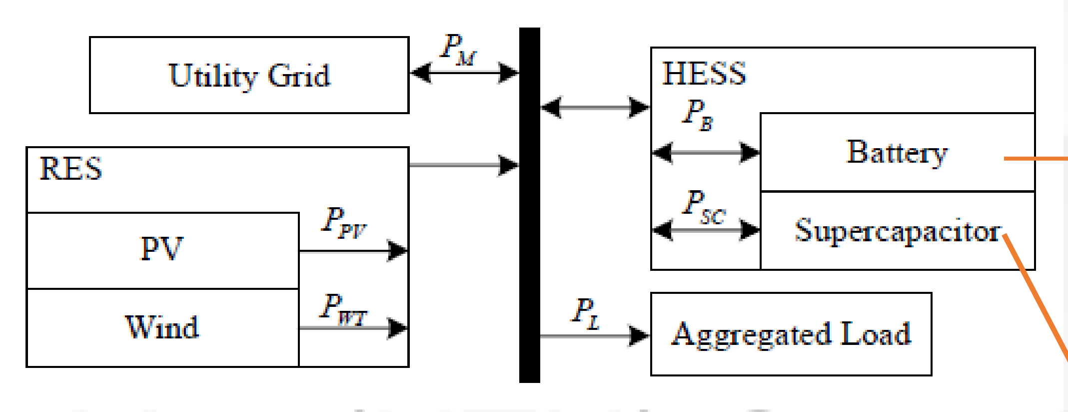
SOLUTION RESULTS FOR BASE CASE UNDER DIFFERENT UNCERTAINTY SETS

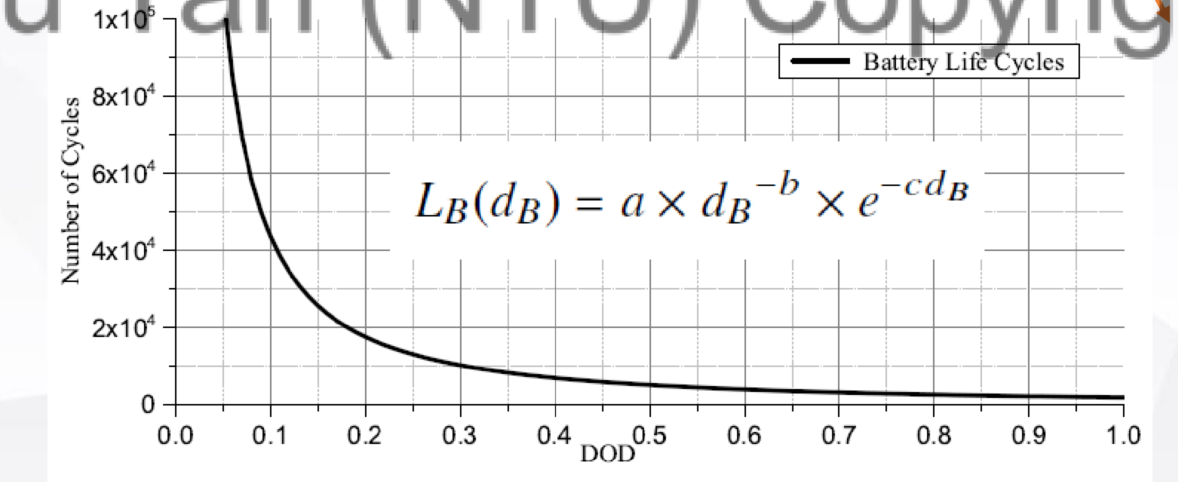
Test No		1	2	3	4	5	6
ES Dis-charging	ES 1	0%	10%	0%	10%	10%	10%
	ES 2	0%	0%	10%	0%	0%	0%
	ES 3	20%	20%	40%	20%	40%	40%
	ES 4	30%	20%	20%	30%	30%	30%
DLC under Worst Case	0-15 min	0%	0%	0%	0%	0%	0%
	15-30 min	46%	0%	43%	39%	38%	38%
	30-45 min	0%	0%	0%	0%	31%	0%
	45-60 min	3%	6%	2%	2%	0%	0%
Profit under Worst Case ($)		192.39	187.94	184.45	179.86	177.30	174.29
Iteration Number		5	5	3	3	3	2
Solution Time (s)		61.39	15.96	12.04	13.84	18.34	7.01



C. Zhang, **Y. Xu**, Z. Y. Dong, "Robust Operation of Microgrids via Two-Stage Coordinated Energy Storage and Direct Load Control," ***IEEE Trans. Power Syst., 2017.***

- Two-Stage Dispatch of Hybrid Energy Storage considering battery health





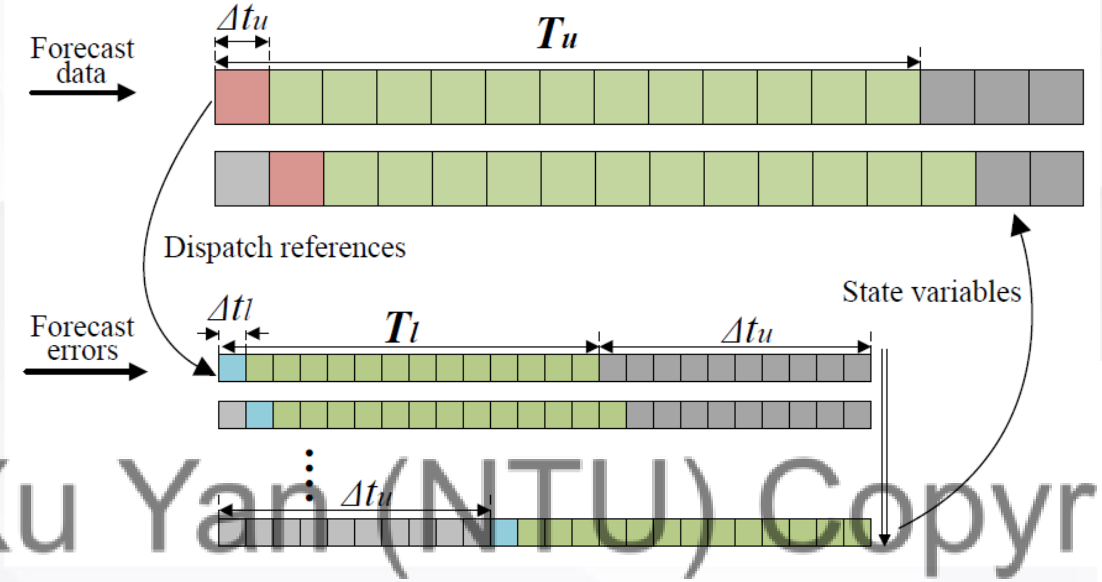
$$L_B(d_B) = a \times d_B^{-b} \times e^{-c d_B}$$

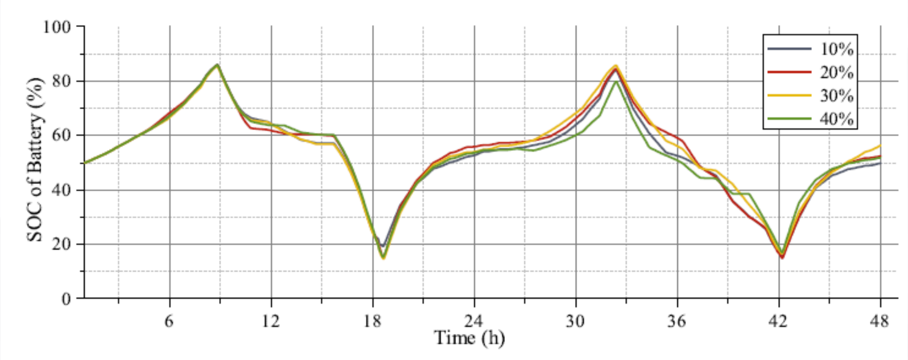
Relationship between the number of life cycles and the DOD of Ni-Cd batteries

C. Ju, P. Wang, L. Goel, and **Y. Xu**, “A two-layer energy management system for microgrids with hybrid energy storage considering degradation costs,” *IEEE Trans. Smart Grid*, 2017. **Web-of-Science Highly Cited Paper**

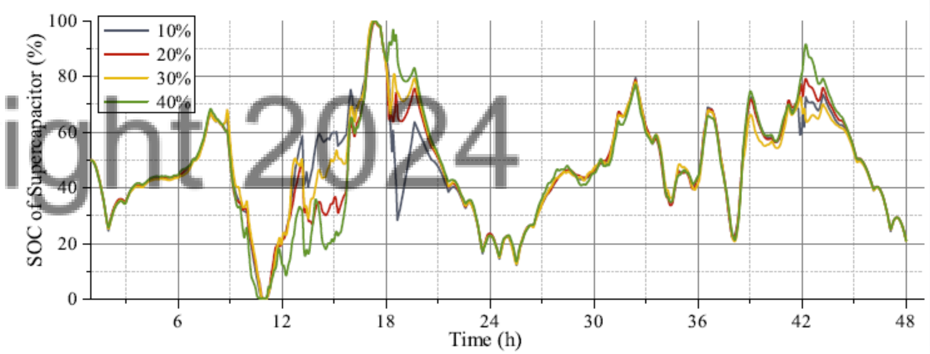
NANYANG TECHNOLOGICAL UNIVERSITY
SINGAPORE

▪ Two-Stage Dispatch of Hybrid Energy Storage considering battery health



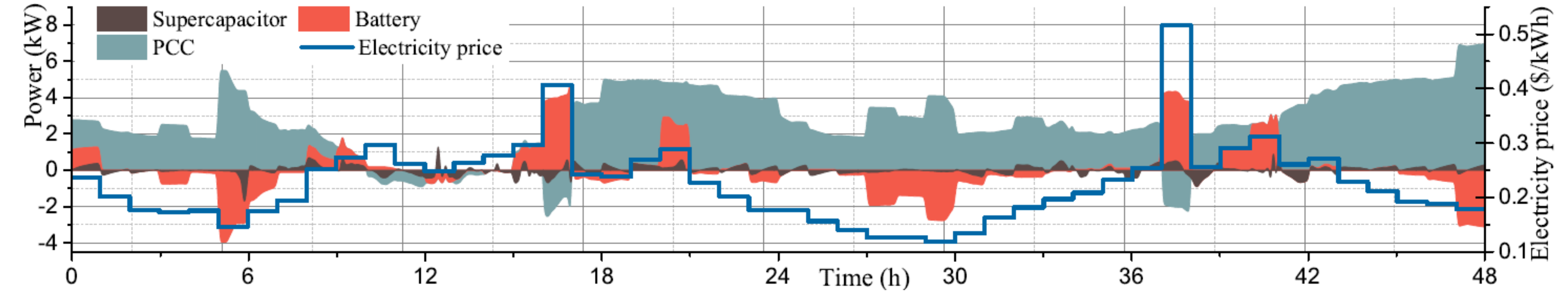


(a) SOC of battery



(b) SOC of supercapacitor

- ✓ **First-stage: battery dispatch with SOH degradation cost**
- ✓ **Second-stage: supercapacitor dispatch**



(b) Optimal dispatch in real-time pricing

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

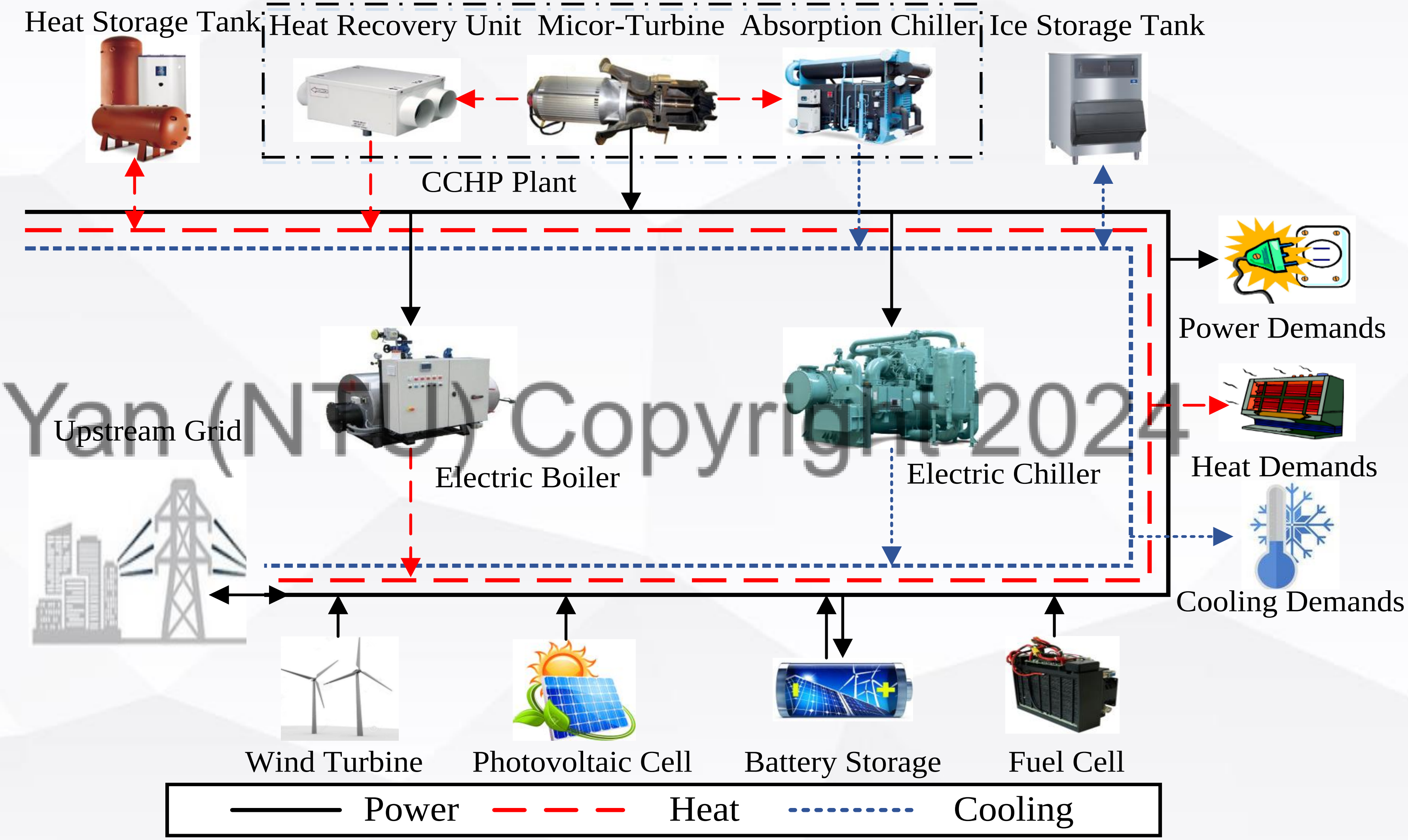
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

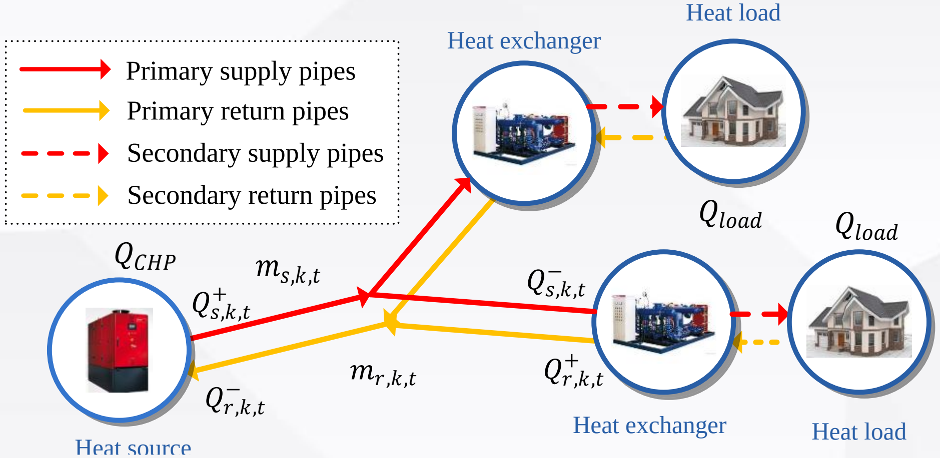
- Multi-Energy Microgrid



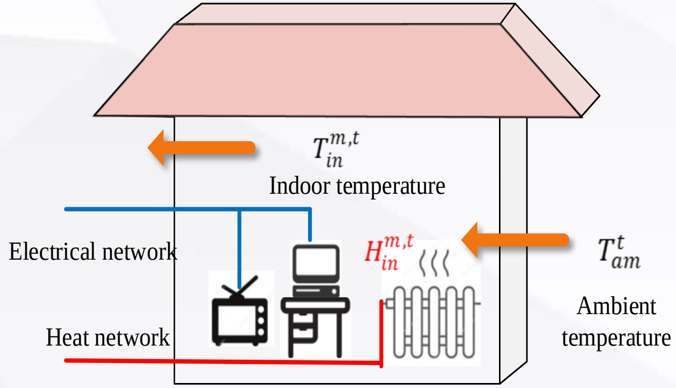
Z. Li and **Y. Xu***, "Optimal coordinated energy dispatch for a multi-energy microgrid in grid-connected and islanded modes," *Applied Energy*, 2017. **Web-of-Science Highly Cited Paper & 2018 Applied Energy Highly Cited Paper Award**

1. REIDS Project
2. Control
1) Islanded mode
2) Grid-tied mode
3. Operation
1) Energy dispatch
2) Volt/Var regulation
4. Hierarchy coordination
5. Trading
1) Centralized trading
2) P2P trading
6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

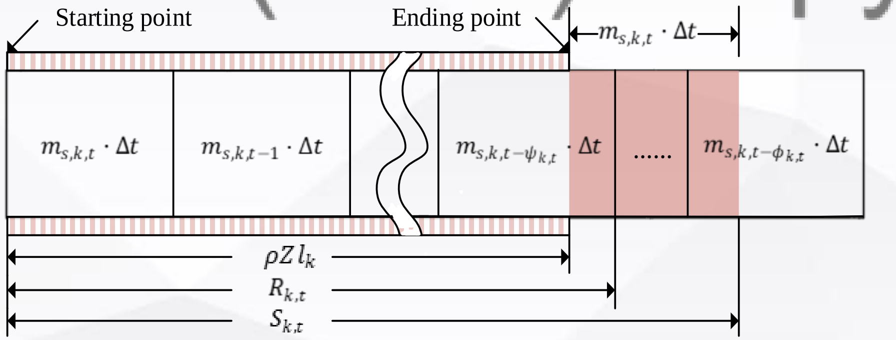
- Multi-Energy Microgrid – Modeling of thermal part



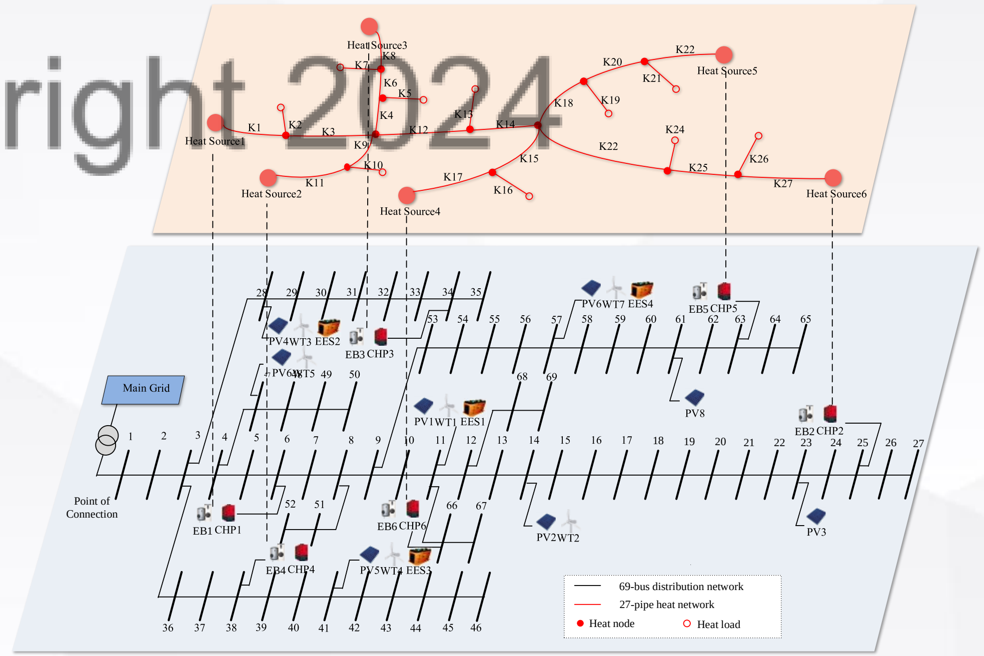
District Heat Network



Thermal conduction of a building



Vertical section of a pipe

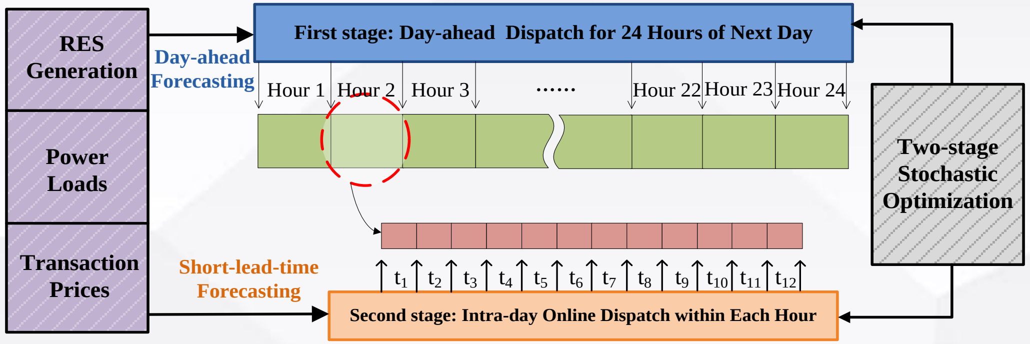


Coupled electric-thermal network

Y. Chen, **Y. Xu***, Z. Li, "Optimally Coordinated Dispatch of Combined-Heat-and-Electrical Network," ***IET Gen. Trans. & Dist.*, 2019.**

Z. Li and **Y. Xu***, "Optimal coordinated energy dispatch for a multi-energy microgrid in grid-connected and islanded modes," ***Applied Energy*, 2017. Web-of-Science Highly Cited Paper & 2018 Applied Energy Highly Cited Paper Award**

■ Multi-Energy Dispatch – Two-Stage Coordinated Operation



Temporally-coordinated Stochastic Operation Framework

$$\min_{z,y_1,y_2\ldots y_n} F(z)+\sum_{n\in N_S}\chi_n L(y_n)$$

$$s.t.\quad z\in F_A$$

$$y_n\in\Omega(z,\omega_n),\ \forall n$$

Two-Stage Sstochastic Optimization model

$$MIN\ F_G = C_{FC}+C_{OM}+C_{EX}+C_{ST}+C_{SD}-C_{HR}$$

$$C_{FC}=\sum_{t\in N_T}\sum_{i\in N_M}(\gamma_G P_{MT}^{t,i}/\eta_{MT}^{t,i})\Delta t$$

$$C_{EX}=\sum_{t\in N_T}(\gamma_B P_{BUY}^{t,1}-\gamma_S P_{SELL}^{t,1})\Delta t$$

$$C_{OM}=\sum_{t\in N_T}\sum_{i\in N_W}[\gamma_{WT}P_{WT}^{t,i}+\ldots+\sum_{i\in N_H}\gamma_{TST}(P_{TSTC}^{t,i}+P_{TSTD}^{t,i})]\Delta t$$

$$C_{ST}=\sum_{t\in N_T}\sum_{i\in(N_M\cup N_E)} max\{0,U_{CG}^{t,i}\text{-}U_{CG}^{t\text{-}1,i}\}C_{CG}^{U}$$

$$C_{SD}=\sum_{t\in N_T}\sum_{i\in(N_M\cup N_E)} max\{0,U_{CG}^{t\text{-}1,i}\text{-}U_{CG}^{t,i}\}C_{CG}^{D}$$

$$C_{HR}=\sum_{t\in N_T}\sum_{i\in N_M}\gamma_{HR}H_L^{t,i}\Delta t$$

$$U_{CG}^{t,i}\cdot P_{CG}^{min,i}\le P_{CG}^{t,i}\le U_{CG}^{t,i}\cdot P_{CG}^{max,i}$$

$$R_{CG}^{down,i}\Delta t\le P_{CG}^{t,i}-P_{CG}^{t\text{-}1,i}\le R_{CG}^{up,i}\Delta t$$

$$1-\Delta V_{BUS}^{\max}\le V_{BUS}^{t,i}\le 1+\Delta V_{BUS}^{\max}$$

$$P_{PF}^{t,b+1}=P_{PF}^{t,b}-P_{PF}^{t,0,b+1}-P_L^{t,i}+\ldots-P_{PT}^{t,i},\ b\in Br(i),\forall i,t$$

$$Q_{PF}^{t,b+1}=Q_{PF}^{t,b}-Q_{PF}^{t,0,b+1}-Q_L^{t,i},b\in Br(i),\forall i,t$$

$$V_{BUS}^{t,i+1}=V_{BUS}^{t,i}-(R^bP_{PF}^{t,b}+X^bQ_{PF}^{t,b})/V_0,\mathrm{b}\in Br(i,i+1),\forall i,t$$

$$H_L^{t,i}=H_{MT}^{t,i}+H_{PT}^{t,i}+P_{TSTD}^{t,i}-P_{TSTC}^{t,i}$$

$$\xi_{ES}^{min,i}Cap_{ES}^{i}\le E_{ES}^{t,i}\le\xi_{ES}^{max,i}Cap_{ES}^{i}$$

Z. Li and **Y. Xu***, “Temporally-Coordinated Optimal Operation of a Multi-energy Microgrid under Diverse Uncertainties,” *Applied Energy*, **2019.**

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

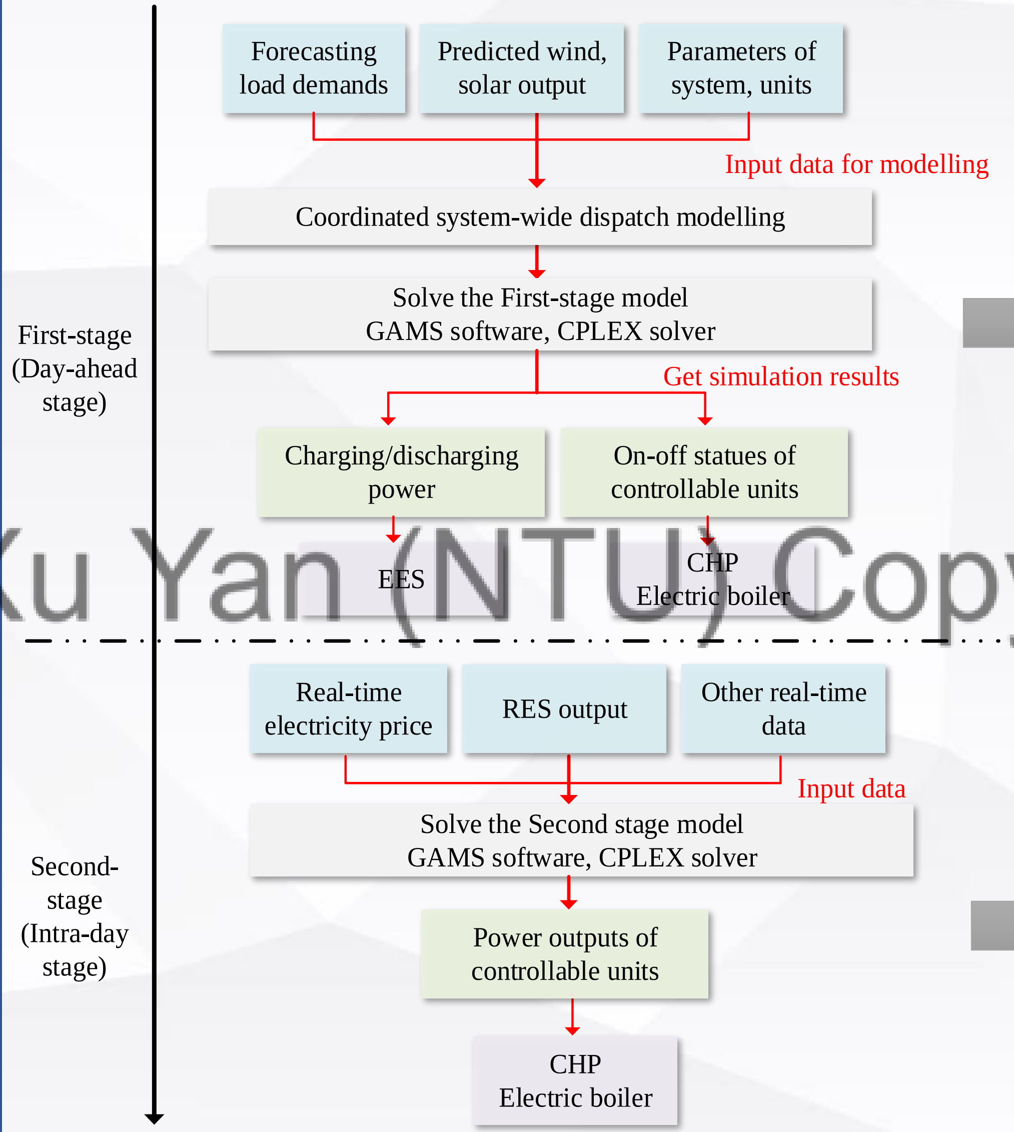
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

Multi-Energy Dispatch – Two-Stage Coordinated Operation



First-stage (Day-ahead stage)

Forecasting load demands | Predicted wind, solar output | Parameters of system, units

Input data for modelling

Coordinated system-wide dispatch modelling

Solve the First-stage model
GAMS software, CPLEX solver

Get simulation results

Charging/discharging power → EES

On-off statues of controllable units → CHP, Electric boiler

Second-stage (Intra-day stage)

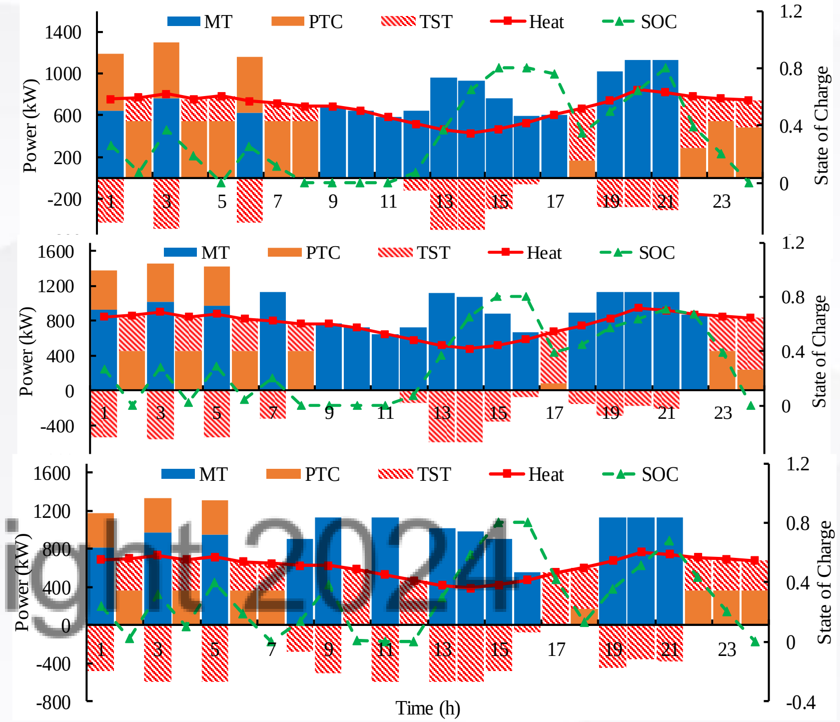
Real-time electricity price | RES output | Other real-time data

Input data

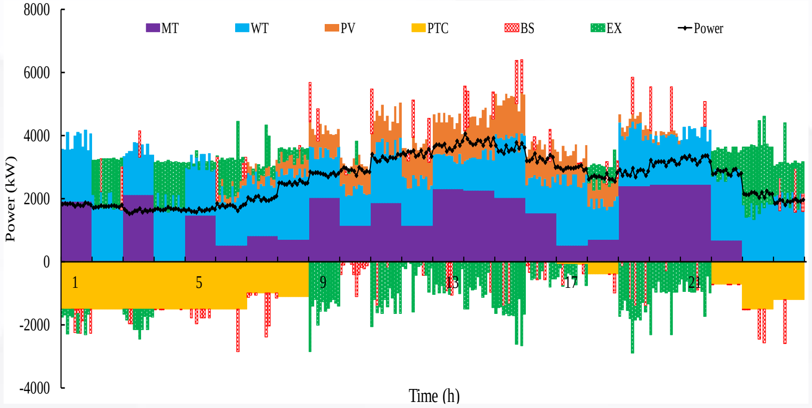
Solve the Second stage model
GAMS software, CPLEX solver

Power outputs of controllable units

CHP
Electric boiler



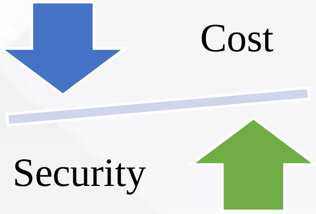
Day-ahead dispatch results



Intra-day dispatch results

Z. Li and **Y. Xu***, "Temporally-Coordinated Optimal Operation of a Multi-energy Microgrid under Diverse Uncertainties," ***Applied Energy*, 2019.**

Multi-Energy Dispatch – Two-Stage Coordinated Operation



- **Method #1**: Single-stage deterministic operation
- **Method #2**: Single-stage stochastic operation
- **Method#3**: Two-stage deterministic optimization

Item	Method #1	Method #2	Method #3	Our Method
Uncertainty level 1 (Lower Uncertainty)				
Average cost ($)	2183.46	2149.65	2468.20	**2440.22**
Average voltage violation (%)	30.40	16.50	0	**0**
Uncertainty level 2 (Medium Uncertainty)				
Average Cost ($)	2218.89	2188.97	2483.19	**2450.78**
Average voltage violation (%)	74.70	49.80	0	**0**
Uncertainty level 3 (High Uncertainty)				
Average Cost ($)	2341.64	2282.66	2556.04	**2508.65**
Voltage violation (%)	97.20	77.90	0	**0**

Z. Li and **Y. Xu***, "Temporally-Coordinated Optimal Operation of a Multi-energy Microgrid under Diverse Uncertainties," ***Applied Energy*, 2019.**

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

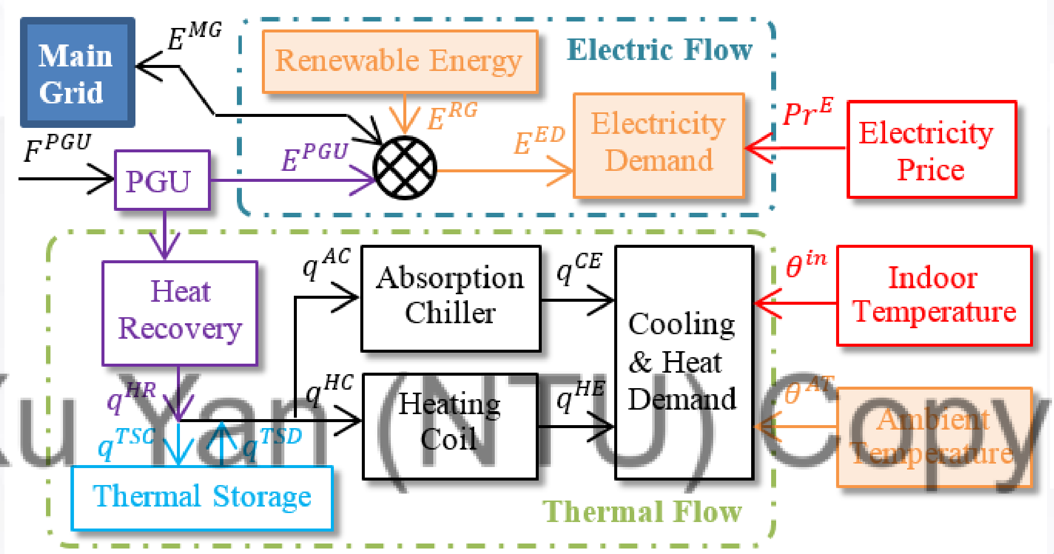
5. Trading
1) Centralized trading
2) P2P trading

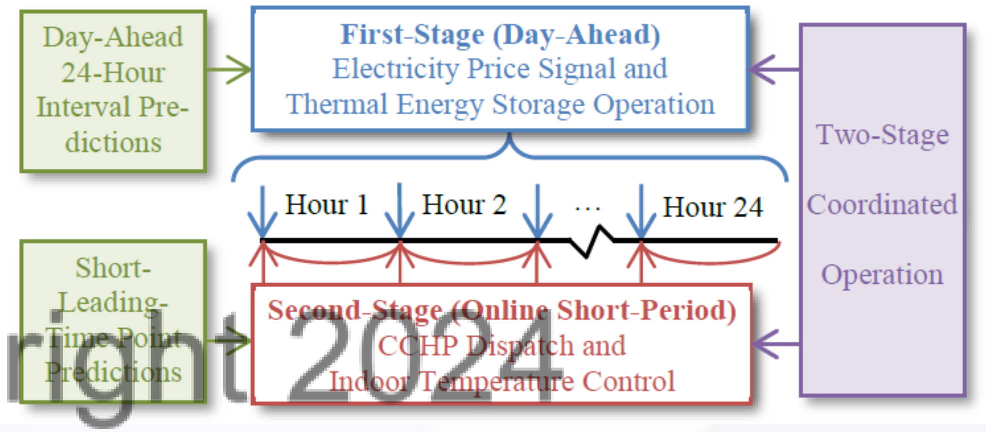
6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

▪ Multi-Energy Demand Response

indoor temperature control (thermal load) and **price-based DR (electric load)** to counteract uncertain renewable power generation, load, and ambient temperature





Day-ahead robust optimization model

$$\min_{x} \max_{u} \min_{y} (C_{CCHP} + C_{OM} + C_{grid} - C_{rev}^{elec} - C_{rev}^{thm}) \quad (48)$$

s.t. (10)-(47)

Intra-day optimization model

$$-C_{rev}^{elec} + \min_{y} (C_{CCHP} + C_{OM} + C_{grid} - C_{rev}^{thm}) \quad (49)$$

s.t. (10)-(14), (25)-(46)

1) x is the *first-stage control variables*, denoting the day-ahead operation decisions including the electricity price $\alpha_{j,t}$ as well as the thermal storage operation state $\beta_{m,t}^{TSC/D}$ and $q_{m,t}^{TSC/D}$;

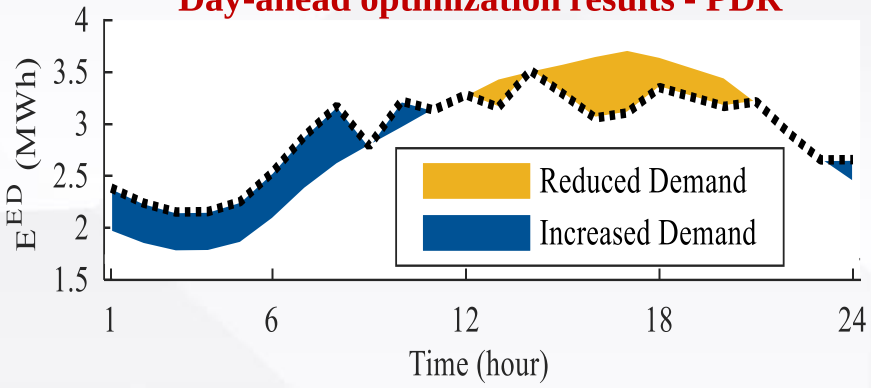
2) y is the *second-stage control variables*, expressing the intra-day operation decisions including the CCHP electric power output $P_{m,t}^{CCHP}$ and the indoor temperature setpoint $\theta_{m,k,t}^{in}$;

3) u is the *uncertain variables* which include the renewable power outputs $P_{n,t}^{WT/PV}$, the electric load demand $P_{0,i,t}^{ED}$ and the ambient temperature $\theta_{m,k,t}^{am}$.

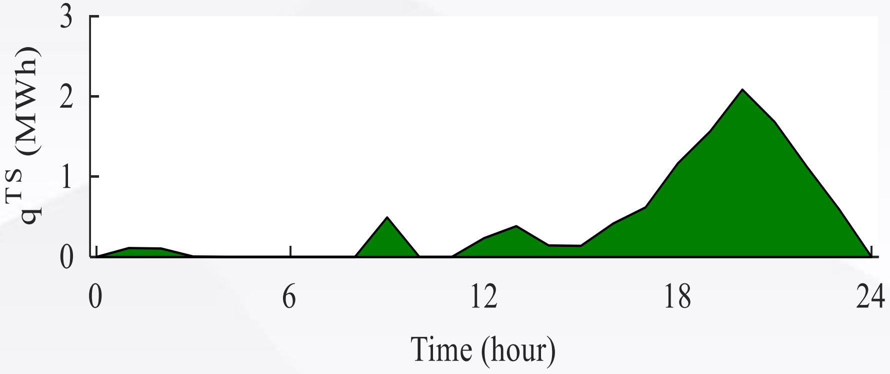
C. Zhang, **Y. Xu***, Z.Y. Dong, "Robustly Coordinated Operation of A Multi-Energy Microgrid with Flexible Electric and Thermal Loads," *IEEE Trans. Smart Grid, 2018.*

- Multi-energy demand response

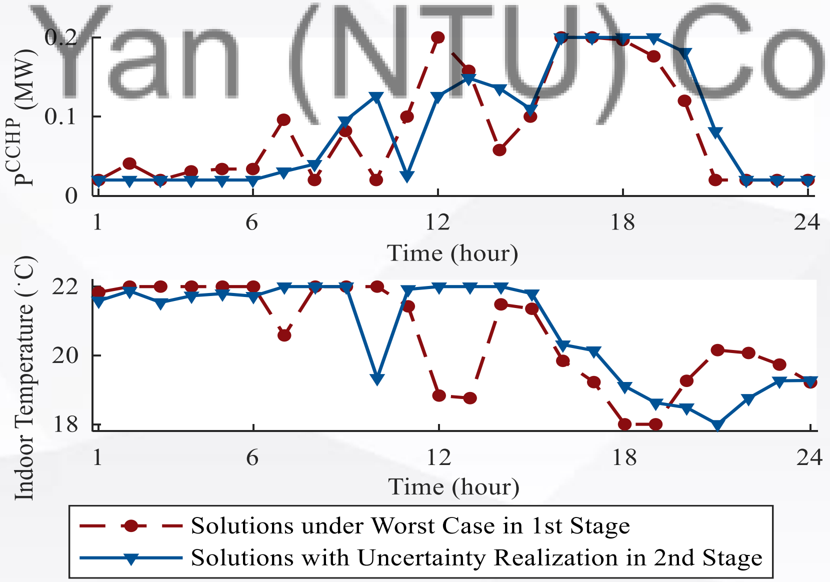
Day-ahead optimization results - PDR



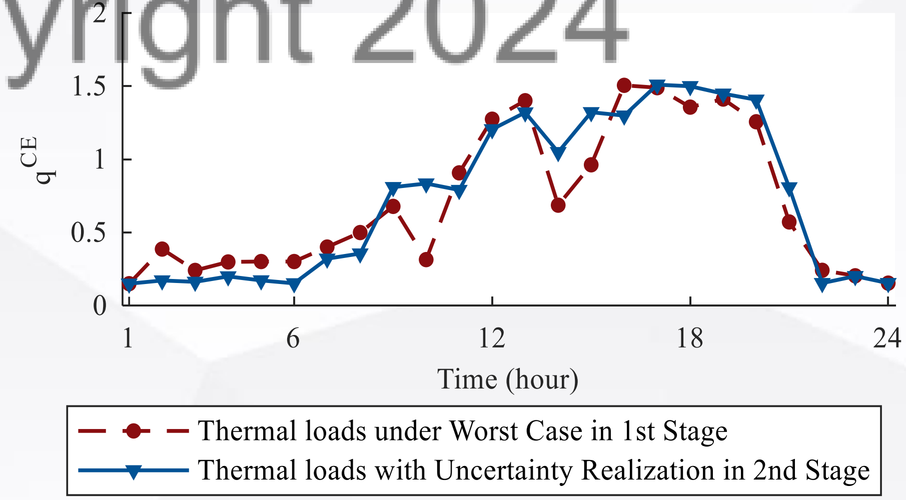
Day-ahead optimization results – thermal ESS



Intra-day results – CCHP and indoor temperature



Intra-day optimization results – thermal load



C. Zhang, **Y. Xu***, Z.Y. Dong, "Robustly Coordinated Operation of A Multi-Energy Microgrid with Flexible Electric and Thermal Loads," ***IEEE Trans. Smart Grid*, 2018.**

▪ Robustness VS Conservativeness

Robustness:

Possibility of a feasible solution (or no operating constraint violation) whatever uncertainties realize (Advantage)

- Full Robustness: Always a feasible solution

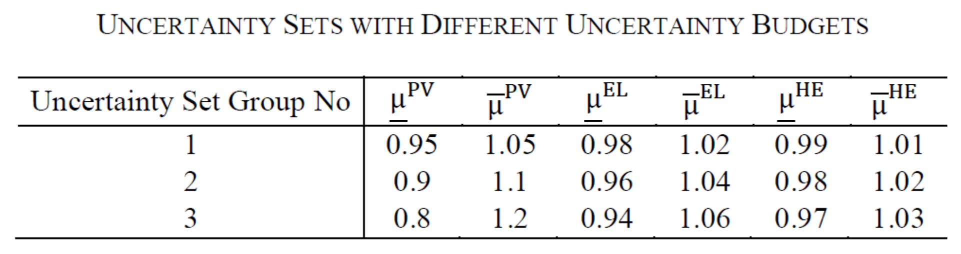
Conservativeness:

Compromise in optimization process when considering uncertainties (Drawback)

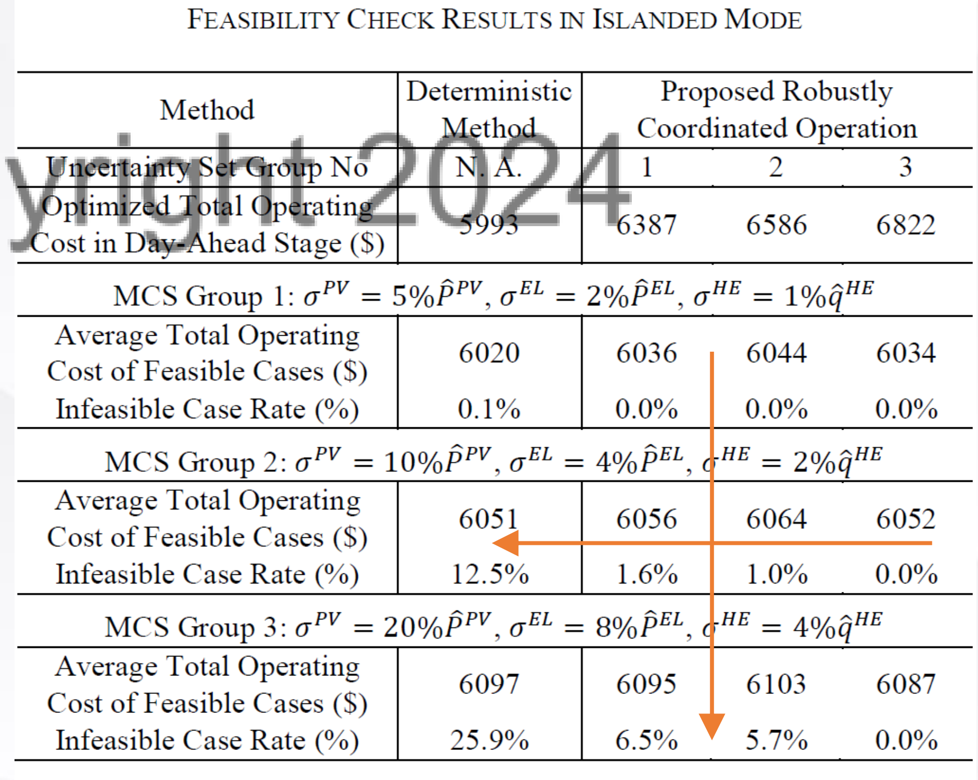
Design of Uncertainty Budgets

- Larger Budgets
  - -> Higher Robustness
  - -> Higher Conservativeness
- Uncertainty Degree Analysis

Robustness under Different Uncertainty Budgets


UNCERTAINTY SETS WITH DIFFERENT UNCERTAINTY BUDGETS

Uncertainty Set Group No	$\underline{\mu}^{PV}$	$\overline{\mu}^{PV}$	$\underline{\mu}^{EL}$	$\overline{\mu}^{EL}$	$\underline{\mu}^{HE}$	$\overline{\mu}^{HE}$
1	0.95	1.05	0.98	1.02	0.99	1.01
2	0.9	1.1	0.96	1.04	0.98	1.02
3	0.8	1.2	0.94	1.06	0.97	1.03

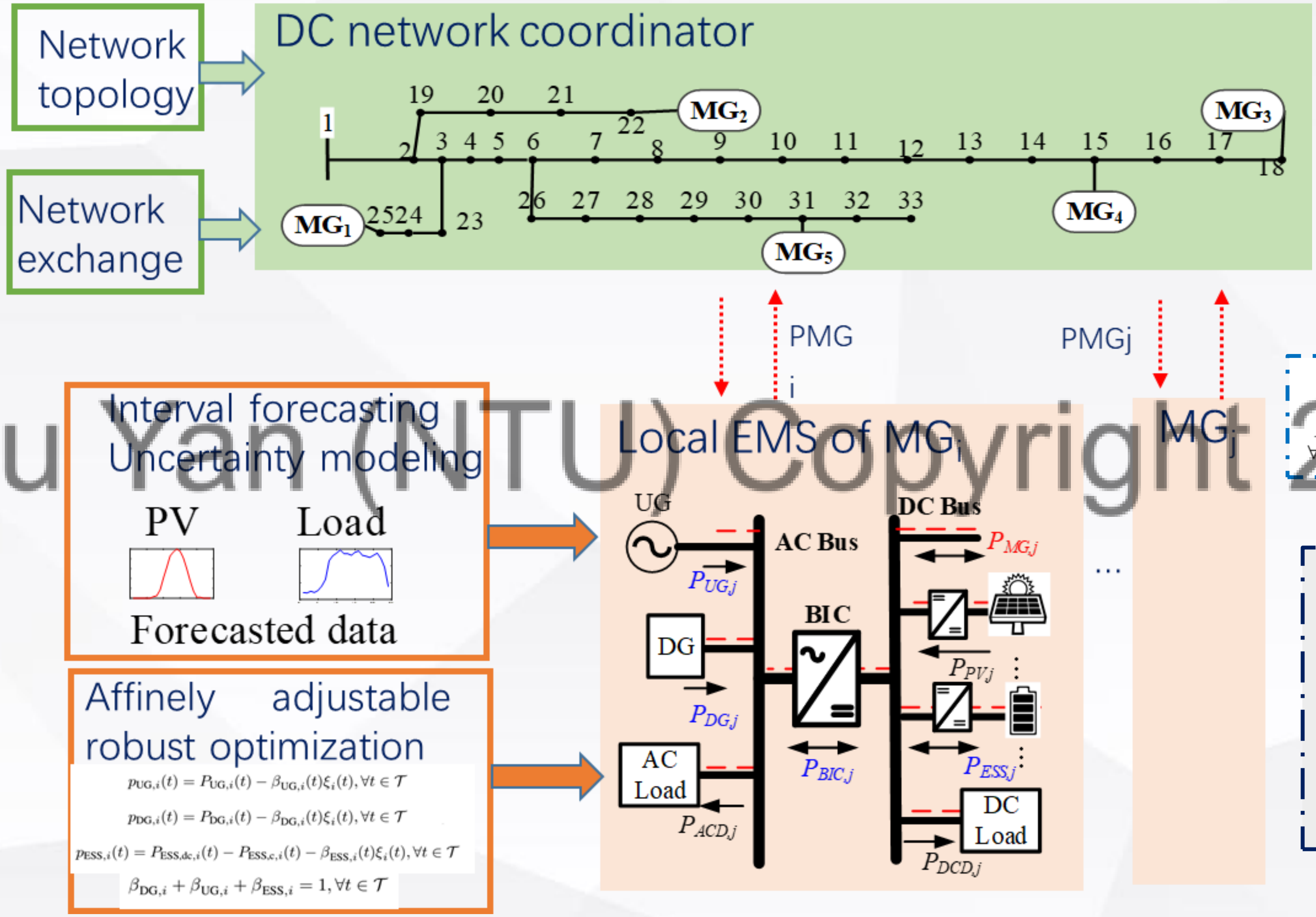

FEASIBILITY CHECK RESULTS IN ISLANDED MODE

Method	Deterministic Method	Proposed Robustly Coordinated Operation		
Uncertainty Set Group No	N. A.	1	2	3
Optimized Total Operating Cost in Day-Ahead Stage ($)	5993	6387	6586	6822
MCS Group 1: $\sigma^{PV} = 5\%\hat{P}^{PV}$, $\sigma^{EL} = 2\%\hat{P}^{EL}$, $\sigma^{HE} = 1\%\hat{q}^{HE}$				
Average Total Operating Cost of Feasible Cases ($)	6020	6036	6044	6034
Infeasible Case Rate (%)	0.1%	0.0%	0.0%	0.0%
MCS Group 2: $\sigma^{PV} = 10\%\hat{P}^{PV}$, $\sigma^{EL} = 4\%\hat{P}^{EL}$, $\sigma^{HE} = 2\%\hat{q}^{HE}$				
Average Total Operating Cost of Feasible Cases ($)	6051	6056	6064	6052
Infeasible Case Rate (%)	12.5%	1.6%	1.0%	0.0%
MCS Group 3: $\sigma^{PV} = 20\%\hat{P}^{PV}$, $\sigma^{EL} = 8\%\hat{P}^{EL}$, $\sigma^{HE} = 4\%\hat{q}^{HE}$				
Average Total Operating Cost of Feasible Cases ($)	6097	6095	6103	6087
Infeasible Case Rate (%)	25.9%	6.5%	5.7%	0.0%

C. Zhang, **Y. Xu***, et.al, "Robustly Coordinated Operation of A Multi-Energy Micro-Grid in Grid-Connected and Islanded Modes under Uncertainties," ***IEEE Trans. Sustain. Energy*, 2020.**

- Robustly Coordinated Energy Management

Distributed robust optimization for Networked-Hybrid AC/DC Microgrids



Affinely adjustable robust optimization

$$p_{\mathrm{UG},i}(t) = P_{\mathrm{UG},i}(t) - \beta_{\mathrm{UG},i}(t)\xi_i(t), \forall t \in \mathcal{T}$$

$$p_{\mathrm{DG},i}(t) = P_{\mathrm{DG},i}(t) - \beta_{\mathrm{DG},i}(t)\xi_i(t), \forall t \in \mathcal{T}$$

$$p_{\mathrm{ESS},i}(t) = P_{\mathrm{ESS,dc},i}(t) - P_{\mathrm{ESS,c},i}(t) - \beta_{\mathrm{ESS},i}(t)\xi_i(t), \forall t \in \mathcal{T}$$

$$\beta_{\mathrm{DG},i} + \beta_{\mathrm{UG},i} + \beta_{\mathrm{ESS},i} = 1, \forall t \in \mathcal{T}$$

Individual MG

$$\min_{\mathbf{P}_i(t),\beta_i(t),\forall t\in\mathcal{T}} \mathbb{E}\sum_{t\in\mathcal{T}} f(\mathbf{P}_i(t),\beta_i(t)) =$$
$$\sum_{t\in\mathcal{T}}[a_{\mathrm{DG},0,i}P^2_{\mathrm{DG},i}(t) + a_{\mathrm{DG},1,i}P_{\mathrm{DG},i}(t) + a_{\mathrm{DG},2,i}+$$
$$a_{\mathrm{DG},0,i}\beta^2_{\mathrm{DG},i}(t) + b_{\mathrm{PV},i}P_{\mathrm{PV},i}(t) + \lambda(t)P_{\mathrm{UG},i}(t)+$$
$$c_{\mathrm{ESS,dc},i}P_{\mathrm{ESS,dc},i}(t) + c_{\mathrm{ESS,c},i}P_{\mathrm{ESS,c},i}(t)]\Delta t$$

Networked-MG

$$\min_{\substack{\mathbf{P}_j(t),\beta_j(t),\\ P_{jk}(t),l_{jk}(t),v_j(t)\\ \forall j\in\mathcal{N},j\to k\in\mathcal{E},t\in\mathcal{T}}} \mathbb{E}\sum_{t\in\mathcal{T}}\{f(\mathbf{P}_i(t),\beta_i(t)) + \sum_{j:j\to k} l_{jk}(t)r_{jk}\}$$

1. Affinely adjustable robust optimization modeling
2. Model convexification
3. Distributed solution based on ADMM

Q. Xu, T Zhao, **Y. Xu***, et al, " A Distributed and Robust Energy Management System for Networked Hybrid AC/DC Microgrids," ***IEEE Transactions on Smart Grid*, 2020.**

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

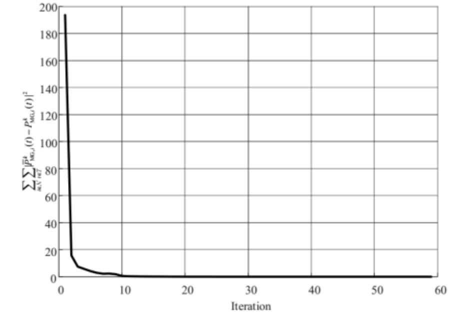
6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

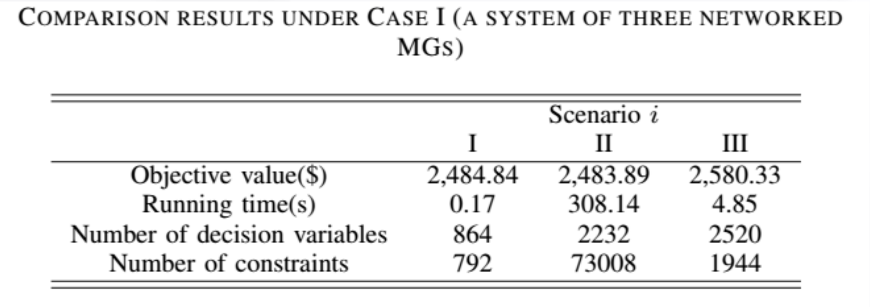
NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

Simulation results

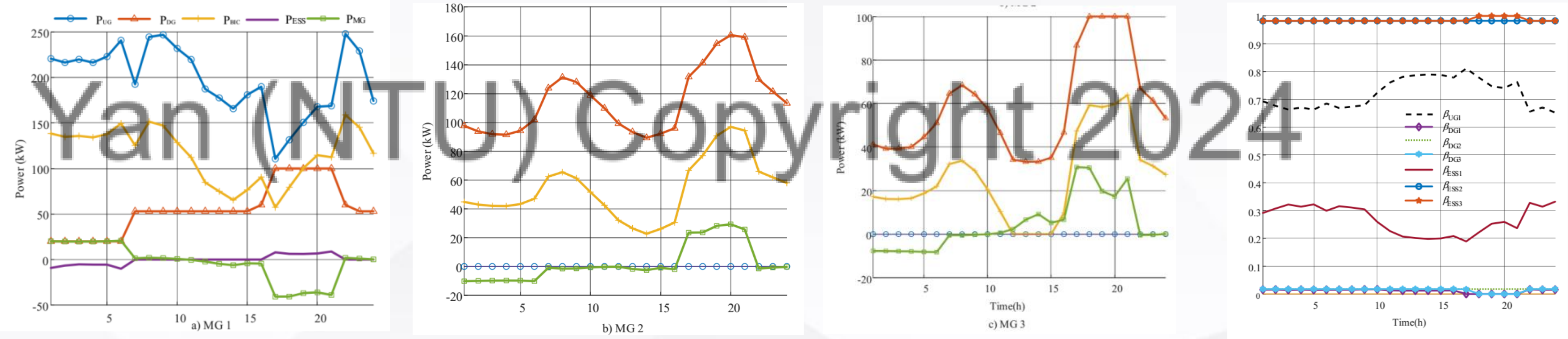
A 3 networked microgrid system in an IEEE 4 bus system

Scenario I: centralized deterministic;
Scenario II: centralized stochastic; (100)
Scenario III: proposed

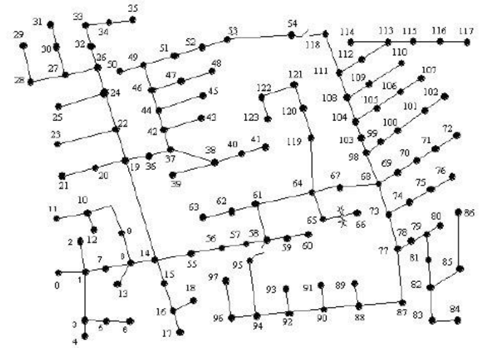


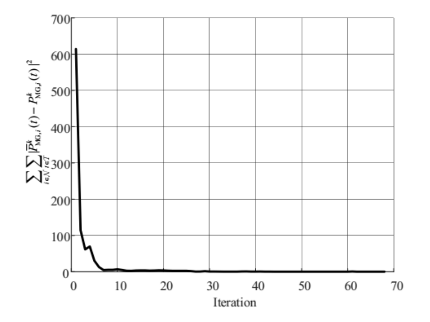

COMPARISON RESULTS UNDER CASE I (A SYSTEM OF THREE NETWORKED MGS)

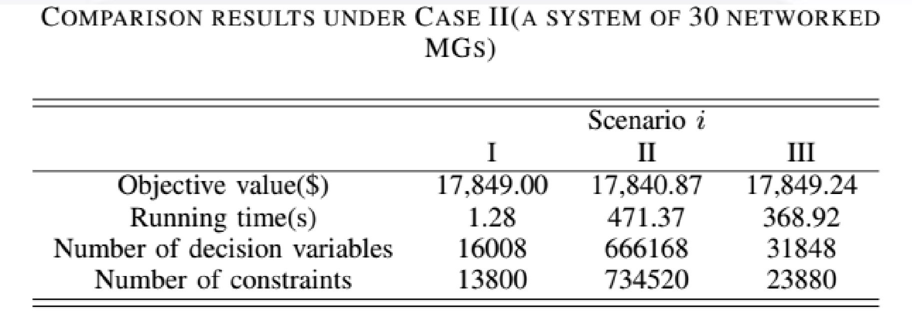
	Scenario i		
	I	II	III
Objective value($)	2,484.84	2,483.89	2,580.33
Running time(s)	0.17	308.14	4.85
Number of decision variables	864	2232	2520
Number of constraints	792	73008	1944



A 30 networked microgrid system in a revised IEEE 123 bus system



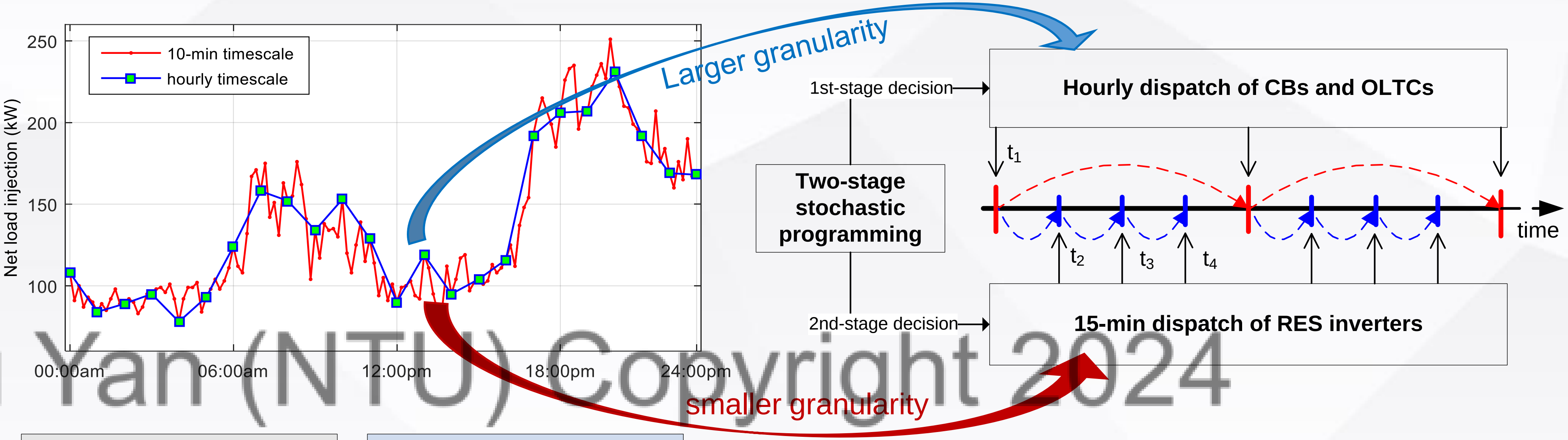



COMPARISON RESULTS UNDER CASE II(A SYSTEM OF 30 NETWORKED MGS)

	Scenario i		
	I	II	III
Objective value($)	17,849.00	17,840.87	17,849.24
Running time(s)	1.28	471.37	368.92
Number of decision variables	16008	666168	31848
Number of constraints	13800	734520	23880

Two-stage Coordinated Volt/Var Regulation under uncertainty

Hourly dispatch of CB and OLTC & 15min dispatch of PV inverters

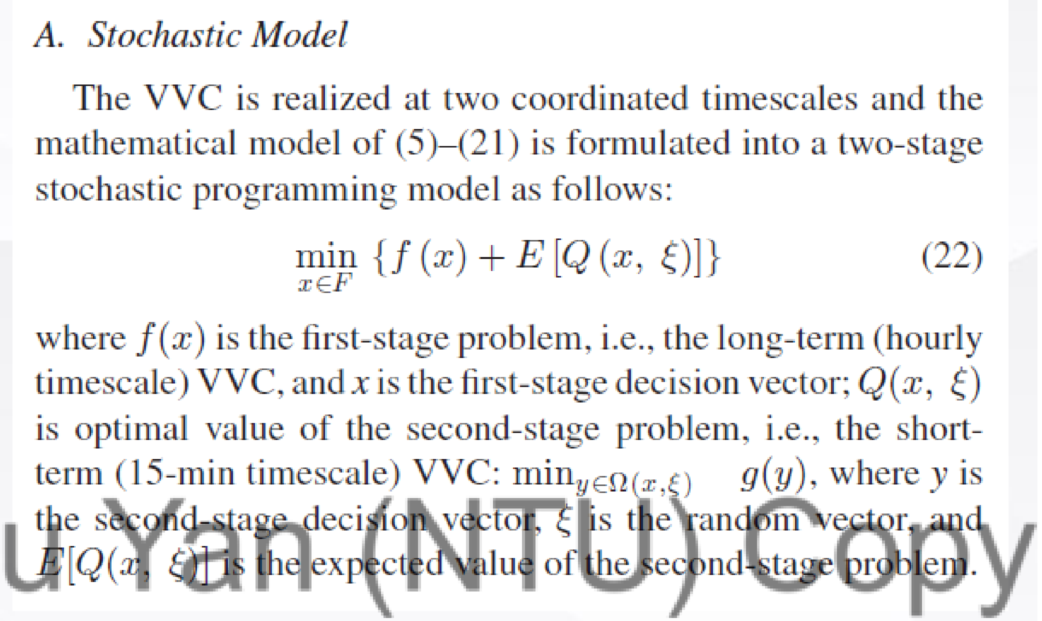


Volt/Var Control Model	Stochastic Programming Model
Two VVC timescale	Two decision stage
CB and OLTC hourly dispatch	*here-and-now* variables
Inverters 15min dispatch	*wait-and-see* variables
Random load and RES	Stochastic variables
Network and utility code	Model state variables
Load and RES forecasting	Scenario construction
VVC signals	Solution results

- **First-Stage:** Slow switching devices such as OLTCs and CBs are scheduled one day ahead.
- **Second-Stage:** Fast responding devices such as PV-associated inverters are updated to operate in short time-window.

Y. Xu*, Z.Y. Dong, et al, "Multi-timescale coordinated voltage/var control of high renewable-penetrated distribution networks," ***IEEE Trans. Power Syst., 2018.***

- Mathematical modeling

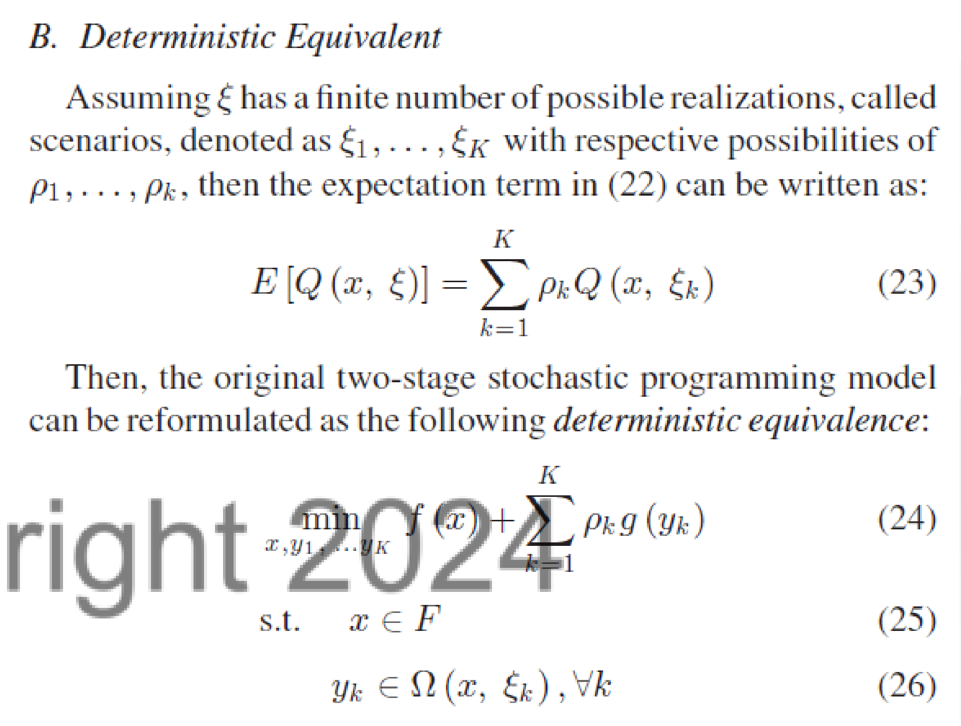


A. *Stochastic Model*

The VVC is realized at two coordinated timescales and the mathematical model of (5)–(21) is formulated into a two-stage stochastic programming model as follows:

$$\min_{x \in F} \{f(x) + E[Q(x, \xi)]\} \tag{22}$$

where $f(x)$ is the first-stage problem, i.e., the long-term (hourly timescale) VVC, and x is the first-stage decision vector; $Q(x, \xi)$ is optimal value of the second-stage problem, i.e., the short-term (15-min timescale) VVC: $\min_{y \in \Omega(x,\xi)} \; g(y)$, where y is the second-stage decision vector, ξ is the random vector, and $E[Q(x, \xi)]$ is the expected value of the second-stage problem.



B. *Deterministic Equivalent*

Assuming ξ has a finite number of possible realizations, called scenarios, denoted as $\xi_1, \ldots, \xi_K$ with respective possibilities of $\rho_1, \ldots, \rho_k$, then the expectation term in (22) can be written as:

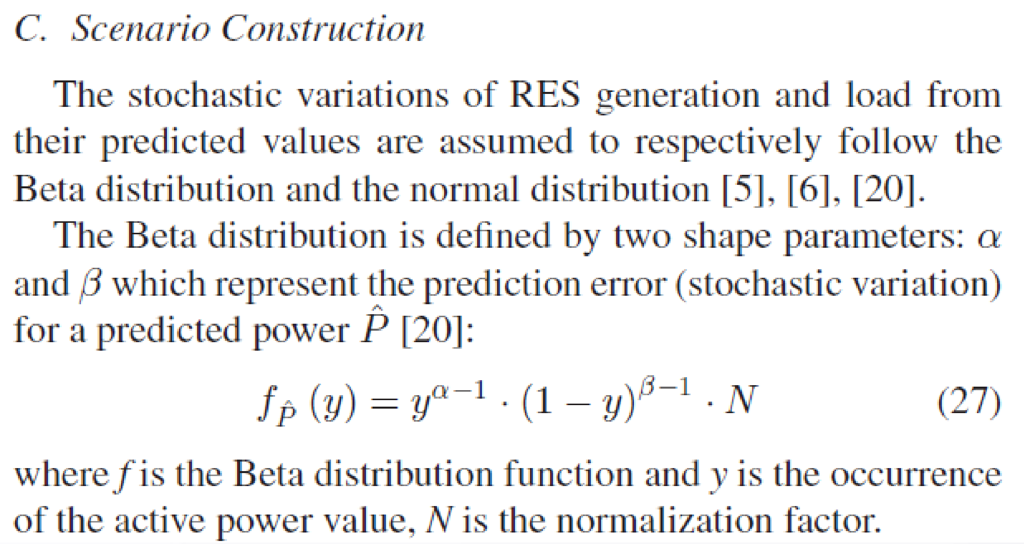
$$E[Q(x, \xi)] = \sum_{k=1}^{K} \rho_k Q(x, \xi_k) \tag{23}$$

Then, the original two-stage stochastic programming model can be reformulated as the following *deterministic equivalence*:

$$\min_{x, y_1, \ldots, y_K} f(x) + \sum_{k=1}^{K} \rho_k g(y_k) \tag{24}$$

$$\text{s.t.} \quad x \in F \tag{25}$$

$$y_k \in \Omega(x, \xi_k), \forall k \tag{26}$$



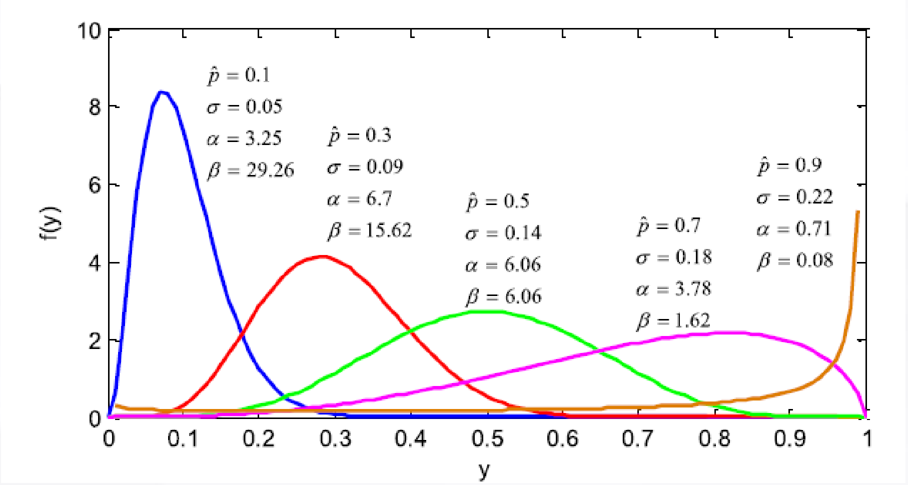
C. *Scenario Construction*

The stochastic variations of RES generation and load from their predicted values are assumed to respectively follow the Beta distribution and the normal distribution [5], [6], [20].

The Beta distribution is defined by two shape parameters: α and β which represent the prediction error (stochastic variation) for a predicted power $\hat{P}$ [20]:

$$f_{\hat{P}}(y) = y^{\alpha-1} \cdot (1-y)^{\beta-1} \cdot N \tag{27}$$

where f is the Beta distribution function and y is the occurrence of the active power value, N is the normalization factor.



1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

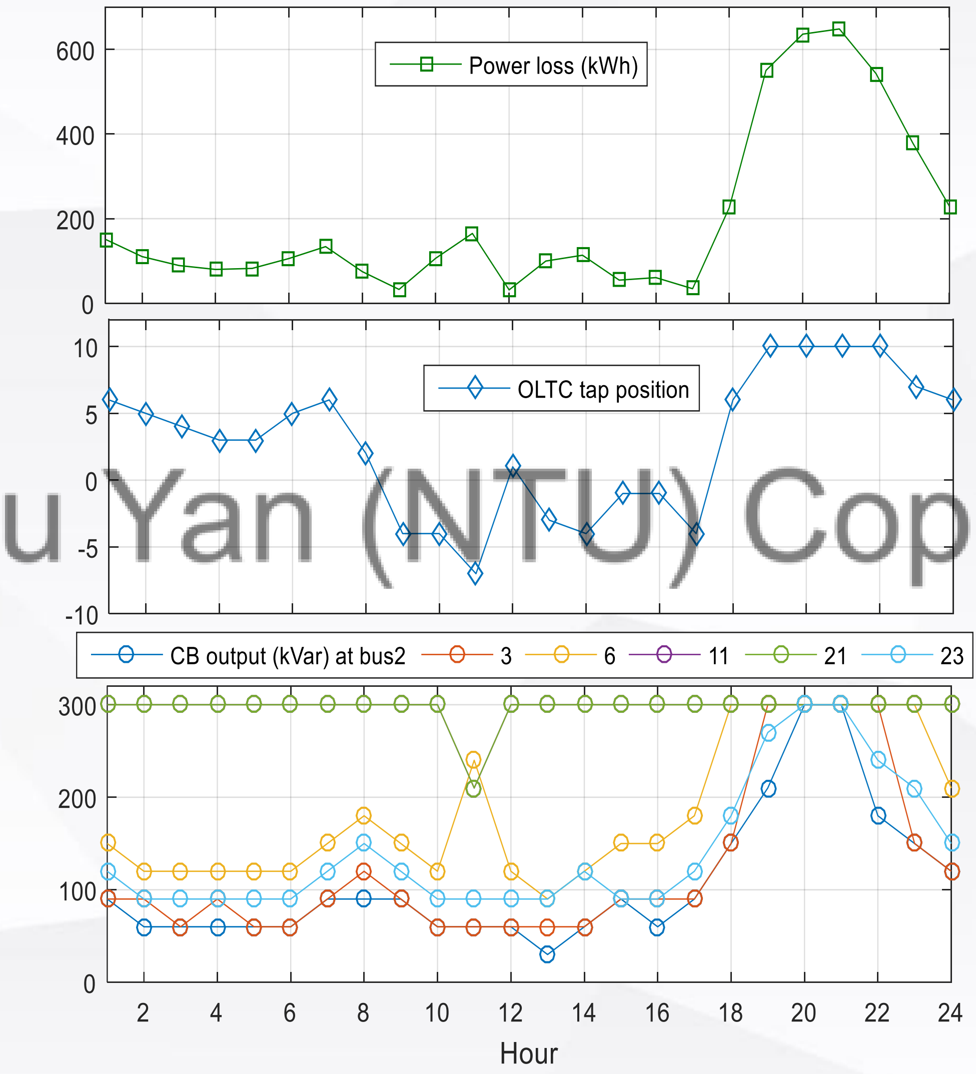
4. Hierarchy coordination

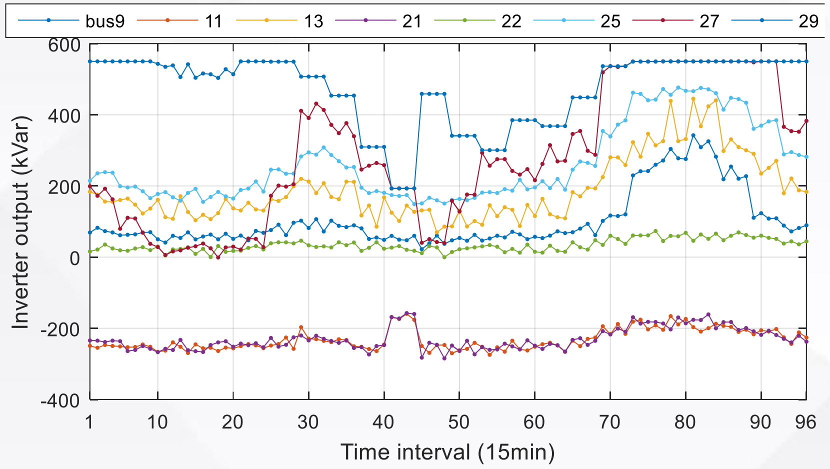
5. Trading
1) Centralized trading
2) P2P trading

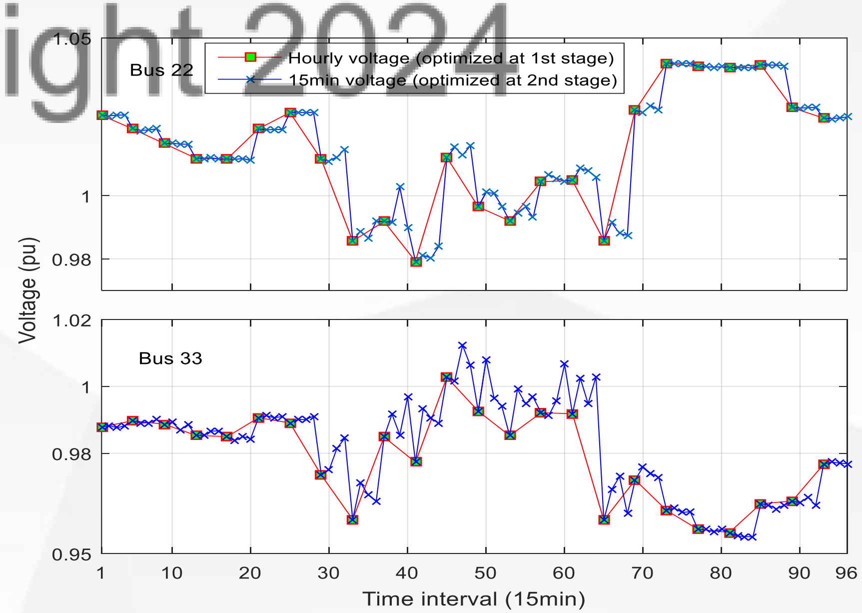
6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

Simulation Results







Y. Xu*, Z.Y. Dong, et al, "Multi-timescale coordinated voltage/var control of high renewable-penetrated distribution networks," *IEEE Trans. Power Syst., 2018.*

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

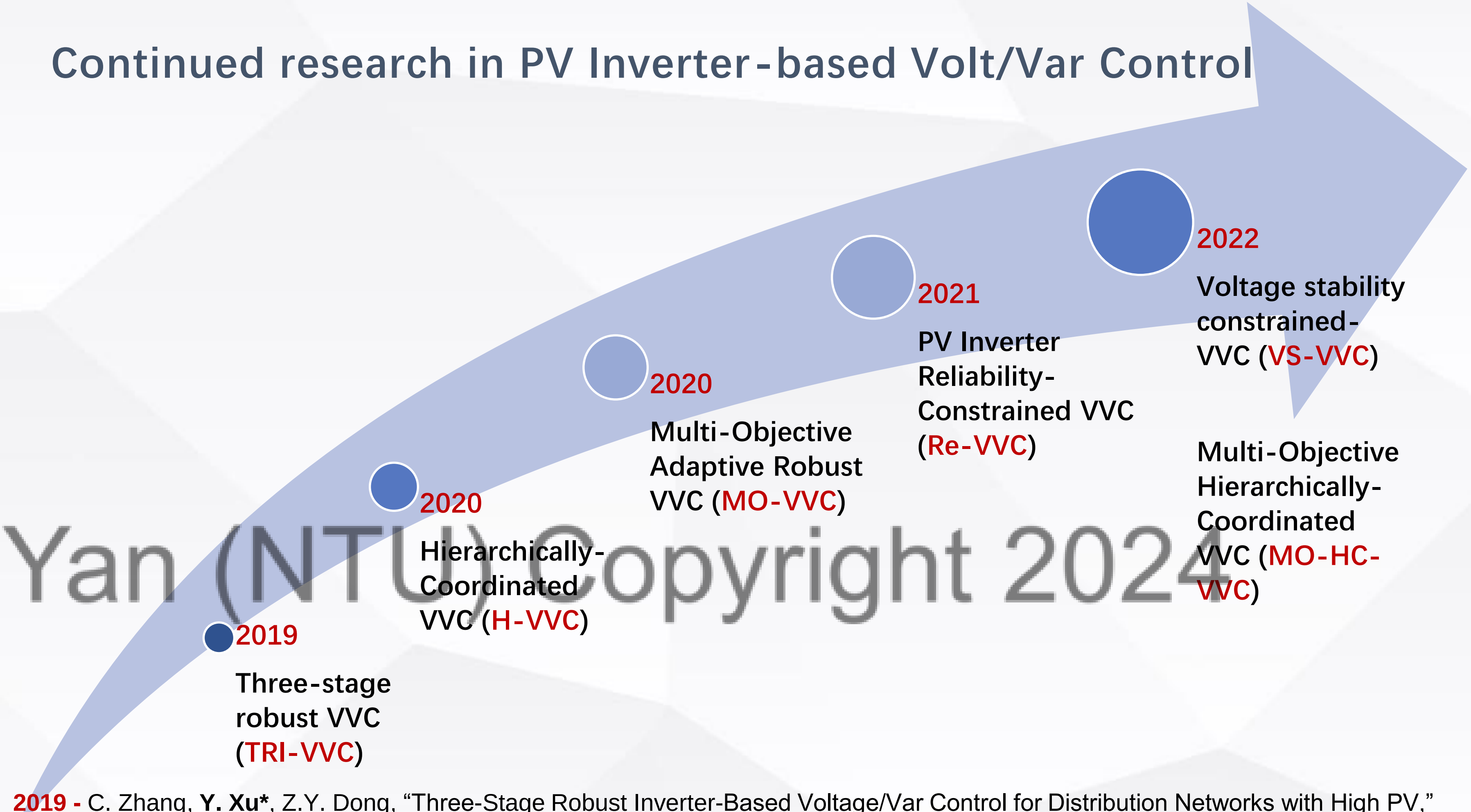
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

- Continued research in PV Inverter-based Volt/Var Control



2019
Three-stage robust VVC (TRI-VVC)

2020
Hierarchically-Coordinated VVC (H-VVC)

2020
Multi-Objective Adaptive Robust VVC (MO-VVC)

2021
PV Inverter Reliability-Constrained VVC (Re-VVC)

2022
Voltage stability constrained-VVC (VS-VVC)

Multi-Objective Hierarchically-Coordinated VVC (MO-HC-VVC)

2019 - C. Zhang, **Y. Xu***, Z.Y. Dong, “Three-Stage Robust Inverter-Based Voltage/Var Control for Distribution Networks with High PV,” *IEEE Trans. Smart Grid,* 2019. **– Web-of-Science Highly Cited Paper**

2020 - C. Zhang and **Y. Xu***, **“**Hierarchically-Coordinated Voltage/VAR Control of Distribution Networks using PV Inverters,” *IEEE Trans. Smart Grid,* 2020. **– 2021 IEEE TSG Outstanding Paper Award**

2020 - C. Zhang, **Y. Xu***, Z.Y. Dong, “Multi-Objective Adaptive Robust Voltage/VAR Control for High-PV Penetrated Distribution Networks,” *IEEE Trans. Smart Grid*, 2020.

2021 - Q. Chai, C. Zhang, **Y. Xu**, and Z.Y. Dong, “PV Inverter Reliability-Constrained Volt/Var Control of Distribution Networks,” *IEEE Trans. Sustainable Energy*, 2021.

2022 - C. Zhang, **Y. Xu***, Y. Wang, “Three-Stage Hierarchically-Coordinated Volt-age/Var Control based on PV Inverters Considering Network Voltage Stability,” *IEEE Trans. Sustainable Energy*, 2022.

2022 - R. Xu, C. Zhang, **Y. Xu**, Z.Y. Dong, and R. Zhang, “Multi-Objective Hierarchically-Coordinated Volt/Var Control for Active Distribution Networks with Droop-Controlled PV Inverters,” *IEEE Trans. Smart Grid*, 2022.

Multi-Objective Adaptive Robust Voltage/VAR Regulation

•Minimizing voltage deviation conflicts with minimizing network power loss.

•Multi-objective "min-max-min" problem

$$\min_{\boldsymbol{x}} \max_{\boldsymbol{u}} \min_{\boldsymbol{y}} [f_1(\boldsymbol{x},\boldsymbol{u},\boldsymbol{y}), f_2(\boldsymbol{x},\boldsymbol{u},\boldsymbol{y})]$$

$$\text{s.t.} \quad \boldsymbol{Ax} \geq \boldsymbol{b}$$

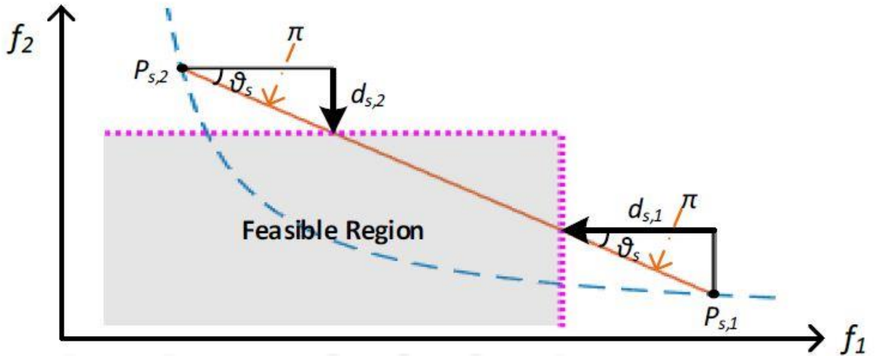
$$\boldsymbol{Cx} + \boldsymbol{Dy} \leq \boldsymbol{v}$$

$$\boldsymbol{Ex} + \boldsymbol{Gy} + \boldsymbol{Hu} = \boldsymbol{w}$$

$$\boldsymbol{u} \in \boldsymbol{U}$$

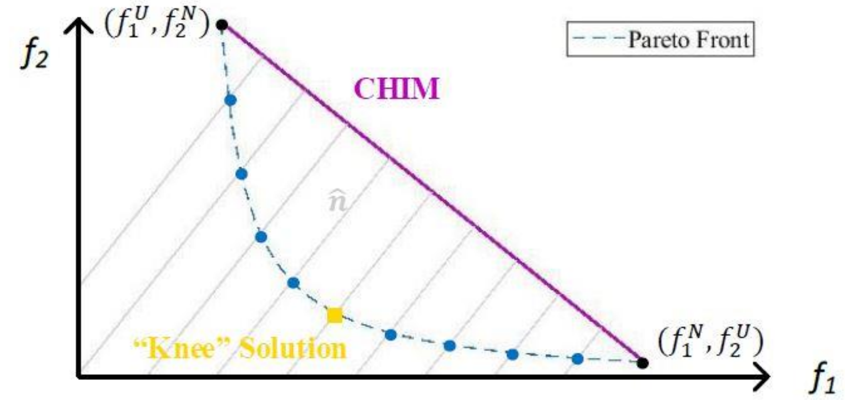
Key point:
1) Voltage deviation index: load-weighted voltage deviation index (LVDI)
2) Which MOP algorithm is more efficient to generat accurate Pareto front and get a fair trade-off?
- a) Classic Weighted-Sum (CWS)
- b) Classic ε-Constrained (CeC)
- c) Adaptive Weighted-Sum (AWS)
- d) Normal Boundary Intersection (NBI)

Adaptive Weighted Sum (AWS)



Reduced feasible region used in AWS algorithm.

Normal Boundary Intersection (NBI)



Pareto front generated by NBI algorithm.

C. Zhang, **Y. Xu***, Z.Y. Dong, "Multi-Objective Adaptive Robust Voltage/VAR Control for High-PV Penetrated Distribution Networks," ***IEEE Trans. Smart Grid*, 2020.**

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

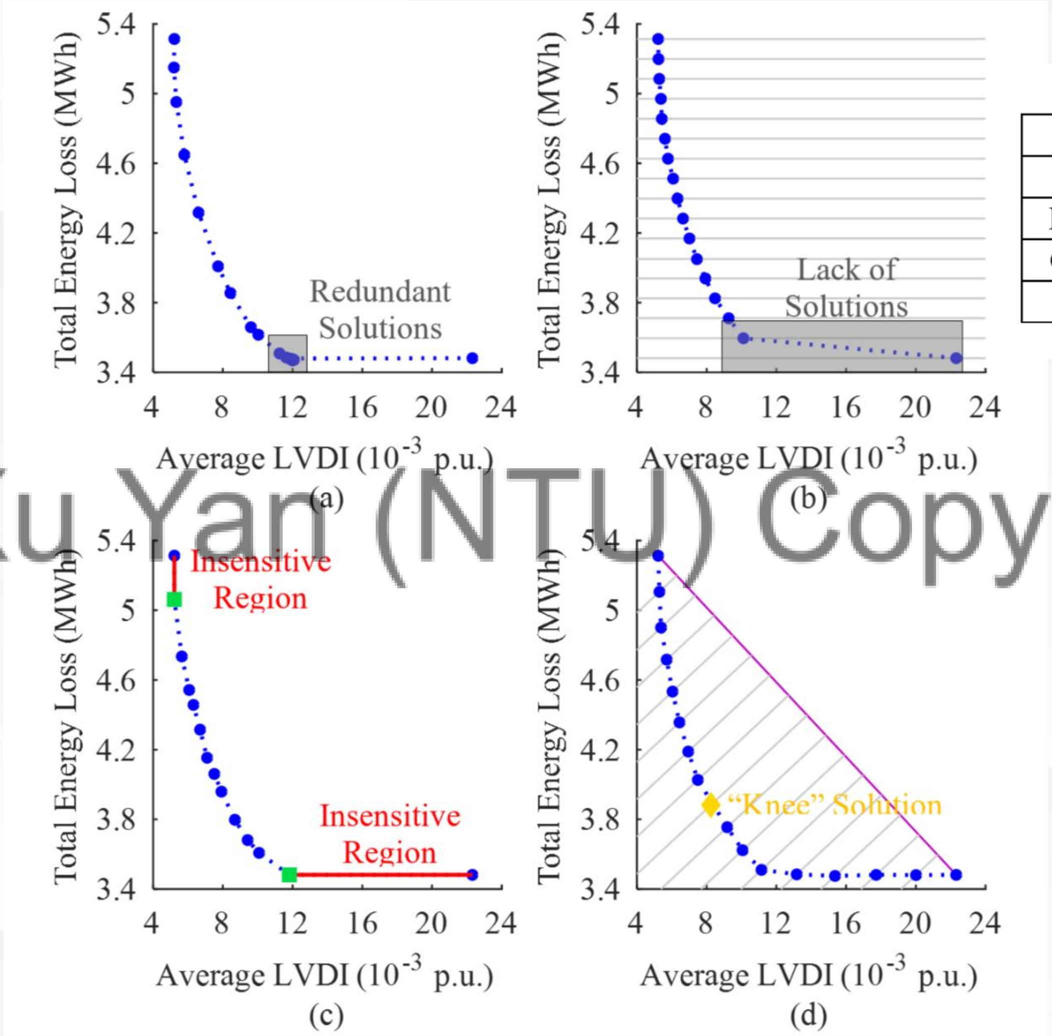
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

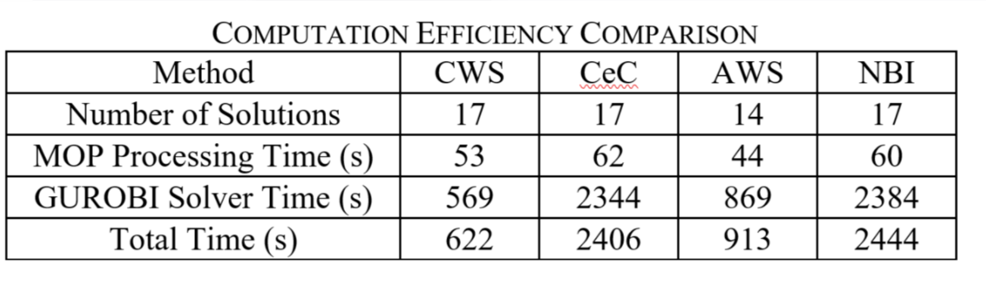
6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG TECHNOLOGICAL UNIVERSITY
SINGAPORE

Multi-Objective Adaptive Robust Voltage/VAR Regulation



(a) CWS; (b) CeC; (c) AWS; (d) NBI



COMPUTATION EFFICIENCY COMPARISON

Method	CWS	CeC	AWS	NBI
Number of Solutions	17	17	14	17
MOP Processing Time (s)	53	62	44	60
GUROBI Solver Time (s)	569	2344	869	2384
Total Time (s)	622	2406	913	2444

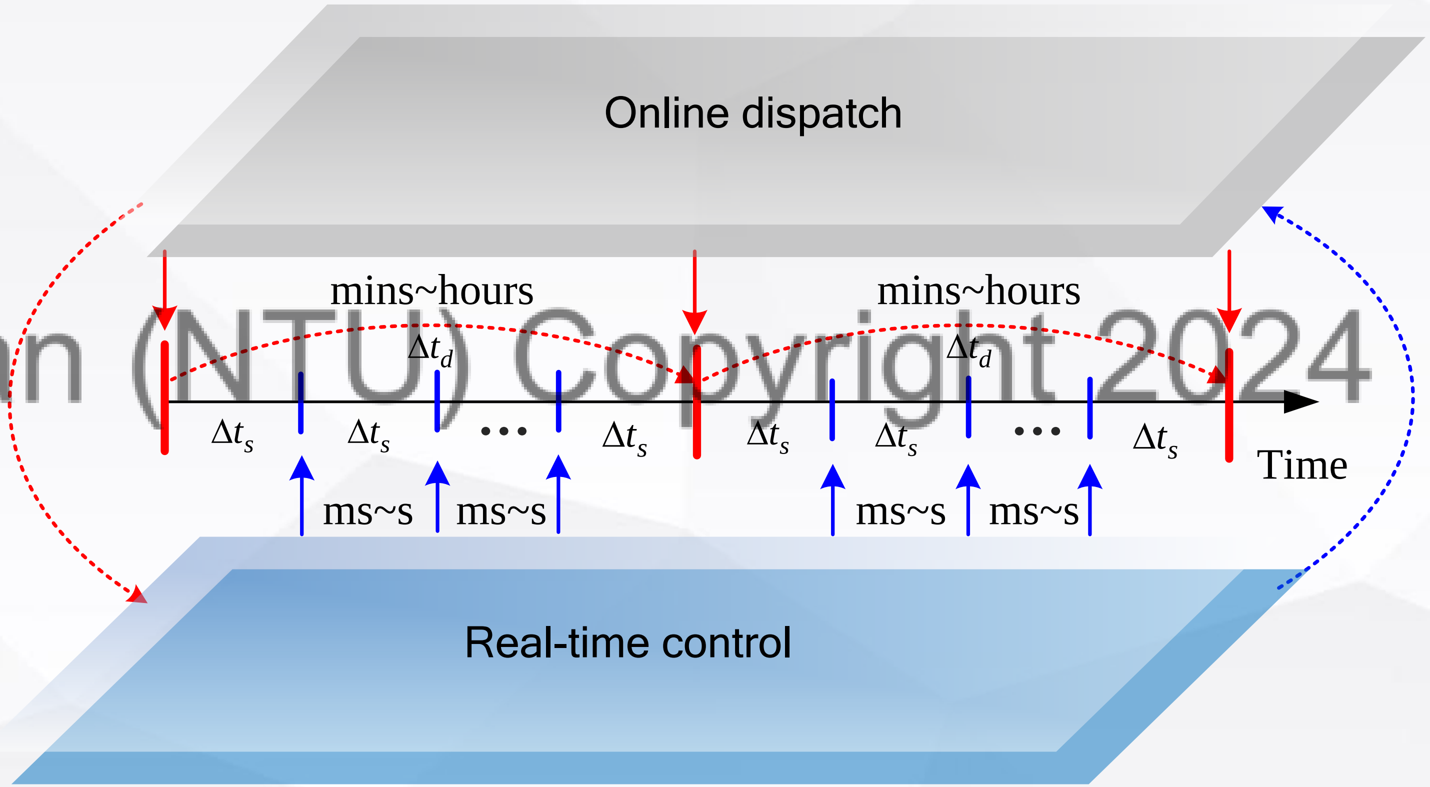
The AWS and NBI algorithms are suggested depending on different optimization requirements.

- ✓ If a relatively accurate Pareto front with high computation efficiency is required, the AWS algorithm is preferred.
- ✓ If a more accurate Pareto front with evenly distributed solutions or the "knee" solution is required, the NBI algorithm is preferred.

C. Zhang, **Y. Xu***, Z.Y. Dong, "Multi-Objective Adaptive Robust Voltage/VAR Control for High-PV Penetrated Distribution Networks," ***IEEE Trans. Smart Grid*, 2020.**

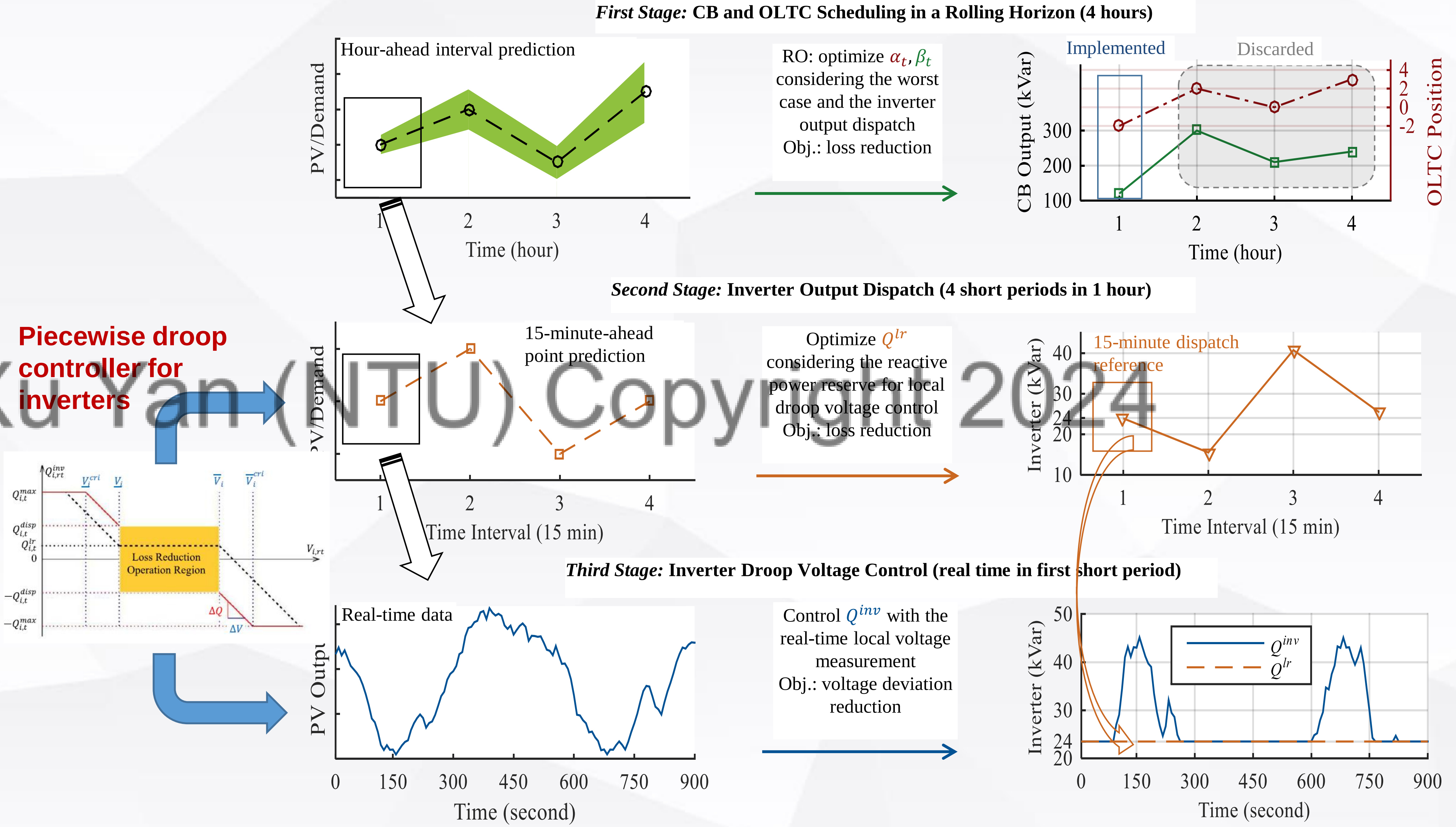
Hierarchically coordinated operation and control of DERs

- ✓ Operational optimization and real-time control are traditionally **decoupled**.
- ✓ Existing two-stage coordination methods are **all for operational timeframe** (e.g., day-ahead & hourly-ahead or hourly-ahead & 15mins-ahead).



- ✓ Need to coordinate the operation level and control level for enhanced system performance, i.e., **optimizing the operation decisions considering the real-time controllers’ effects, or simultaneously optimizing operational variables and controller parameters .**

Three-Stage Robust Volt/Var Control (TRI-VVC)



First Stage: **CB and OLTC Scheduling in a Rolling Horizon (4 hours)**

RO: optimize α_t, β_t considering the worst case and the inverter output dispatch
Obj.: loss reduction

Second Stage: **Inverter Output Dispatch (4 short periods in 1 hour)**

Optimize Q^{lr} considering the reactive power reserve for local droop voltage control
Obj.: loss reduction

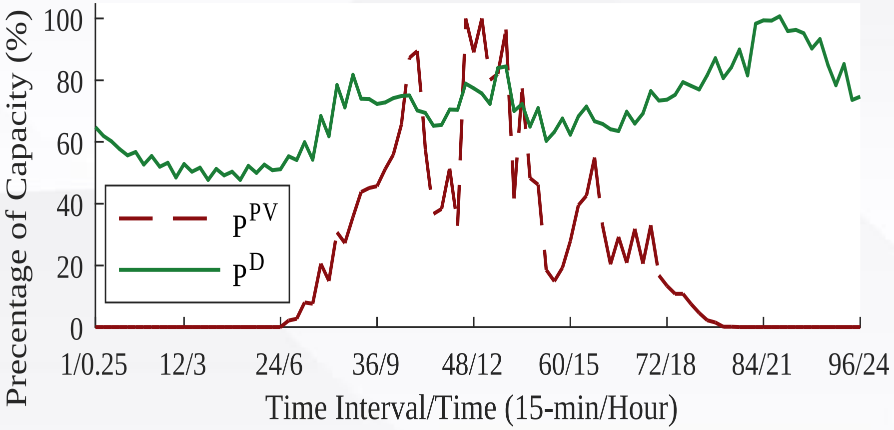
Third Stage: **Inverter Droop Voltage Control (real time in first short period)**

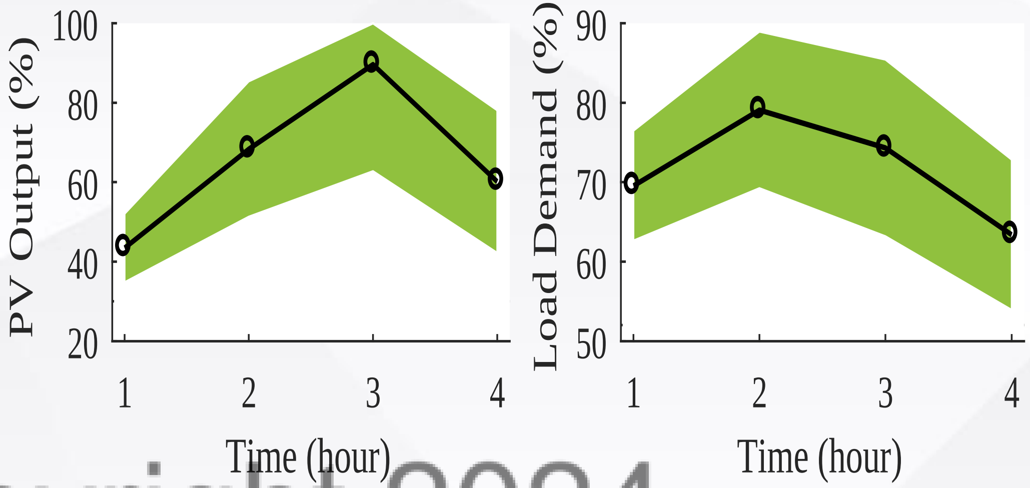
Control Q^{inv} with the real-time local voltage measurement
Obj.: voltage deviation reduction

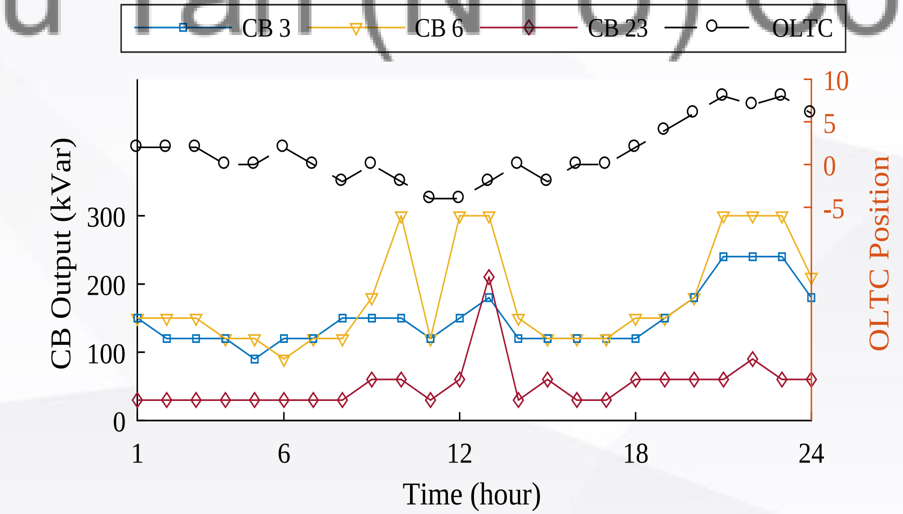
Piecewise droop controller for inverters

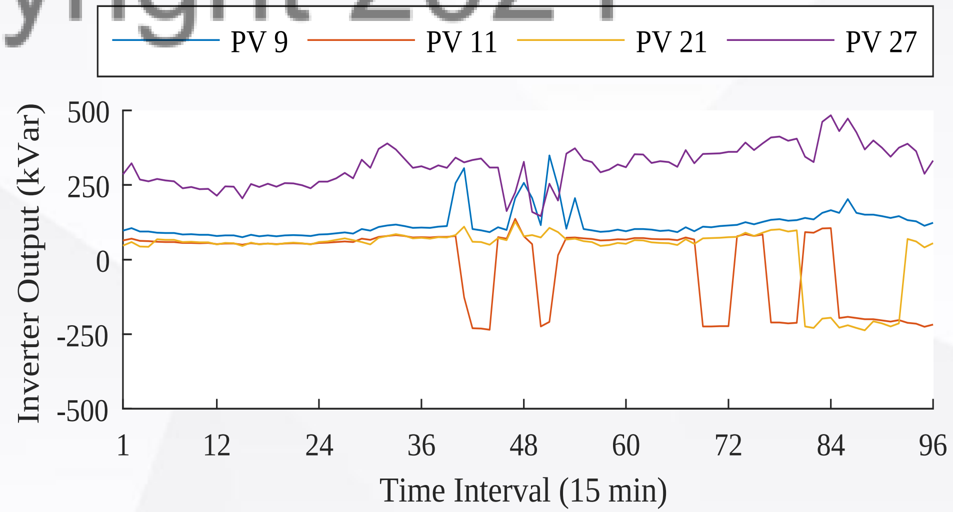
C. Zhang, **Y. Xu***, Z.Y. Dong, et al "Three-Stage Robust Inverter-Based Voltage/Var Control for Distribution Networks with High PV," *IEEE Trans. Smart Grid*, 2018. **Web-of-Science Highly Cited Paper**

- Simulation Results





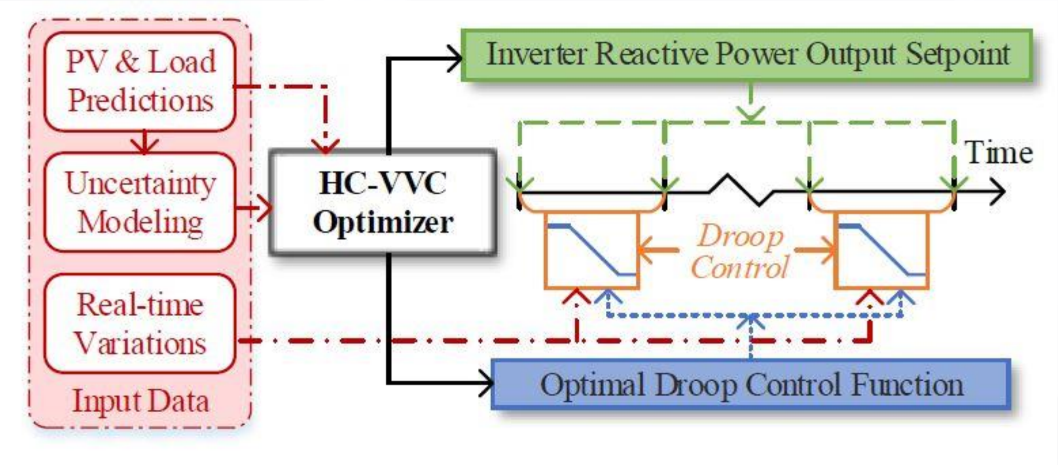


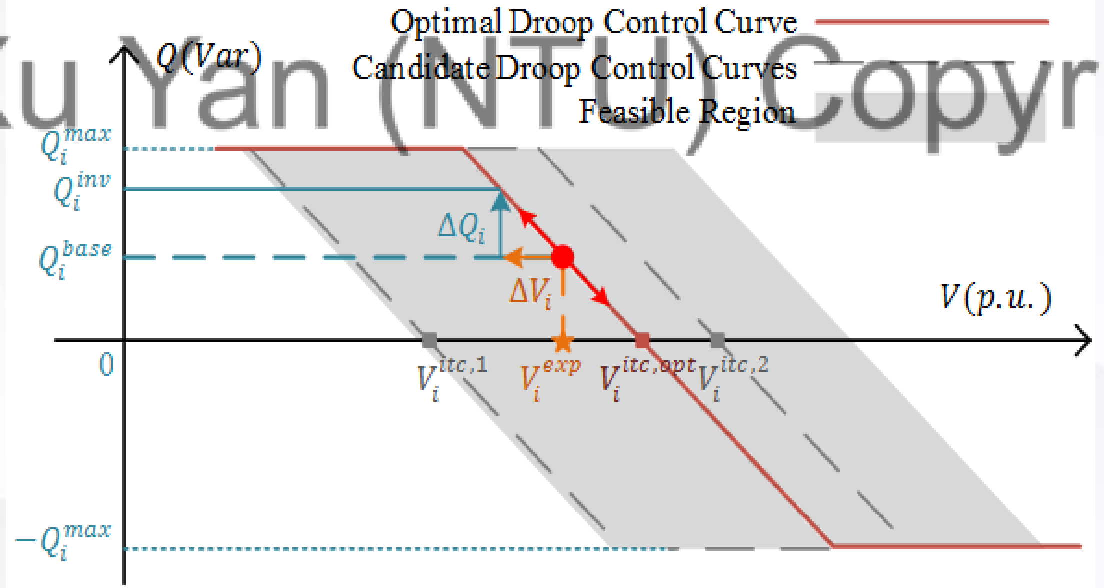


C. Zhang, **Y. Xu***, Z.Y. Dong, et al "Three-Stage Robust Inverter-Based Voltage/Var Control for Distribution Networks with High PV," *IEEE Trans. Smart Grid, 2018.* **Web-of-Science Highly Cited Paper**

Hierarchically-Coordinated Voltage/VAR Control (HC-VVC)

- ✓ Central VVC considers the network level information (power flow)
- ✓ Local VVC focuses on the real-time variation (bus voltage)





linear droop controller for inverters

Inverter Droop Control Model

- The central VVC hierarchy implements the base reactive power output setpoint of each inverter, i.e. Q_i^{base} under the expected operating condition.
- The local VVC hierarchy implements the local droop control by adjusting the reactive power output responding to the local voltage deviation. $\Delta Q = f(\Delta V)$

C. Zhang and **Y. Xu***, "Hierarchically-Coordinated Voltage/VAR Control of Distribution Networks Using PV Inverters," ***IEEE Trans. Smart Grid*, 2020.** **2021 IEEE TSG Outstanding Paper Award**

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

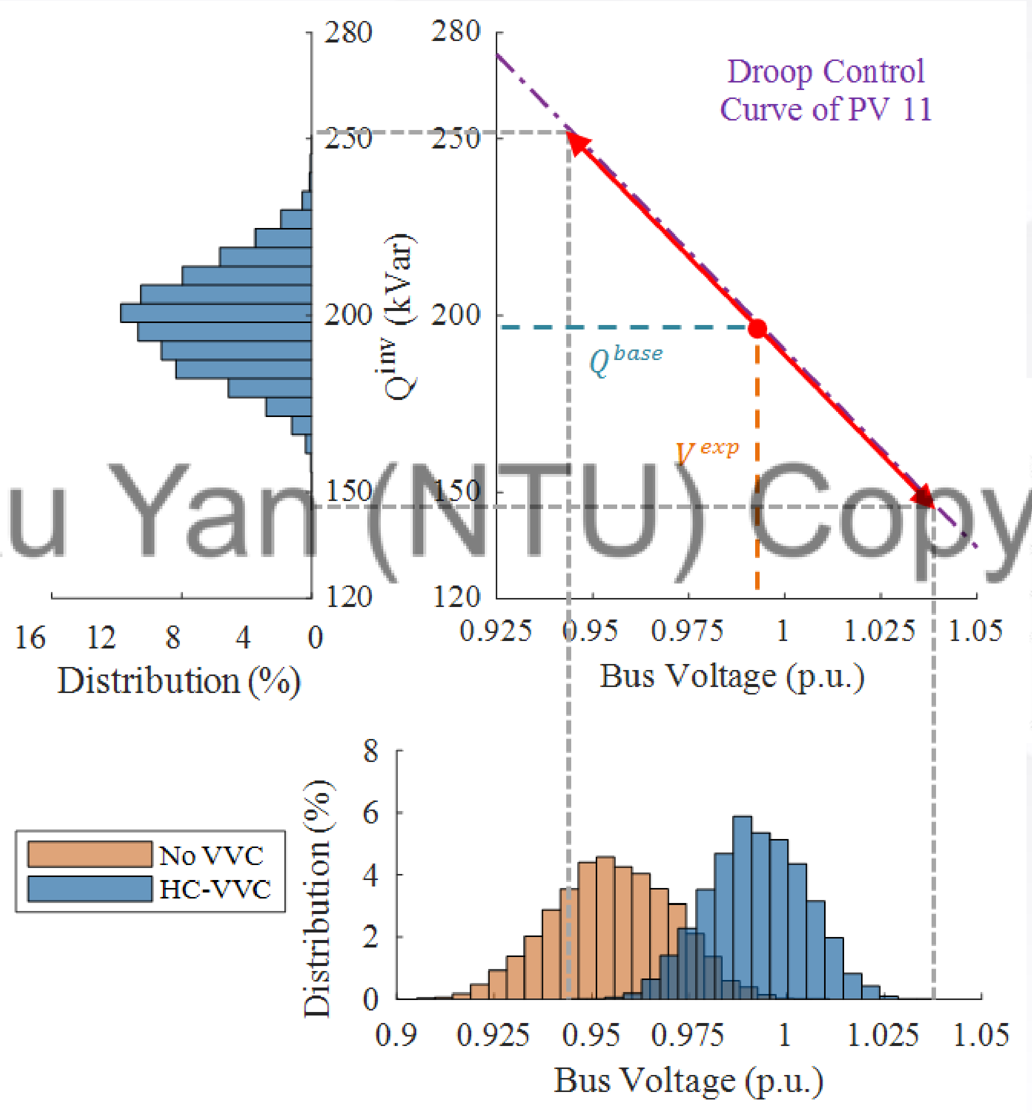
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

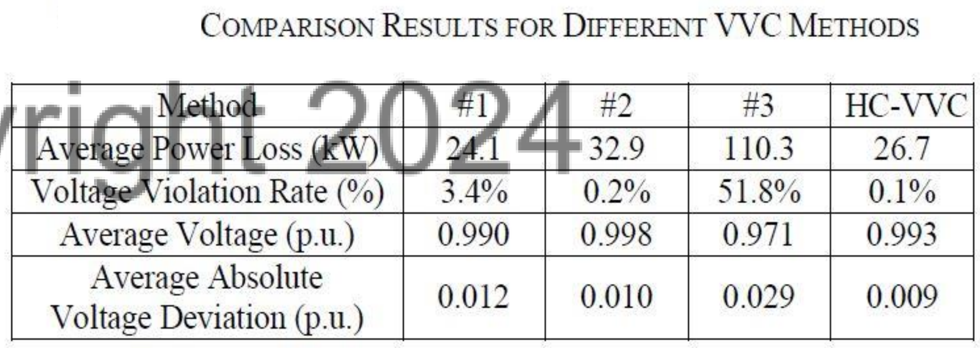
▪ Hierarchically-Coordinated Voltage/VAR Control (HC-VVC)



Voltage control results:

In response to the local bus voltage variation, the inverter reactive power output moves along the droop control curve.

The mean bus voltage magnitude with the HC-VVC is very close to 1 p.u.



COMPARISON RESULTS FOR DIFFERENT VVC METHODS

Method	#1	#2	#3	HC-VVC
Average Power Loss (kW)	24.1	32.9	110.3	26.7
Voltage Violation Rate (%)	3.4%	0.2%	51.8%	0.1%
Average Voltage (p.u.)	0.990	0.998	0.971	0.993
Average Absolute Voltage Deviation (p.u.)	0.012	0.010	0.029	0.009

Comparison with other VVC methods

HC-VVC: least voltage violation rate; least voltage magnitude deviation; second least average power loss; second average voltage close to 1 p.u.

C. Zhang and **Y. Xu***, "Hierarchically-Coordinated Voltage/VAR Control of Distribution Networks Using PV Inverters," ***IEEE Trans. Smart Grid*, 2020.** **2021 IEEE TSG Outstanding Paper Award**

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

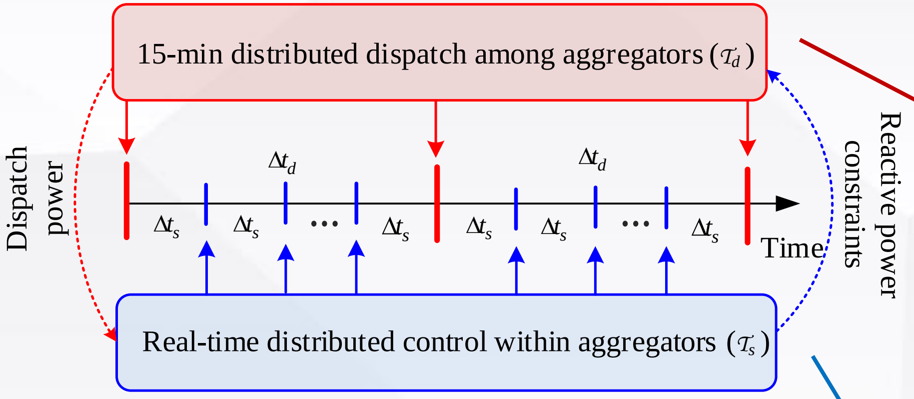
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

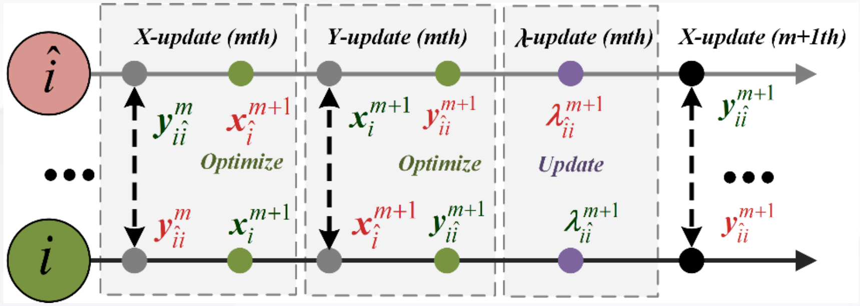
6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

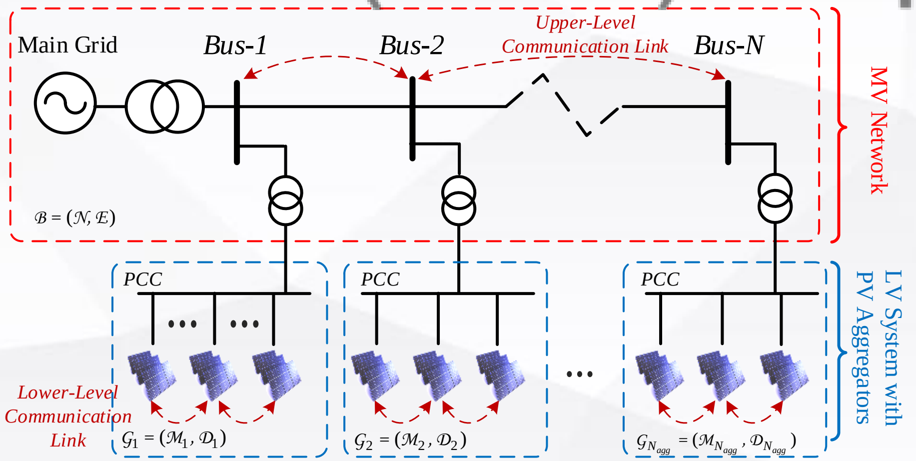
▪ Fully Distributed Two-Level Volt/Var Control

Two-level VVC with time scale coordination

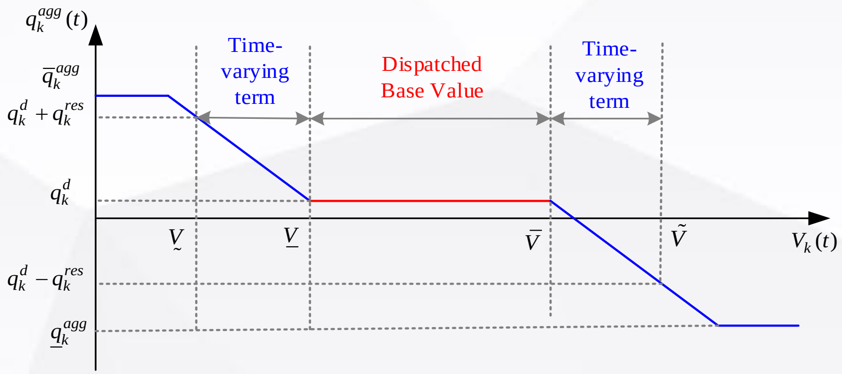


Distributed dispatch by ADMM





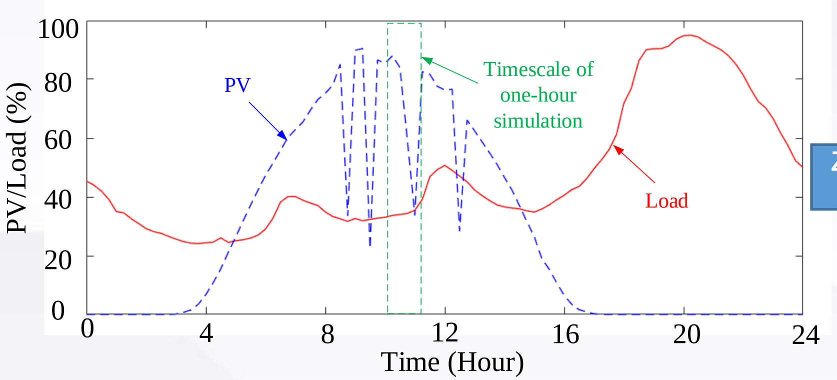
Distributed real-time voltage control



Y. Wang, T. Zhao, C. Ju, **Y. Xu***, P. Wang “Two-Level Distributed Voltage/Var Control of Aggregated PV Inverters in Distribution Networks,” ***IEEE Trans. Power Delivery*, 2019**.

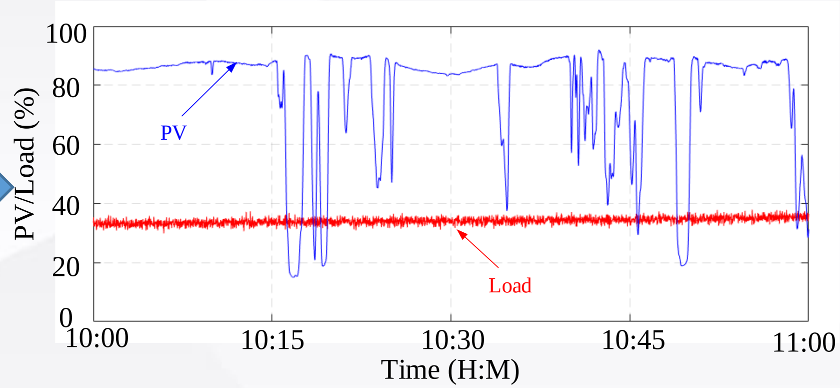
Simulation Results

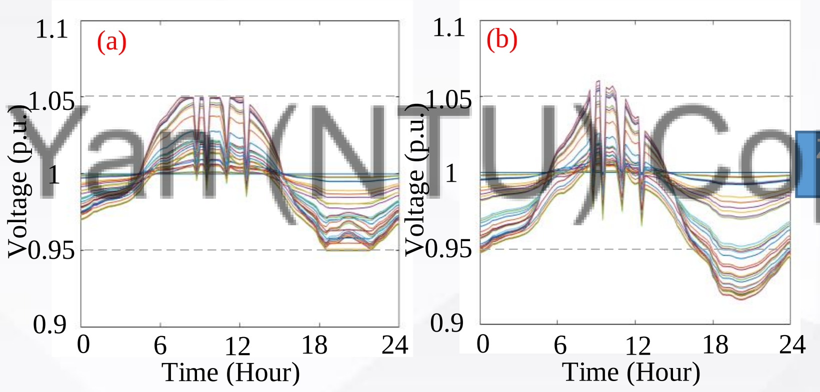
24-hour simulation with 15 minutes sampling



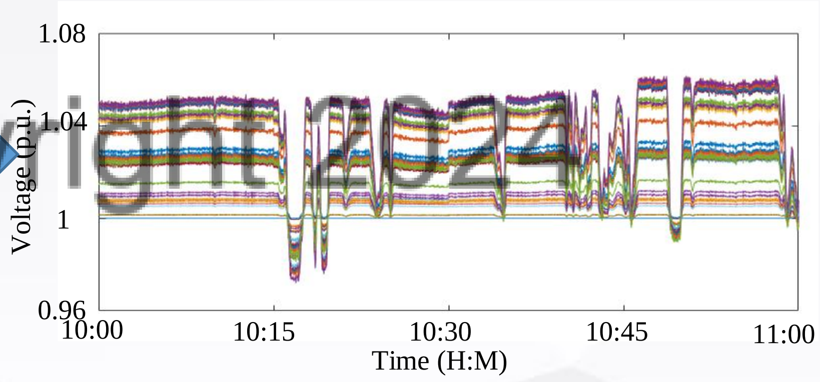
Zoom in

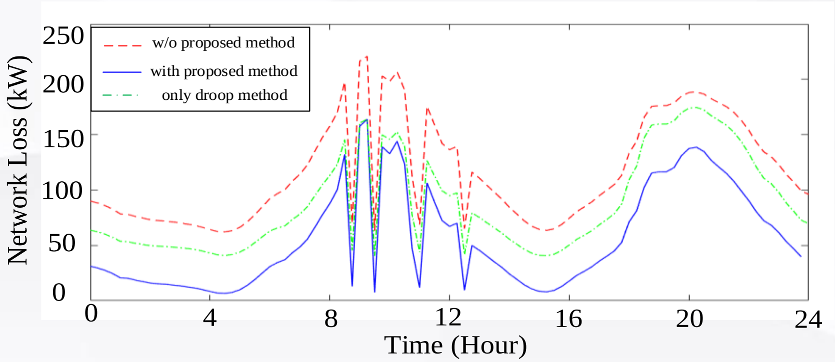
One-hour simulation with 1 second sampling

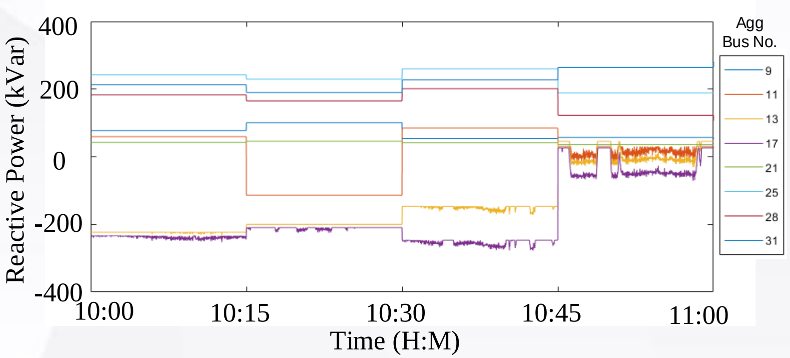




Zoom in







Y. Wang, T. Zhao, C. Ju, **Y. Xu***, P. Wang "Two-Level Distributed Voltage/Var Control of Aggregated PV Inverters in Distribution Networks," ***IEEE Trans. Power Delivery*, 2019**.

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

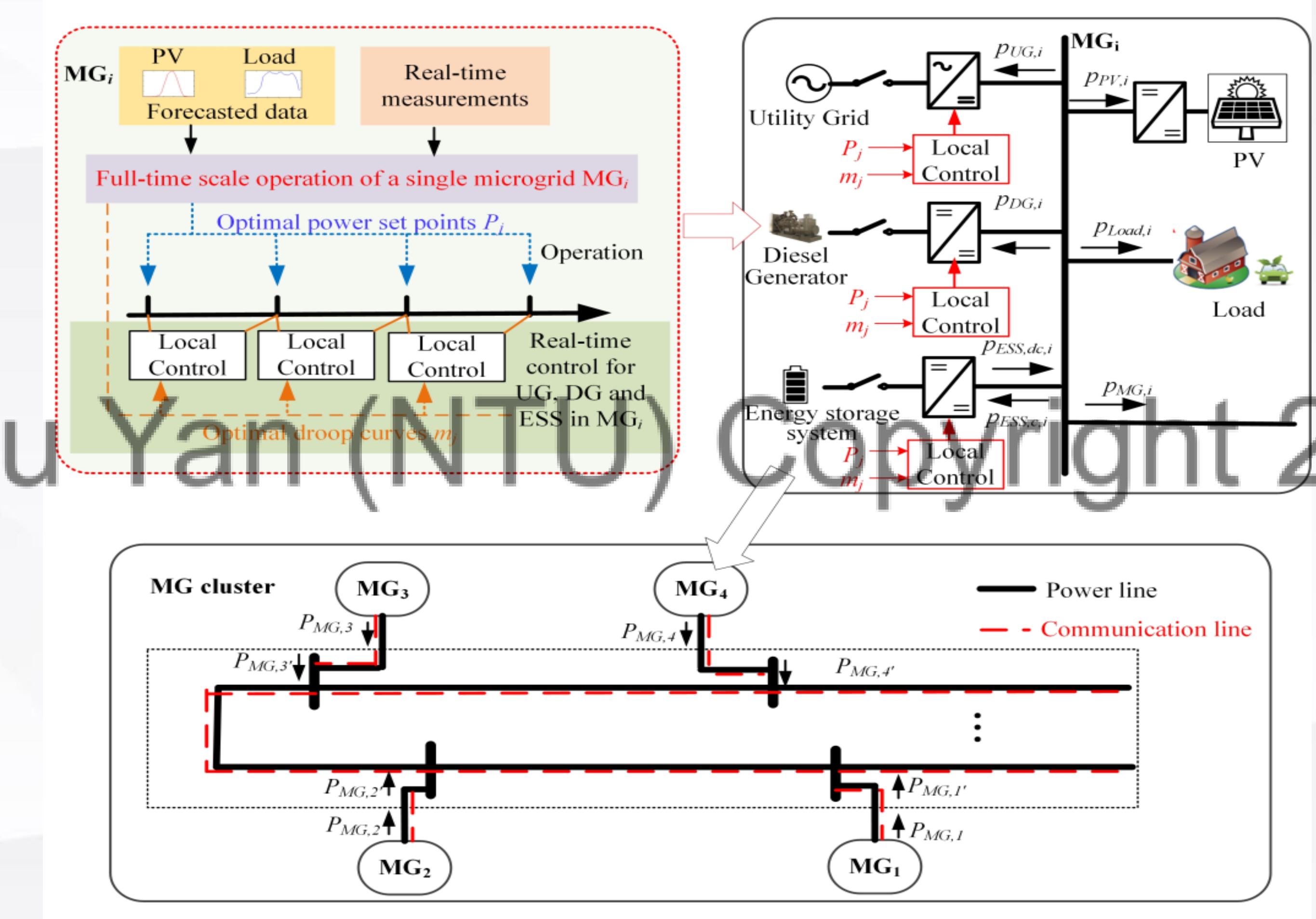
4. Hierarchy coordination

5. Trading
1) Centralized trading
2) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

Hierarchically Coordinated Operation and Control for DC microgrid clusters



$$\min_{\substack{\mathbf{P}_j(t),\beta_j(t),\\ P_{jk}(t),l_{jk}(t),v_j(t)\\ \forall j\in\mathcal{N},j\to k\in\mathcal{E},t\in\mathcal{T}}} \mathbb{E}\sum_{t\in\mathcal{T}}\{f(\mathbf{P}_i(t),\beta_i(t))+\sum_{j:j\to k} l_{jk}(t)r_{jk}\}$$

$$p_{\mathrm{UG},i}-P_{\mathrm{UG},i}=\beta_{\mathrm{UG}\ ,i}\xi_i$$

$$p_{\mathrm{DG},i}-P_{\mathrm{DG},i}=\beta_{\mathrm{DG},i}\xi_i$$

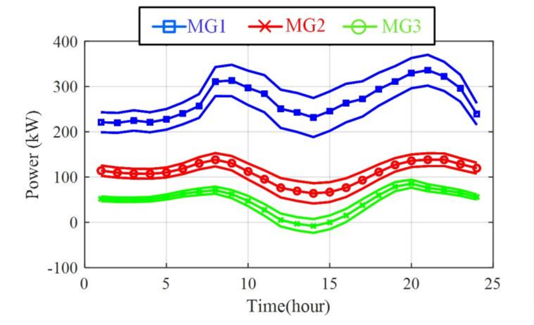
$$p_{\mathrm{ESS},i}-P_{\mathrm{ESS,dc},i}+P_{\mathrm{ESS,c},i}=\beta_{\mathrm{ESS},i}\xi_i$$

$$\beta_{\mathrm{UG},i}+\beta_{\mathrm{DG},i}+\beta_{\mathrm{ESS},i}=1$$

$$m_{UG,i}=\frac{k_i}{\beta_{UG,i}},\, m_{UG,i}\in\left(0,\frac{\Delta V_{\max}}{P_{UG,\max}}\right)$$

$$m_{DG,i}=\frac{k_i}{\beta_{DG,i}},\, m_{DG,i}\in\left(0,\frac{\Delta V_{\max}}{P_{DG,\max}}\right)$$

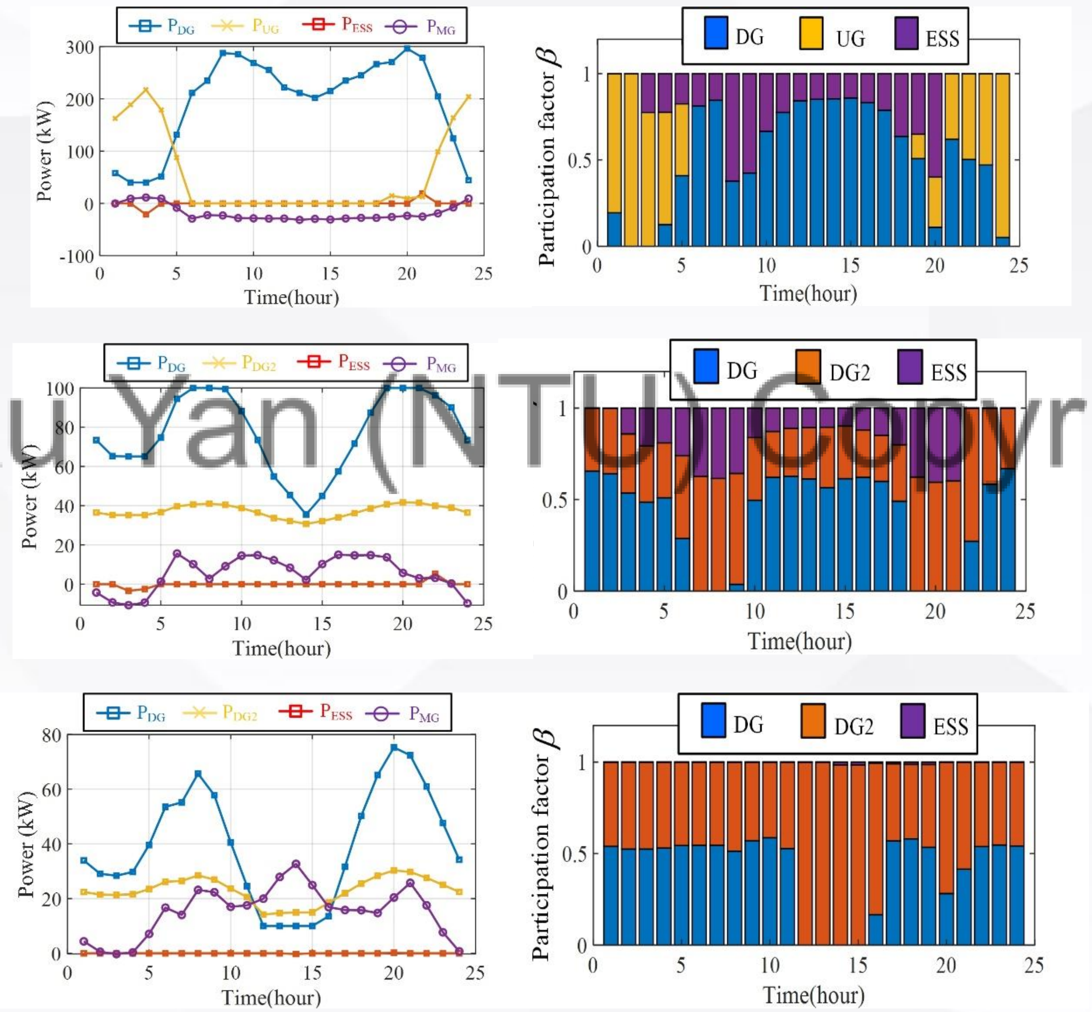
$$m_{ESS,i}=\frac{k_i}{\beta_{ESS,i}},\, m_{ESS,i}\in\left(0,\frac{\Delta V_{\max}}{P_{ESS,\max}}\right)$$

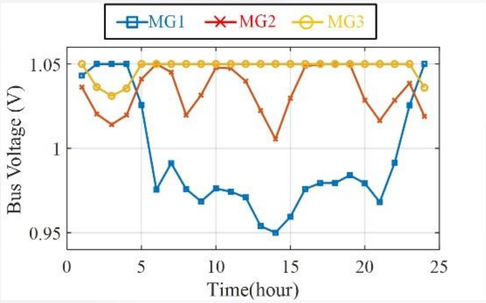


Q. Xu, **Y. Xu***, et al, " A Hierarchically Coordinated Operation and Control Scheme for DC Microgrid Clusters under Uncertaint," ***IEEE Transactions on Sustainable Energy*, 2020.**

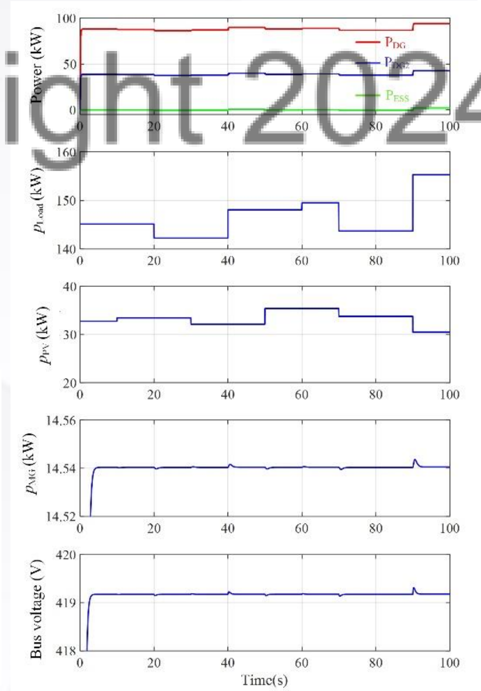
- Hierarchically Coordinated Operation and Control for DC microgrid clusters

Dispatch results

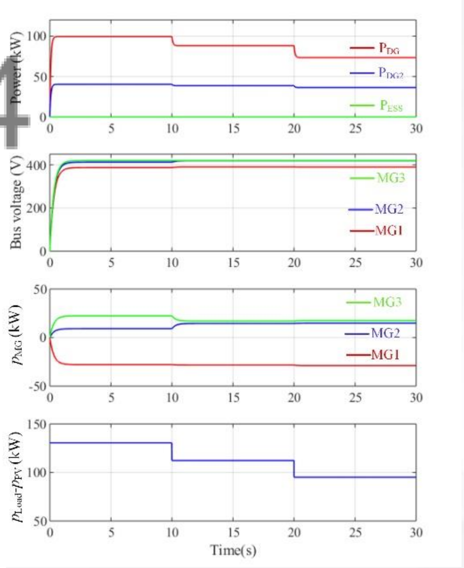




Real-time control results



Simulation results of MG2 during 9h-10h with PV and loadfluctuations in Matlab/Simulink.

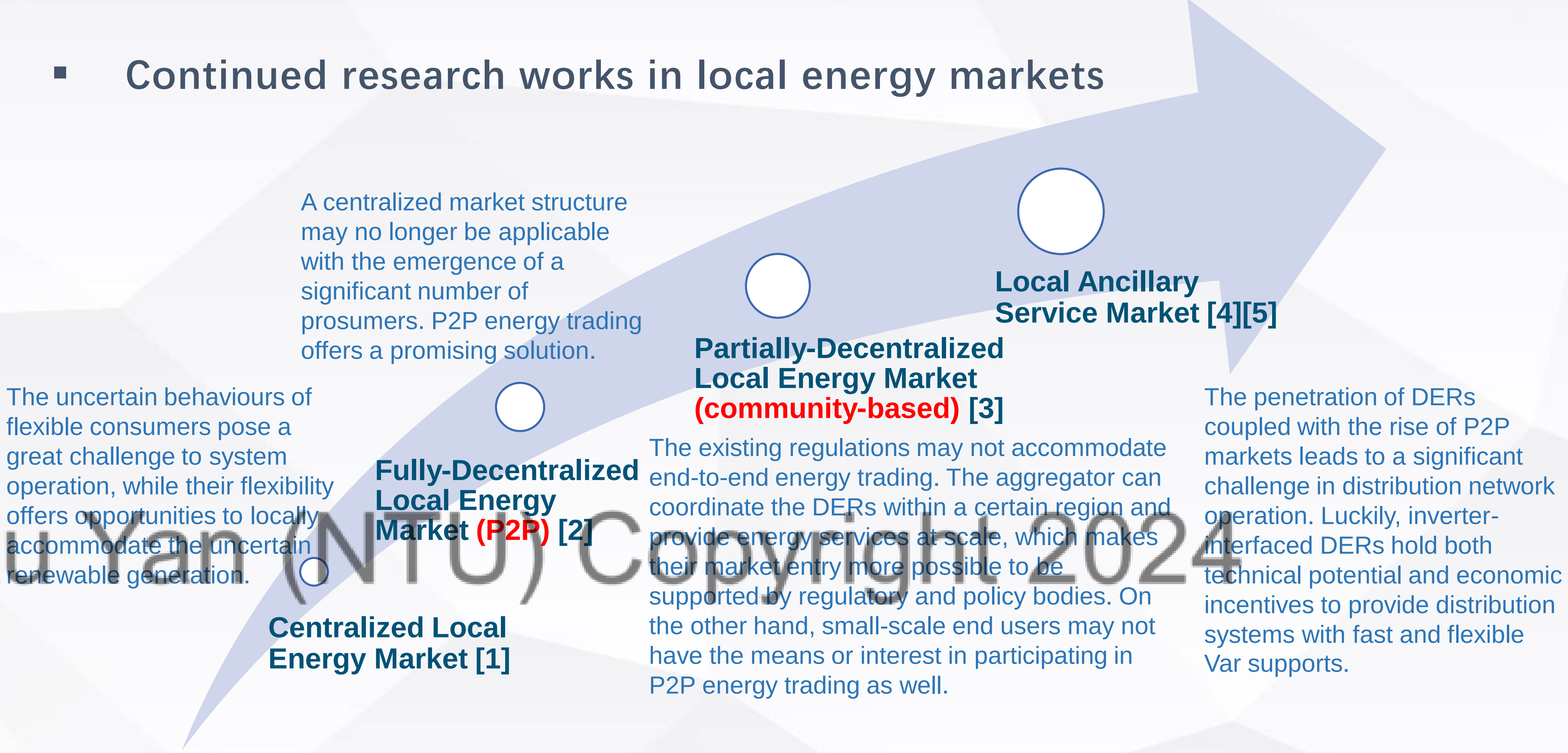


Simulation results when local controller responds to the scheduling results from operation level of MG2 at 9h, 10h and 11h (which is at 10s, 20s and 30s in the simulation)

Q. Xu, **Y. Xu***, et al, " A Hierarchically Coordinated Operation and Control Scheme for DC Microgrid Clusters under Uncertaint," ***IEEE Transactions on Sustainable Energy*, 2020.**

NANYANG TECHNOLOGICAL UNIVERSITY
SINGAPORE

- Continued research works in local energy markets



Centralized Local Energy Market [1]

The uncertain behaviours of flexible consumers pose a great challenge to system operation, while their flexibility offers opportunities to locally accommodate the uncertain renewable generation.

Fully-Decentralized Local Energy Market (P2P) [2]

A centralized market structure may no longer be applicable with the emergence of a significant number of prosumers. P2P energy trading offers a promising solution.

Partially-Decentralized Local Energy Market (community-based) [3]

The existing regulations may not accommodate end-to-end energy trading. The aggregator can coordinate the DERs within a certain region and provide energy services at scale, which makes their market entry more possible to be supported by regulatory and policy bodies. On the other hand, small-scale end users may not have the means or interest in participating in P2P energy trading as well.

Local Ancillary Service Market [4][5]

The penetration of DERs coupled with the rise of P2P markets leads to a significant challenge in distribution network operation. Luckily, inverter-interfaced DERs hold both technical potential and economic incentives to provide distribution systems with fast and flexible Var supports.

[1] Y. Zou, **Y. Xu***, and C. Zhang, “A Risk-Averse Adaptive Stochastic Optimization Method for Transactive Energy Management of a Multi-Energy Microgrid,” *IEEE Transactions on Sustainable Energy*, 2023.

[2] Y. Zou, **Y. Xu***, X. Feng, and H. D. Nguyen, “Peer-to-Peer Transactive Energy Trading in a Reconfigurable Multi-Energy Network,” *IEEE Transactions on Smart Grid*, 2022.

[3] Y. Zou, **Y. Xu***, and J. Li, “Aggregator-Network Coordinated Peer-to-Peer Multi-Energy Trading via Adaptive Robust Stochastic Optimization,” *IEEE Transactions on Power Systems*, 2024.

[4] Y. Zou, and **Y. Xu***, “Design of Robust Var Reserve Contract for Enhancing Reactive Power Ancillary Service Market Efficiency,” *CSEE Journal of Power and Energy Systems*, 2023.

[5] Y. Zou, and **Y. Xu***, “DER-Inverter Based Reactive Power Ancillary Service for Supporting Peer-to-Peer Transactive Energy Trading in Distribution Networks,” *IEEE Transactions on Power Systems*, 2024.

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

5. Trading
1) Design
2) Energy trading
3) Ancillary service

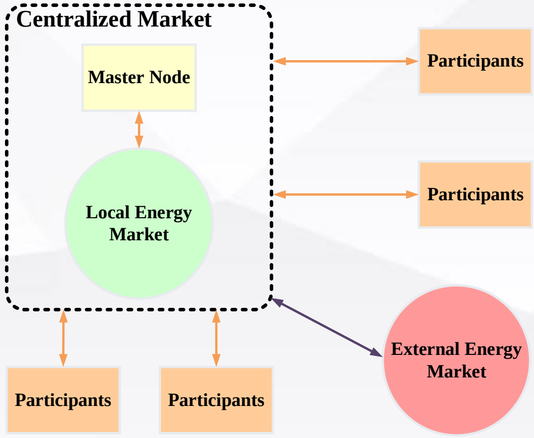
6. Planning
1) DG planning
2) ESS planning
3) Joint planning

Transactive Energy System (TES) Classification

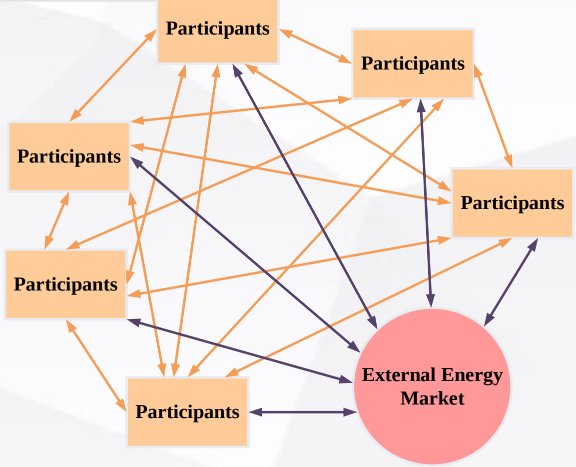
Transactive Energy System (TES)

- **Market Participant**
  - **Energy Providers**
  - **Energy Consumers**
  - **Energy Providers and Consumers**
    - **Energy Prosumers**
- **Market Structure**
  - **Centralized Market**
  - **Partially-Decentralized Market**
  - **Fully-Decentralized Market**
    - **Without Distributed Ledger Technologies**
    - **With Distributed Ledger Technologies**
- **Clearing Method**
  - **Distribution Locational Marginal Pricing**
  - **Auction Mechanism**
    - **Single Auction**
    - **Double Auction**
    - **Reverse Auction**
  - **Game Theory**
    - **Cooperative Game**
    - **Non-cooperative Game**
    - **Stackelberg Game**
    - **Mixed Game**
- **Solution Algorithm**
  - **Centralized Optimization**
  - **Distributed Optimization**
  - **Optimization Under Uncertainties**
    - **Stochastic Optimization**
    - **Robust Optimization**
    - **Machine Learning Techniques**
- **Trading Commodity**
  - **Electrical Energy**
  - **Multiple Energies**
- **Supporting Market Tool**
  - **Penalty Mechanism**
  - **Loss Allocation Mechanism**

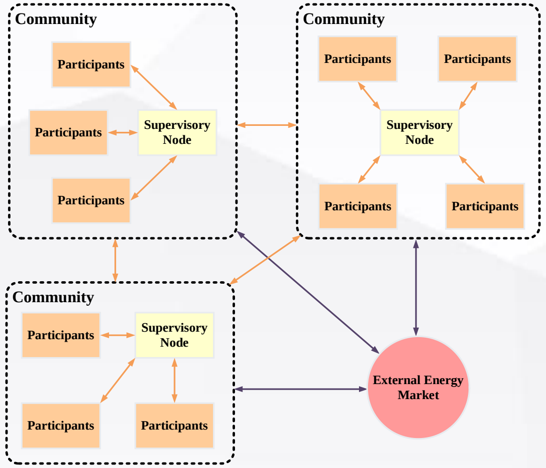
Centralized market



P2P market



Community-based market



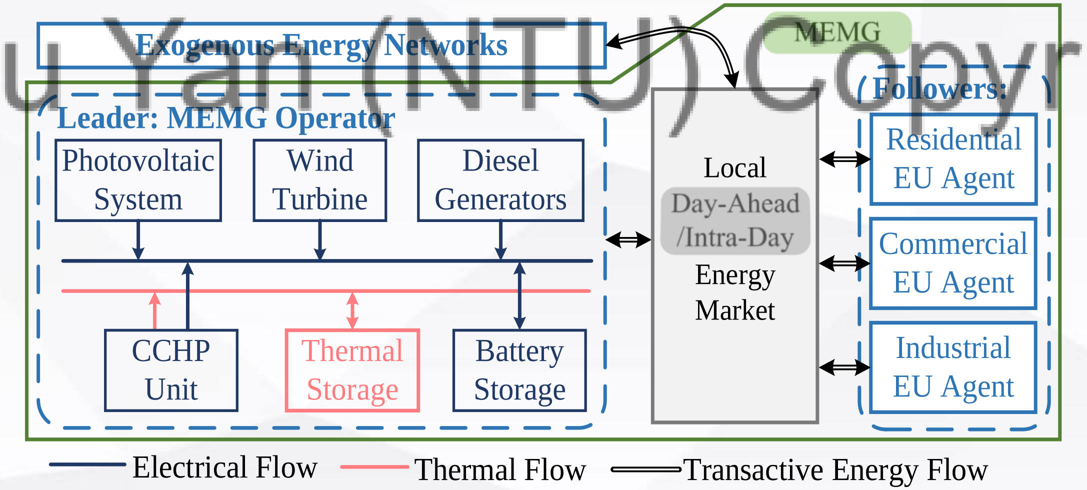
Y. Zou, **Y. Xu***, X. Feng, R. T. Naayagi, and B. H. Soong, "Transactive Energy System in Active Distribution Networks: A Comprehensive Review, " *CSEE Journal of Power and Energy Systems*, 2022.

Centralized Local Market: Risk-Averse Transactive Energy Management

Main motivation: The uncertain behaviours of flexible consumers is challenging MES operation, while their flexibility offers opportunities to locally accommodate the uncertain renewable generation.

Strategy of the MEMG operator:

- To schedule all the physical DER units;
- To determine the energy trading prices for desired demand-side response. **(as a price maker)**


Exogenous Energy Networks
MEMG
Leader: MEMG Operator
Photovoltaic System
Wind Turbine
Diesel Generators
CCHP Unit
Thermal Storage
Battery Storage
Local Day-Ahead /Intra-Day Energy Market
(Followers:)
Residential EU Agent
Commercial EU Agent
Industrial EU Agent
Electrical Flow
Thermal Flow
Transactive Energy Flow

Strategy of the energy user (EU) agents:

- To transact with the MEMG operator; **(as price takers)**
- To trade energies with the exogenous energy networks.

Y. Zou, **Y. Xu***, and C. Zhang, "A Risk-Averse Adaptive Stochastic Optimization Method for Transactive Energy Management of a Multi-Energy Microgrid, " ***IEEE Transactions on Sustainable Energy*, 2023**.

Mathematical Formulation

The interactions between the MEMG operator and EU agents are captured by a Stackelberg game, which is expressed as a bi-level model.

Upper-Level Model for MEMG Operator

$$\max \sum_{t\in N_T}\begin{bmatrix}\sum_{i\in N_I}\left(\lambda_{i,t}^{elec}P_{i,t}^{elec}+\lambda_{i,t}^{thm}P_{i,t}^{thm}\right)\\ -\sum_{j\in N_J}\kappa_j^{DG}P_{j,t}^{DG}-\kappa^{BS}(P_t^{BSC}+P_t^{BSD})\\ -\kappa^{TS}(P_t^{TSC}+P_t^{TSD})-\kappa^{CCHP}P_t^{CCHP,el}\end{bmatrix}$$

Subject to:

$$\sum_{j\in N_J}P_{j,t}^{DG}+P_t^{CCHP,el}+P_t^{PV}+P_t^{WT}-P_t^{BSC}+P_t^{BSD}=\sum_{i\in N_I}P_{i,t}^{elec}$$

$$P_t^{CCHP,th}-P_t^{TSC}+P_t^{TSD}=\sum_{i\in N_I}P_{i,t}^{thm}$$

Operating constraints of physical DER units, including CCHP, DGs, BS and TS.

Trading price

$\lambda_{i,t}^{elec}, \lambda_{i,t}^{thm}$

Trading qty.

$P_{i,t}^{elec}, P_{i,t}^{thm}$

Lower-Level Models for EU Agents

$$\min \sum_{t\in N_T}\begin{bmatrix}\lambda_{i,t}^{elec}P_{i,t}^{elec}+\lambda_{i,t}^{thm}P_{i,t}^{thm}\\ +\lambda_{exo,t}^{elec}P_{i,t}^{el,e}+\lambda_{exo,t}^{thm}P_{i,t}^{th,e}+\\ \alpha_{i,t}\left(P_{i,t}^{ed}-P_{i,t}^{exp}\right)^2+\beta_{i,t}\left(\theta_{i,t}^{td}-\theta_{i,t}^{exp}\right)^2\end{bmatrix}$$

Subject to:

$$P_{i,t}^{ed,min}\le P_{i,t}^{ed}\le P_{i,t}^{ed,max}: \mu_{i,t}^{ed,min}, \mu_{i,t}^{ed,max}$$

$$\sum_{t\in N_T}P_{i,t}^{ed}\ge\gamma_i\sum_{t\in N_T}P_{i,t}^{exp} : \mu_i^{ed}$$

$$P_{i,t}^{td}=C_i^{air}\left(\theta_{i,t-1}^{td}-\theta_{i,t}^{td}\right)+\frac{\left(\theta_{i,t}^{am}-\theta_{i,t}^{td}\right)}{R_i^T} : \nu_{i,t}^{in}$$

$$\theta_{i,t}^{td,min}\le\theta_{i,t}^{td}\le\theta_{i,t}^{td,max} : \mu_{i,t}^{td,min}, \mu_{i,t}^{td,max}$$

Constraints associated with trading quantities.

Risk aversion towards uncertainties:

$$\max_{x\in\chi,y_s\in\Omega,\eta\in\mathcal{R}} \boldsymbol{c}^T\boldsymbol{x}+\sum_{s\in N_s}\pi_s\mathcal{L}(\boldsymbol{x},\boldsymbol{d_s})+\rho\cdot CVaR_\vartheta$$

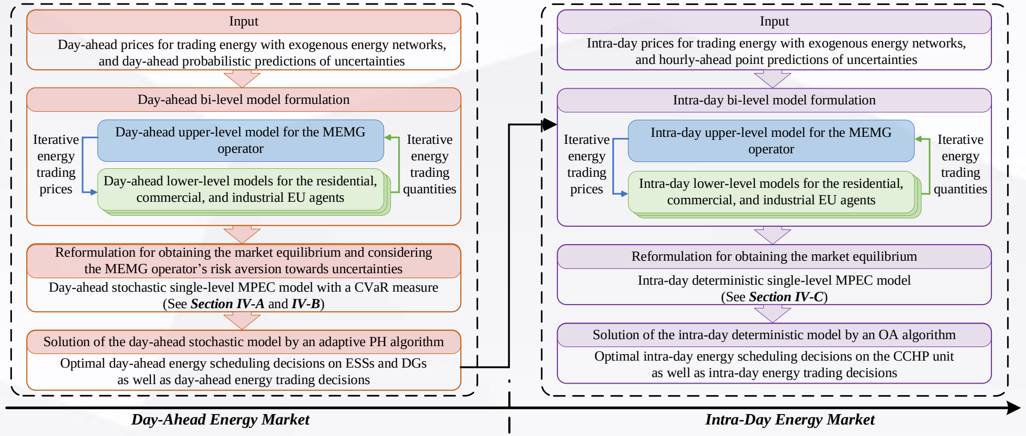
Subject to: $\boldsymbol{x}\in\chi$

$$\mathcal{L}(\boldsymbol{x},\boldsymbol{d_s})=\max_{\boldsymbol{y}_s\in\Omega(\boldsymbol{x},\boldsymbol{d_s})}\boldsymbol{b}^T\boldsymbol{y}_s$$

$$CVaR_\vartheta=\max_{\eta\in\mathcal{R}}\left\{\eta+\frac{1}{1-\vartheta}\sum_{s\in N_s}[f_P^s-\eta]^-\pi_s\right\}$$

where $\Omega(\boldsymbol{x},\boldsymbol{d_s})=\{\boldsymbol{y}_s|\boldsymbol{A}\boldsymbol{x}+\boldsymbol{B}\boldsymbol{y}_s\ge\boldsymbol{r},\ \boldsymbol{E}\boldsymbol{x}+\boldsymbol{F}\boldsymbol{y}_s=\boldsymbol{d_s}\}$,

$f_P^s=\boldsymbol{c}^T\boldsymbol{x}+\mathcal{L}(\boldsymbol{x},\boldsymbol{d_s})$ denotes the profit under scenario *s*.



Input

Day-ahead prices for trading energy with exogenous energy networks, and day-ahead probabilistic predictions of uncertainties

Day-ahead bi-level model formulation

Day-ahead upper-level model for the MEMG operator

Day-ahead lower-level models for the residential, commercial, and industrial EU agents

Iterative energy trading prices

Iterative energy trading quantities

Reformulation for obtaining the market equilibrium and considering the MEMG operator's risk aversion towards uncertainties

Day-ahead stochastic single-level MPEC model with a CVaR measure (See ***Section IV-A*** and ***IV-B***)

Solution of the day-ahead stochastic model by an adaptive PH algorithm

Optimal day-ahead energy scheduling decisions on ESSs and DGs as well as day-ahead energy trading decisions

Day-Ahead Energy Market

Input

Intra-day prices for trading energy with exogenous energy networks, and hourly-ahead point predictions of uncertainties

Intra-day bi-level model formulation

Intra-day upper-level model for the MEMG operator

Intra-day lower-level models for the residential, commercial, and industrial EU agents

Iterative energy trading prices

Iterative energy trading quantities

Reformulation for obtaining the market equilibrium

Intra-day deterministic single-level MPEC model (See ***Section IV-C***)

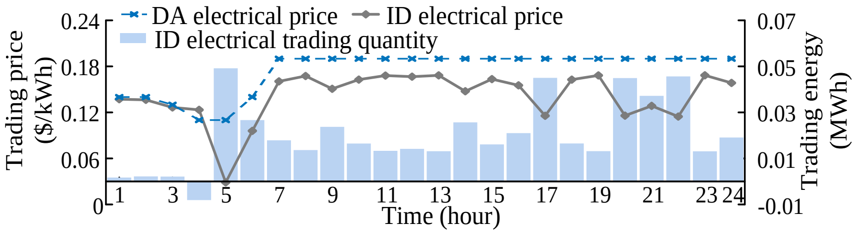
Solution of the intra-day deterministic model by an OA algorithm

Optimal intra-day energy scheduling decisions on the CCHP unit as well as intra-day energy trading decisions

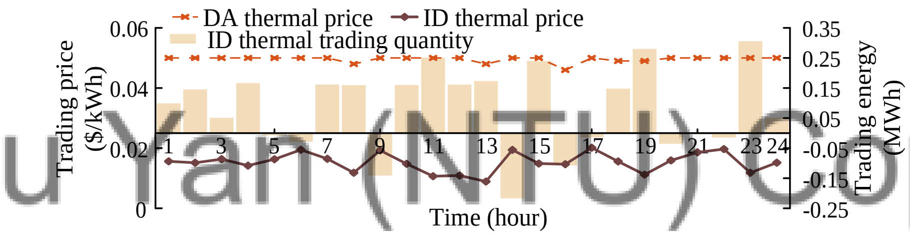
Intra-Day Energy Market

Simulation Results

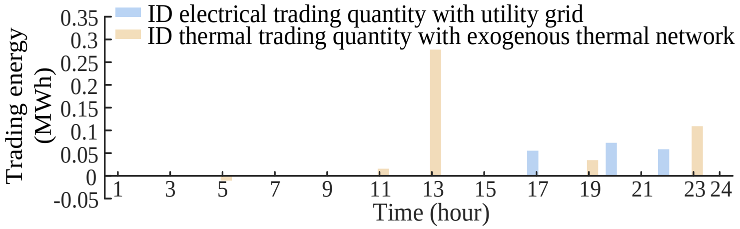
☐ Intra-day energy trading



(a) Intra-day electrical trading between MEMG operator and residential agent



(d) Intra-day thermal trading between MEMG operator and residential agent



(f) Intra-day energy trading between MEMG operator and exogenous networks

- ➢ MEMG operator uses price signals to guide users' behaviors, thereby reducing reliance and impact on external grids.

☐ Computation performance

Computational Performance for Day-Ahead Stochastic MILP

Solution Approach	No. of Variables	Solution Time (s)	Objective Value ($)	Optimality Accuracy
Direct Use of GUROBI	14862 continuous 4641 binary for all scenarios	79.70 Hours	7501.01	100%
PH Algorithm 1*	3938 continuous 2781 binary for each scenario	≥16.03 Hours	N/A	N/A
PH Algorithm 2$^+$		2.82 Hours	7478.15	99.7%
Adaptive PH Algorithm$^\#$		3.56 Hours	7492.69	99.9%

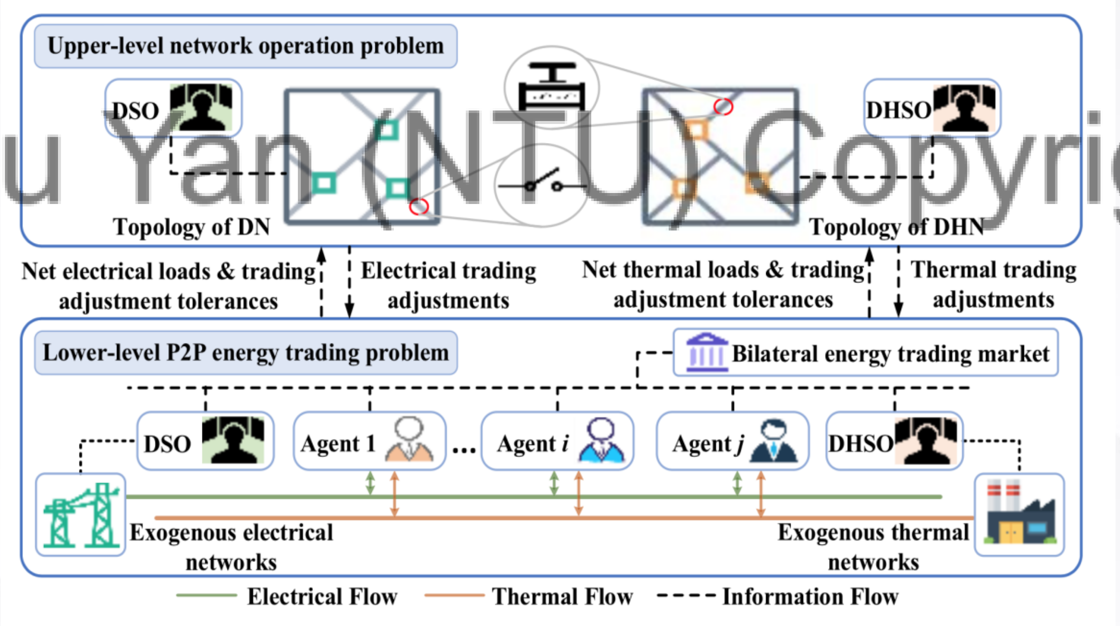
Computational Performance for the Intra-Day Bilinear Problem

Bilinear Term Linearization Approach	Step Size ($/kWh)	Convergence Tolerance	Average Time (s)
Price Discretizing	0.001	N/A	191.95
OA Algorithm	→ 0	10^{-5}	13.51

- ➢ Problem scale is reduced by adaptive PH algorithm through scenario decomposition. Bilinear terms of price times quantity are efficiently handled by OA algorithm.

▪ P2P Transactive Energy Trading in A Reconfigurable Multi-Energy Networ

Main motivation: P2P trading can address operational complexities arising from the emergence of prosumers, facilitating local energy balance, but it may also worsen network operation, e.g., voltage drops and line congestion.



Strategy of DSO and DHSO (at upper level):

- ➢ To reconfigure the DN and DHN;
- ➢ To request the lower-level agents to make necessary trading adjustments**.**

Strategy of nodal agents (at lower level):

- ➢ To schedule the local DERs (e.g., CCHP, ESS, flexible loads);
- ➢ To transact with other agents or exogenous networks in a bilateral manner;
- ➢ To submit the current net loads to the DSO and DHSO.

Y. Zou, **Y. Xu***, X. Feng, and H. D. Nguyen, “Peer-to-Peer Transactive Energy Trading in a Reconfigurable Multi-Energy Network,” ***IEEE Transactions on Smart Grid*, 2022**.

Mathematical Formulation

A. Lower-level P2P energy trading problem

Modeling for P2P energy trading

❑ *Objective function:*

$$C_i = \sum_{t \in N_T} (C_{i,t}^{Gen} + C_{i,t}^{Bill} + C_{i,t}^{Disc} + C_{i,t}^{Ser}) + C_i^{P2P}$$

$$\tilde{C}_i = \sum_{t \in N_T} (C_{i,t}^{Gen} + C_{i,t}^{Bill} + C_{i,t}^{Disc})$$

$$\max \prod_{i=1}^{\mathcal{N}} (\tilde{C}_i - C_i)^{\mathcal{MP}_i}$$

where $\mathcal{MP}_i$ is a positive value denoting the bargaining power of agent *i*.

❑ *Key constraints:*

$$e_{ij,t}^{DN} + e_{ji,t}^{DN} = 0,\ \forall t, \forall i, \forall j \in \mathcal{N} \backslash i$$

$$e_{ij,t}^{DHN} + e_{ji,t}^{DHN} = 0, \forall t, \forall i, \forall j \in \mathcal{N} \backslash i$$

$$\phi_{ij}^{P2P} + \phi_{ji}^{P2P} = 0,\ \forall i, \forall j \in \mathcal{N} \backslash i$$

$$\tilde{C}_i \geq C_i,\ \forall i$$

Nash bargaining theory
with the concept of bargaining power

❑ **Nash product**: to maximize agents' benefits from participating in P2P energy trading (i.e., $\tilde{C}_i - C_i$)

❑ **Bargaining power** $\mathcal{MP}_i$:

❖ If $\mathcal{MP}_i$=1 for $\forall i$, all agents will be awarded with the equal benefits regardless of their market contributions. (traditional Nash bargaining theory)

❖ If $\mathcal{MP}_i$ is set as

$$\mathcal{MP}_i = \frac{\sum_{t \in N_T} \left(\left| \sum_{j \in \mathcal{N} \backslash i} e_{ij,t}^{DN} \right| + \left| \sum_{j \in \mathcal{N} \backslash i} e_{ij,t}^{DHN} \right| \right)}{\sum_{h \in \mathcal{N}} \sum_{t \in N_T} \left(\left| \sum_{j \in \mathcal{N} \backslash h} e_{hj,t}^{DN} \right| + \left| \sum_{j \in \mathcal{N} \backslash h} e_{hj,t}^{DHN} \right| \right)}$$

then the allocated benefit for each agent will be directly proportional to the respective P2P trading contribution.

B. Upper-level network operation problem

Modeling for reconfigurable DN operation

❑ *Objective function:*

$$\min \sum_{t \in N_T} \left(\sum_{mn \in N_{Br}^{DN}} PL_{mn,t}^{Loss} + \partial \sum_{m \in N_{Ag}^{DN}} \left| \Delta e_{m,t}^{DN} \right| \right)$$

❑ *Constraints:*

- Linearized DistFlow with reconfiguration variables
- Spanning tree constraints:

$$\theta_{mn,t} + \theta_{nm,t} = \mathcal{K}_{mn,t}, \qquad \forall mn \in N_{Br}^{DN}, \forall t$$

$$\sum_{n \in \{N_m^{DN+} \cup N_m^{DN-}\}} \theta_{mn,t} \leq 1,\ \forall m \in N_{Ag}^{DN}, \forall t$$

$$\sum_{n \in \{N_m^{DN+} \cup N_m^{DN-}\}} \theta_{mn,t} = 0,\ \forall m \in N_{St}^{DN}, \forall t$$

- Spanning tree constraints (to strictly ensure radiality)

$$\sum_{n \in N_m^{DN+}} F_{mn,t} + D_{m,t} = \sum_{n \in N_m^{DN-}} F_{nm,t}$$

$$-\mathcal{K}_{mn,t} M \leq F_{mn,t} \leq \mathcal{K}_{mn,t} M, \forall m \in N_{Ag}^{DN}, \forall t$$

Modeling for reconfigurable DHN operation

❑ *Objective function:*

$$\min \sum_{t \in N_T} \left(\sum_{gk \in N_{Pi}^{DHN}} HL_{gk,t}^{Loss} + \partial \sum_{g \in N_{Ag}^{DHN}} \left| \Delta e_{g,t}^{DHN} \right| \right)$$

❑ *Constraints:*

- Linearized thermal flow model with reconfiguration variables, independent of mass flow rate and water temperature.
- Valve switching constraints (XOR operation):

$$\sum_{gk \in N_{Pi}^{DHN}} (\mathcal{V}_{gk,t} + \mathcal{V}_{gk,(t-1)} - 2\xi_{gk,t}) \leq N^{VA},\ \forall t$$

$$\xi_{gk,t} - \mathcal{V}_{gk,t} \leq 0, \forall gk, \forall t$$

$$\xi_{gk,t} - \mathcal{V}_{gk,(t-1)} \leq 0, \forall gk, \forall t$$

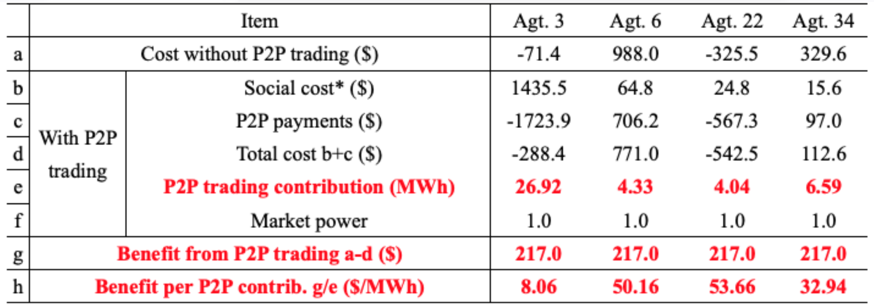
$$\mathcal{V}_{gk,t} + \mathcal{V}_{gk,(t-1)} - \xi_{gk,t} \leq 1, \forall gk, \forall t$$

$$\xi_{gk,t} \geq 0,\ \forall gk, \forall t$$

▪ Simulation Results

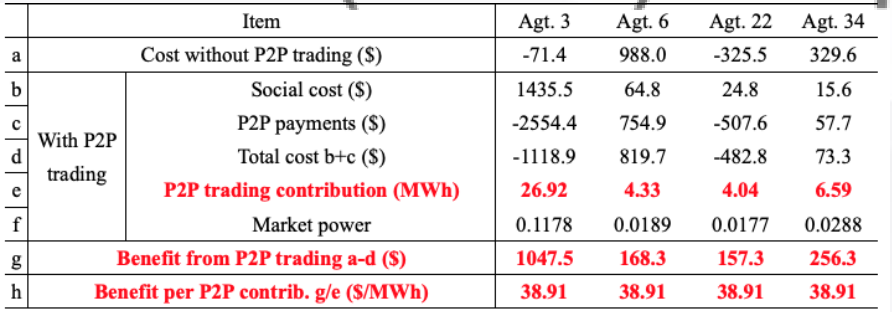
❑ Lower-level P2P trading results

Benefit Distribution for four Representative Agents
based on Traditional Nash Bargaining Theory



	Item		Agt. 3	Agt. 6	Agt. 22	Agt. 34
a	Cost without P2P trading ($)		-71.4	988.0	-325.5	329.6
b	With P2P trading	Social cost* ($)	1435.5	64.8	24.8	15.6
c		P2P payments ($)	-1723.9	706.2	-567.3	97.0
d		Total cost b+c ($)	-288.4	771.0	-542.5	112.6
e		**P2P trading contribution (MWh)**	**26.92**	**4.33**	**4.04**	**6.59**
f		Market power	1.0	1.0	1.0	1.0
g	**Benefit from P2P trading a-d ($)**		**217.0**	**217.0**	**217.0**	**217.0**
h	**Benefit per P2P contrib. g/e ($/MWh)**		**8.06**	**50.16**	**53.66**	**32.94**

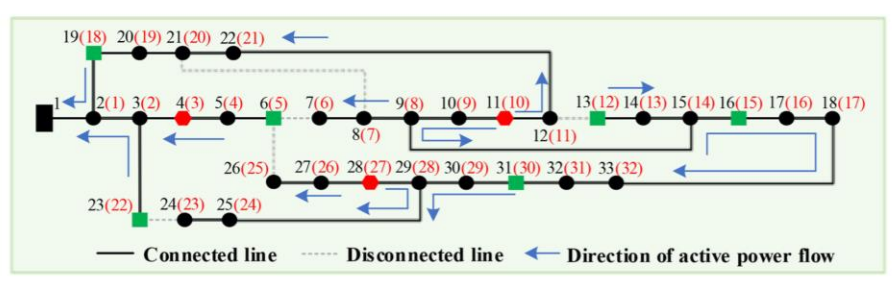
Benefit Distribution for four Representative Agents
based on Modified Nash Bargaining Theory

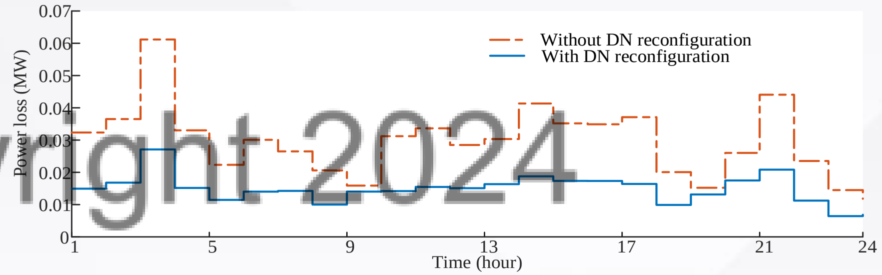


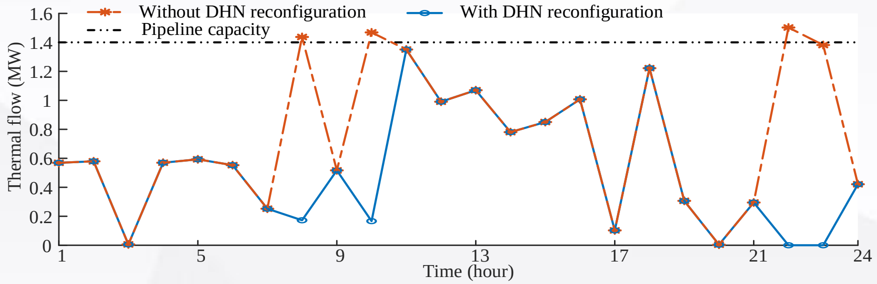
	Item		Agt. 3	Agt. 6	Agt. 22	Agt. 34
a	Cost without P2P trading ($)		-71.4	988.0	-325.5	329.6
b	With P2P trading	Social cost ($)	1435.5	64.8	24.8	15.6
c		P2P payments ($)	-2554.4	754.9	-507.6	57.7
d		Total cost b+c ($)	-1118.9	819.7	-482.8	73.3
e		**P2P trading contribution (MWh)**	**26.92**	**4.33**	**4.04**	**6.59**
f		Market power	0.1178	0.0189	0.0177	0.0288
g	**Benefit from P2P trading a-d ($)**		**1047.5**	**168.3**	**157.3**	**256.3**
h	**Benefit per P2P contrib. g/e ($/MWh)**		**38.91**	**38.91**	**38.91**	**38.91**

- ➢ Proposed mechanism ensures a fairer benefit allocation after P2P trading. Each agent obtains an equal benefit per P2P trading contribution.

❑ Upper-level network operation results



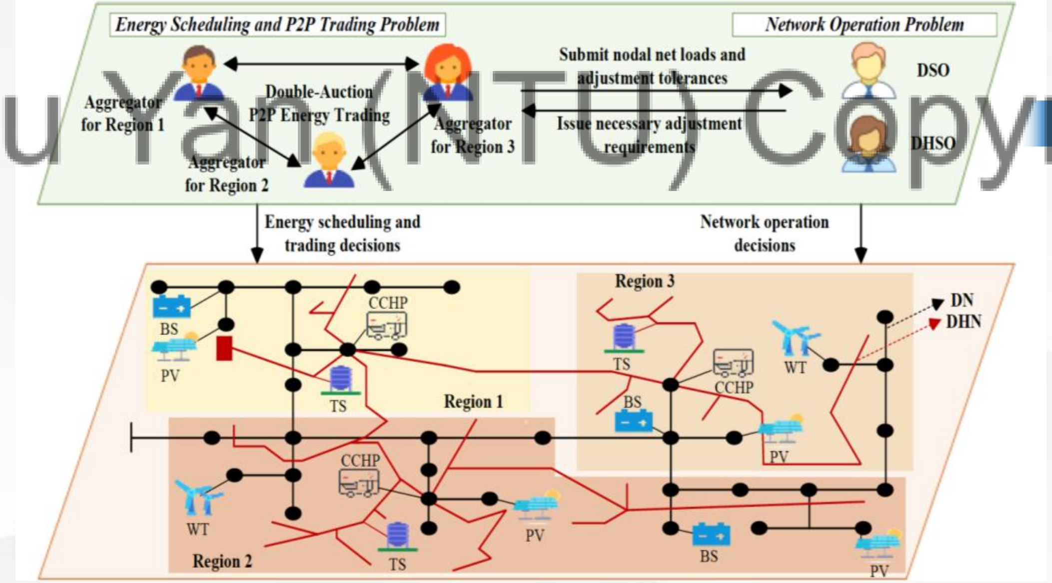




- ➢ P2P energy trading can be facilitated by network reconfiguration, in terms of alleviating network operation violations as well as reducing line losses.

▪ Community-Based Market: Aggregator-Network Coordinated P2P Trading

Main motivation: The existing regulations may not accommodate end-to-end energy trading. And small-scale end users may not have the means or interest in participating in P2P energy trading as well.



☐ **Distributed energy resources (DERs)**

- ➢ Invested and owned by private entities
- ➢ Managed by corresponding aggregators

☐ **Aggregators**

- ➢ Manage (internal coordination + external trading) contracted geographically adjacent or dispersed DERs

☐ **Multi-energy networks**

- ➢ Owned by the network asset companies
- ➢ Operated by a distribution system operator (DSO) and a district heating system operator (DHSO)

Y. Zou, **Y. Xu***, and J. Li, "Aggregator-Network Coordinated Peer-to-Peer Multi-Energy Trading via Adaptive Robust Stochastic Optimization," ***IEEE Transactions on Power Systems*, 2024**.

▪ Mathematical Formulation

A. Double-auction P2P trading among aggregators

Modeling for dynamic double-auction negotiation

❑ *Augmented Lagrangian:*

$$\mathcal{L}_m\left(\boldsymbol{x}_{m,t},\hat{\boldsymbol{e}}_{m,t},\boldsymbol{\lambda}_{m,t}\right) = \sum_{t\in N_T}\begin{bmatrix} C_{m,t}^{Gen}+C_{m,t}^{Bill}+C_{m,t}^{Disc}+C_{m,t}^{RSV}+ \\ \frac{\varrho}{2}\left\|\boldsymbol{e}_{m,t}-\hat{\boldsymbol{e}}_{m,t}\right\|_2^2+\left(\boldsymbol{\lambda}_{m,t}\right)^T\left(\boldsymbol{e}_{m,t}-\hat{\boldsymbol{e}}_{m,t}\right)\end{bmatrix}$$

s.t., $\hat{\boldsymbol{e}}_{mn,t}+\hat{\boldsymbol{e}}_{nm,t}=\boldsymbol{0},\ \forall t,\forall m\in N_M,\forall n\in N_M\backslash m$

DER operational constraint

Power balance constraints

❑ *Dynamic P2P negotiations:*

Update of P2P trading quantity $\boldsymbol{e}_{m,t}$*:*

$$\{\boldsymbol{x}_{m,t}^{[\tau+1]}\}_{t\in N_T}=\underset{\boldsymbol{x}_{m,t}\in\boldsymbol{\mathcal{X}}_{m,t}}{\operatorname{argmin}}\ \mathcal{L}_m\left(\boldsymbol{x}_{m,t},\hat{\boldsymbol{e}}_{m,t}^{[\tau]},\boldsymbol{\lambda}_{m,t}^{[\tau]}\right)$$

Update of auxiliary variable $\hat{\boldsymbol{e}}_{m,t}$*:*

$$\hat{\boldsymbol{e}}_{mn,t}^{[\tau+1]}=-\hat{\boldsymbol{e}}_{nm,t}^{[\tau+1]}=\frac{\boldsymbol{e}_{mn,t}^{[\tau+1]}-\boldsymbol{e}_{nm,t}^{[\tau+1]}}{2}+\frac{\boldsymbol{\lambda}_{mn,t}^{[\tau]}-\boldsymbol{\lambda}_{nm,t}^{[\tau]}}{2\varrho}$$

Update of P2P trading price $\boldsymbol{\lambda}_{m,t}$*:*

$$\boldsymbol{\lambda}_{m,t}^{[\tau+1]}=\boldsymbol{\lambda}_{m,t}^{[\tau]}+\varrho[\boldsymbol{e}_{m,t}^{[\tau+1]}-\hat{\boldsymbol{e}}_{m,t}^{[\tau+1]}]$$

❑ *Market equilibrium:*

$$\left|\boldsymbol{e}_{mn,t}^{[\tau+1]}\right|,\boldsymbol{\lambda}_{mn,t}^{[\tau+1]}=\left|\boldsymbol{e}_{nm,t}^{[\tau+1]}\right|,\boldsymbol{\lambda}_{nm,t}^{[\tau+1]},\forall t,\forall m\in N_M,\forall n\in N_M\backslash m$$

B. Network operation problem

Modeling for three-phased unbalance DN operation

$$\min_{\boldsymbol{x}^{DSO}}\sum_{t\in N_T}\begin{bmatrix}\sum_{ij\in\mathcal{E}^{DN}}(\lambda_t^{DN,b}PL_{ij,t}^{Loss}+\kappa^D\omega_{ij,t}+\kappa^C\varpi_{ij,t}) \\ +\partial\sum_{i\in\mathcal{N}_{Agg}^{DN}}\boldsymbol{1}^T\left|\Delta\boldsymbol{e}_{i,t}^{DN}\right|\end{bmatrix}$$

Linearized three-phase DistFlow model

$$\Delta\boldsymbol{e}_{i,t}^{DN}-\boldsymbol{P}_{i,t}^{Net*}=\sum_{j\in\mathcal{N}_i^{DN+}}\boldsymbol{PL}_{ij,t}-\sum_{j\in\mathcal{N}_i^{DN-}}\boldsymbol{PL}_{ji,t},\forall t$$

$$\boldsymbol{P}_{i,t}=\sum_{j\in\mathcal{N}_i^{DN+}}\boldsymbol{PL}_{ij,t}-\sum_{j\in\mathcal{N}_i^{DN-}}\boldsymbol{PL}_{ji,t},\forall i\in\mathcal{N}_{Ss}^{DN},\forall t$$

$$\boldsymbol{Q}_{i,t}=\sum_{j\in\mathcal{N}_i^{DN+}}\boldsymbol{QL}_{ij,t}-\sum_{j\in\mathcal{N}_i^{DN-}}\boldsymbol{QL}_{ji,t},\ \forall i\in\mathcal{N}^{DN},\forall t$$

$$\begin{bmatrix}2\mathrm{Re}\left(\tilde{\boldsymbol{z}}_{ij}^*\boldsymbol{S}_{ij,t}\right)-\left(1-\mathcal{K}_{ij,t}\right)\mathbf{M}\le\boldsymbol{U}_{i,t}-\boldsymbol{U}_{j,t} \\ \le 2\mathrm{Re}\left(\tilde{\boldsymbol{z}}_{ij}^*\boldsymbol{S}_{ij,t}\right)+\left(1-\mathcal{K}_{ij,t}\right)\mathbf{M}\end{bmatrix},\forall ij\in\mathcal{E}^{DN},\forall t$$

Unbalanced voltage:

$$\max_{\varphi\in\Phi}\left|\frac{U_{\varphi,i,t}-\widetilde{U}_{i,t}}{\widetilde{U}_{i,t}}\right|\le\epsilon,\forall i\in\mathcal{N}_{Agg}^{DN},\forall t$$

$$\widetilde{U}_{i,t}=\frac{1}{3}\sum_{\varphi\in\Phi}U_{\varphi,i,t},\forall i\in\mathcal{N}_{Agg}^{DN},\forall t$$

Three-phase power loss:

$$PL_{ij,t}^{Loss}=\frac{\boldsymbol{S}_{ij}^H\tilde{\boldsymbol{r}}_{ij}\boldsymbol{S}_{ij,t}}{{V_0}^2},\forall ij\in\mathcal{E}^{DN},\forall t$$

Other constraints are similar to those in the single-phase distribution network modeling.

▪ Uncertainty Handling

❑ Scenario-Based Ambiguity Set

The uncertain renewable generation is captured by

$$\mathcal{F}=\left\{\mathbb{P}\in\mathcal{P}_0\left(\mathbb{R}^{|U|}\times S\right)\middle|\begin{array}{c}(\tilde{\boldsymbol{u}},\tilde{s})\sim\mathbb{P}\\ \mathbb{E}_{\mathbb{P}}[\tilde{\boldsymbol{u}}|\tilde{s}\in S]\in\mathcal{Q}\\ \mathbb{P}[\tilde{\boldsymbol{u}}\in U_s|\tilde{s}=s]=1,\forall s\in S\\ \mathbb{P}[\tilde{s}=s]=p_s,\forall s\in S\\ \boldsymbol{p}\in\mathcal{P}\end{array}\right\}$$

The scenario-based ambiguity set is a highly generalized formulation.

Remark 1: It provides a unified uncertainty formulation for SO, RO and DRO. A RSO model with the scenario-based ambiguity set can shrink to a SO model when U_s is reduced to the sample vector $\hat{\boldsymbol{u}}_s$ for each scenario s. The RSO can become a RO model when $|S|=1$.

Remark 2: It encompasses most existing ambiguity sets. For instance, a Wasserstein metric-based ambiguity set can be mapped into the format of a scenario-based ambiguity set as:

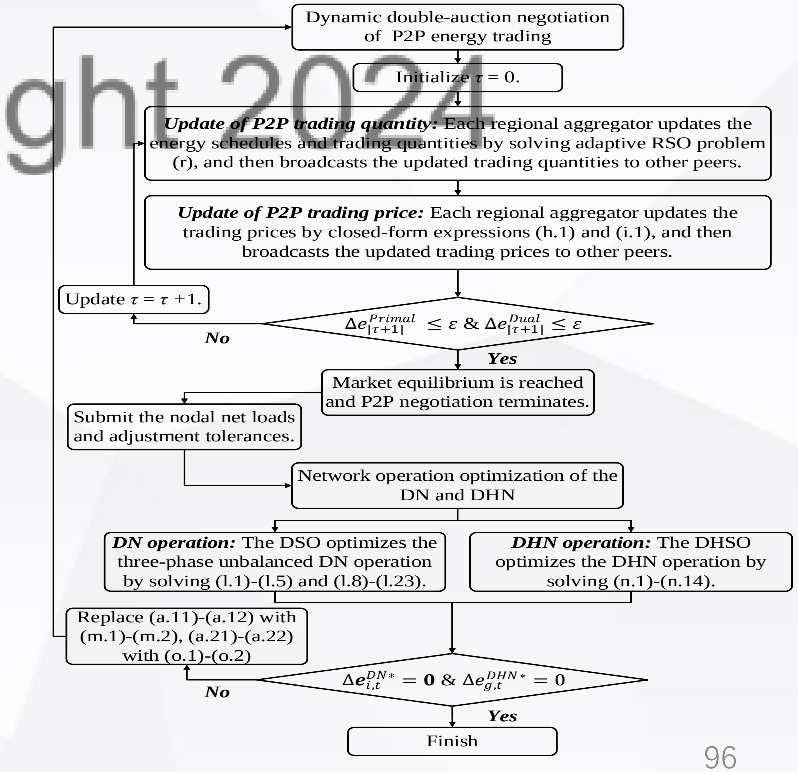
$$\mathcal{F}_W^1=\left\{\mathbb{P}\in\mathcal{P}_0\left(\mathbb{R}^{|U|}\times S\right)\middle|\begin{array}{l}(\tilde{\boldsymbol{u}},\tilde{s})\sim\mathbb{P}\\ \mathbb{E}_{\mathbb{P}}[d(\tilde{\boldsymbol{u}},\hat{\boldsymbol{u}}_{\tilde{s}})|\tilde{s}\in S]\le\Gamma\\ P[\tilde{\boldsymbol{u}}\in U_s|\tilde{s}=s]=1,\forall s\in S\\ P[\tilde{s}=s]=1/|S|,\forall s\in S\end{array}\right\}$$

❑ Adaptive Robust Stochastic (RSO) Optimization

Based on the developed scenario-based ambiguity set for uncertainties, the update of trading quantity during dynamic double-auction negotiation is rewritten as:

$$\left\{\boldsymbol{x}_{m,t}^{NA,[\tau+1]},\boldsymbol{x}_{m,t}^{A,[\tau+1]}\right\}_{t\in N_T}=\underset{(\boldsymbol{x}_{m,t}^{NA},\boldsymbol{x}_{m,t}^{A})\in\boldsymbol{\mathcal{X}}_{m,t}}{\operatorname{argmin}}\ \sup_{\mathbb{P}\in\mathcal{F}_W^{2,m}}\mathbb{E}_{\mathbb{P}}\left[\mathcal{L}_m\left((\boldsymbol{x}_{m,t}^{NA},\boldsymbol{x}_{m,t}^{A}),\hat{\boldsymbol{e}}_{m,t}^{[\tau]},\boldsymbol{\lambda}_{m,t}^{[\tau]}\right)\right]$$

❑ Implementation


Dynamic double-auction negotiation of P2P energy trading

Initialize $\tau=0$.

Update of P2P trading quantity: Each regional aggregator updates the energy schedules and trading quantities by solving adaptive RSO problem (r), and then broadcasts the updated trading quantities to other peers.

Update of P2P trading price: Each regional aggregator updates the trading prices by closed-form expressions (h.1) and (i.1), and then broadcasts the updated trading prices to other peers.

$\Delta e_{[\tau+1]}^{Primal}\le\varepsilon$ & $\Delta e_{[\tau+1]}^{Dual}\le\varepsilon$

No

Update $\tau=\tau+1$.

Yes

Market equilibrium is reached and P2P negotiation terminates.

Submit the nodal net loads and adjustment tolerances.

Network operation optimization of the DN and DHN

DN operation: The DSO optimizes the three-phase unbalanced DN operation by solving (l.1)-(l.5) and (l.8)-(l.23).

DHN operation: The DHSO optimizes the DHN operation by solving (n.1)-(n.14).

$\Delta\boldsymbol{e}_{i,t}^{DN*}=\boldsymbol{0}$ & $\Delta e_{g,t}^{DHN*}=0$

No

Replace (a.11)-(a.12) with (m.1)-(m.2), (a.21)-(a.22) with (o.1)-(o.2)

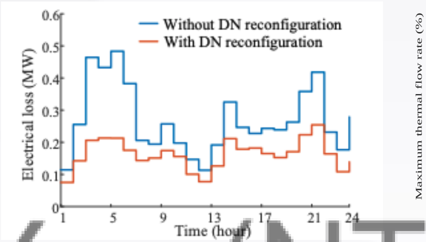
Yes

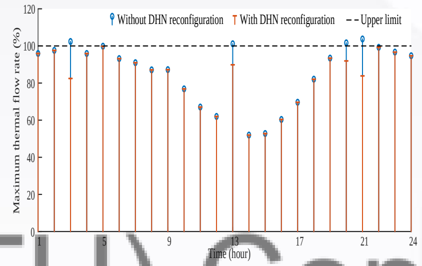
Finish

Simulation Results

❑ Coordination between aggregators and networks

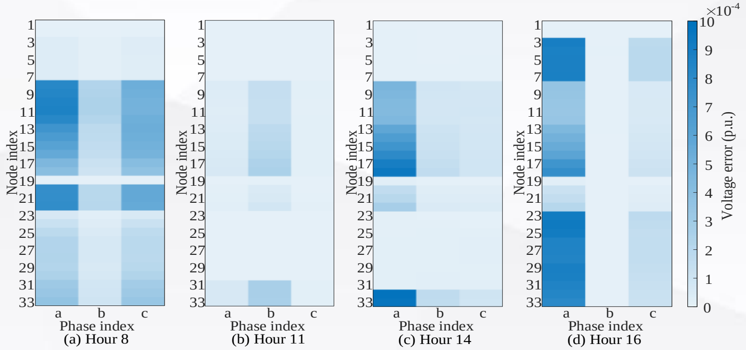
	Regional aggregator (RA)		RA 1	RA 2	RA 3	Total
a	Cost without P2P trading ($)		2778.2	3042.8	5329.6	11150.6
b	With P2P trading	Social cost ($)	3022.6	3689.2	3862.9	10574.7
c		P2P payments ($)	-304.3	-857.2	1161.5	0
d		Total cost [b+c] ($)	2718.3	2832.0	5024.4	10574.7
e	Benefit from P2P trading [a-d] ($)		59.9	210.8	305.2	575.9





- ➢ The double-auction P2P trading mechanism is incentive compatible, and the coordination between aggregators and networks helps reduce network losses and prevent possible network operation issues.

❑ Accuracy

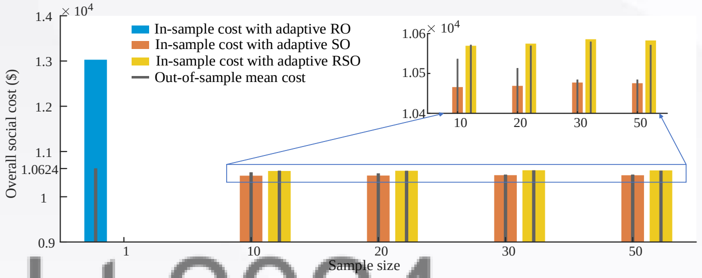


(a) Hour 8 (b) Hour 11 (c) Hour 14 (d) Hour 16

- ➢ Voltage errors stay below 10^{-3}.

❑ Performance of adaptive RSO approach

	Percentage of feasible out-of-sample cases				
Sample size	1*	10	20	30	50
Adaptive RO	100%	-	-	-	-
Adaptive SO	-	35.4%	76.3%	85.9%	92.7%
Adaptive RSO	-	98.2%	100%	100%	100%



- ➢ Adaptive RSO offers a superior performance for uncertainty handling than adaptive RO and SO.

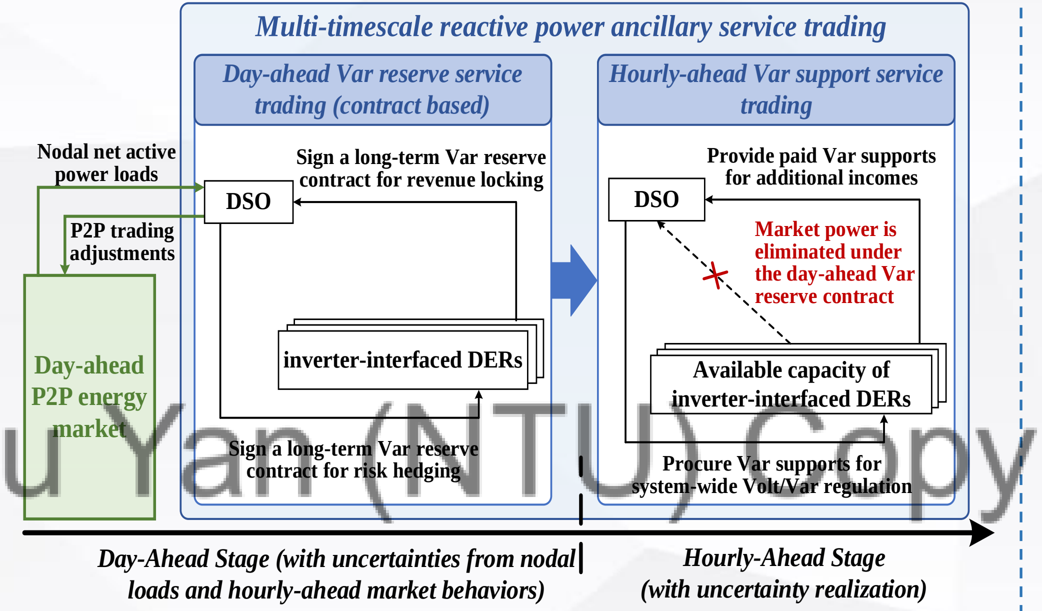
❑ Scalability

Index	No. of aggregators	Lower-layer energy scheduling and P2P trading		
		No. of variables*	No. of iterations	Time
Case 1	3	4057	83	271.79s
Case 2	5	7599	96	287.01s

Index	Upper-layer DN operation			Upper-layer DHN operation		
	Nodes	No. of variables	Time	Nodes	No. of variables	Time
Case 1	33	24072	210.69s	23	4488	5.09s
Case 2	123	86400	244.75s	37	7416	7.88s

- ➢ The proposed aggregator-network coordinated P2P trading method is scalable in practice.

▪ Reactive Power Ancillary Services for Supporting P2P Energy Trading



☐ Day-ahead P2P energy market

After P2P negotiation, each agent is required to submit their respective nodal net active power loads to the DSO.

☐ Reactive power ancillary service market

Day-ahead Var reserve service trading:

DSO: has a clear incentive to sign a day-ahead Var reserve contract with some DERs for eliminating potential market power.

DERs: are also in favour of a day-ahead contract for revenue protection.

Causes for market power (must-run capacity):
1) **system configuration deficiency**
2) **market structure flaws**

Hourly-ahead Var support service trading:

DSO: needs Var supports for system-wide voltage regulation and loss reduction, after uncertainty realization.

DERs: have incentives to provide available inverter capacity for additional profit earning.

Y. Zou, and **Y. Xu***, "DER-Inverter Based Reactive Power Ancillary Service for Supporting Peer-to-Peer Transactive Energy Trading in Distribution Networks," ***IEEE Transactions on Power Systems*, 2024**.

▪ Mathematical Formulation

Day-ahead Var reserve service trading: a two-stage robust optimization problem

$$\min_{\boldsymbol{x}} \sum_{i\in\mathcal{J}} \pi^{RSV} Q_i^{RSV} + \sum_{t\in\mathcal{T}} \sum_{m\in\mathcal{N}_{Ag}^{DN}} \partial \left|\Delta e_{m,t}^{DN}\right| +$$

$$\max_{\boldsymbol{u}} \min_{\boldsymbol{y}} \sum_{t\in\mathcal{T}} \Big(\sum_{h\in\mathcal{N}_{St}^{DN}} \pi_t^{HV.Q} \left|Q_{h,t}^{HV}\right| + \sum_{i\in\mathcal{J}} \pi_{i,t}^{INV} \left|Q_{i,t}^{INV.ST}\right| + \sum_{mn\in\mathcal{E}^{DN}} \pi_t^{HV.P} PL_{mn,t}^{Loss} \Big)$$

Market clearing based on a uniform price auction:

$$0 \le Q_i^{RSV} \le \mathscr{r}_i^{DER} \mathcal{B}Q_i^{DER}, \forall i \in \mathcal{J}$$

$$\mathscr{r}_i^{DER} \mathcal{B}P_i^{DER} \le \pi^{RSV}, \forall i \in \mathcal{J}$$

Uncertainty sets for nodal power loads and hourly-ahead market behaviors:

$$U^{MRKT} = \left\{ \begin{matrix} a_{i,t}^{INV}, \\ \pi_{i,t}^{INV} \end{matrix} \middle| \begin{matrix} N^{INV} - n^{MP} \le \sum_{i\in\mathcal{J}} a_{i,t}^{INV} \le N^{INV}, \forall t \\ \underline{\pi}_{i,t}^{INV} \le \pi_{i,t}^{INV} \le \bar{\pi}_{i,t}^{INV}, \forall i \in \mathcal{J}, \forall t \end{matrix} \right\}$$

$$U^{Load} = \left\{ \begin{matrix} P_{m,t}^{Net}, \\ Q_{m,t}^{L} \end{matrix} \middle| \begin{matrix} \underline{P}_{m,t}^{Net} \le P_{m,t}^{Net} \le \bar{P}_{m,t}^{Net}, \forall m \in \mathcal{N}_{Ag}^{DN}, \forall t \\ \underline{Q}_{m,t}^{L} \le Q_{m,t}^{L} \le \bar{Q}_{m,t}^{L}, \forall m \in \mathcal{N}^{DN}, \forall t \\ \underline{\mu}^{AcLoad} \le \dfrac{\sum_{t\in\mathcal{T}} \sum_{m\in\mathcal{N}_{Ag}^{DN}} P_{m,t}^{Net}}{\sum_{t\in\mathcal{T}} \sum_{m\in\mathcal{N}_{Ag}^{DN}} \check{P}_{m,t}^{Net}} \le \bar{\mu}^{AcLoad} \\ \underline{\mu}^{ReLoad} \le \dfrac{\sum_{t\in\mathcal{T}} \sum_{m\in\mathcal{N}^{DN}} Q_{m,t}^{L}}{\sum_{t\in\mathcal{T}} \sum_{m\in\mathcal{N}^{DN}} \check{Q}_{m,t}^{L}} \le \bar{\mu}^{ReLoad} \end{matrix} \right\}$$

Hourly-ahead Var support service trading: a non-cooperative game

Distribution system operator (DSO):

$$\min_{\{\boldsymbol{y},\phi_{i,t}^{INV}\}} \sum_{h\in\mathcal{N}_{St}^{DN}} \pi_t^{HV.Q} \left|Q_{h,t}^{HV}\right| + \sum_{i\in\mathcal{J}} \phi_{i,t}^{INV} + \sum_{mn\in\mathcal{E}^{DN}} \pi_t^{HV.P} PL_{mn,t}^{Loss}$$

s.t.

$$\boldsymbol{f}_t^{DSO}\left(\boldsymbol{x}^*, \boldsymbol{y}, \boldsymbol{u}^\dagger\right) \le 0$$

Inverter-interfaced DERs:

$$\max_{\{\ddot{Q}_{i,t}^{INV.ST}, \ddot{\phi}_{i,t}^{INV}\}} \ddot{\phi}_{i,t}^{INV} - \left[\mathcal{C}_{i,t}^{INV}\left(Q_{i,t}^{INV}\right) - \mathcal{C}_{i,t}^{INV}\left(Q_i^{RSV*}\right)\right]$$

s.t.

$$Q_{i,t}^{INV} = Q_i^{RSV*} + \left|\ddot{Q}_{i,t}^{INV.ST}\right|$$

$$\left|\ddot{Q}_{i,t}^{INV.ST}\right| \le a_{i,t}^{INV\dagger}\left(\bar{Q}_{i,t}^{INV\prime} - Q_i^{RSV*}\right)$$

$$\mathcal{C}_{i,t}^{INV}\left(Q_{i,t}^{INV}\right) = \mathcal{C}_{i,t}^{INV.PL}\left(Q_{i,t}^{INV}\right) + \mathcal{C}_{i,t}^{INV.LT}\left(Q_{i,t}^{INV}\right)$$

Dynamic negotiation based on Nash Mechanism:

$$Q_{i,t}^{INV.ST} = \frac{1}{2}\left(\mathcal{B}Q_{i,t}^{DSO2INV} + \mathcal{B}Q_{i,t}^{INV2DSO}\right), \forall i \in \mathcal{J}$$

$$\phi_{i,t}^{INV} = \frac{1}{2}\mathcal{B}P_{i,t}^{INV2DSO}\left(\mathcal{B}Q_{i,t}^{DSO2INV} + \mathcal{B}Q_{i,t}^{INV2DSO}\right) + \left(\mathcal{B}P_{i,t}^{DSO2INV} - \mathcal{B}P_{i,t}^{INV2DSO}\right)^2, \forall i \in \mathcal{J}$$

Reactive power cost incurred by additional power loss in the inverter:

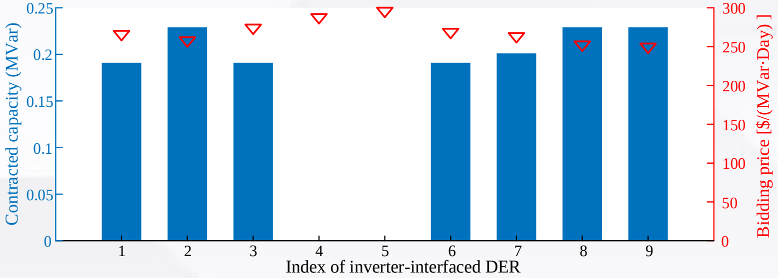
$$\Delta P_{i,t}^{INV.Loss} = \begin{cases} \xi_{INV}^{PL.0} + \xi_{INV}^{PL.1} Q_{i,t}^{INV} + \xi_{INV}^{PL.2}\left(Q_{i,t}^{INV}\right)^2, & if\ P_{i,t}^{INV} = 0 \\ \xi_{INV}^{PL.1}\left(S_{i,t}^{INV} - P_{i,t}^{INV}\right) + \xi_{INV}^{PL.2}\left(Q_{i,t}^{INV}\right)^2, & if\ P_{i,t}^{INV} \ne 0 \end{cases}$$

Reactive power cost reflecting inverter lifetime degradation by higher thermal stress:

$$\mathcal{C}_{i,t}^{INV.LT}\left(Q_{i,t}^{INV}\right) = \xi_{INV}^{LT.0} + \xi_{INV}^{LT.1} Q_{i,t}^{INV} + \xi_{INV}^{LT.2}\left(Q_{i,t}^{INV}\right)^2 + \xi_{INV}^{LT.3}\left(Q_{i,t}^{INV}\right)^3$$

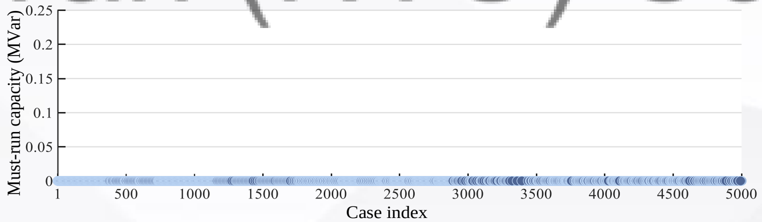
▪ Simulation Results

☐ Settlement for day-ahead Var reserve service

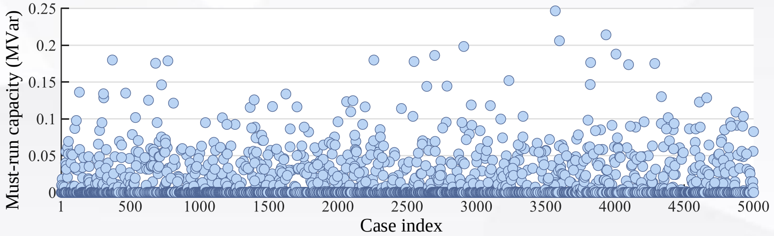


- ➢ Uniform price auction motivates DERs to reduce their Var costs, thereby lowering their bidding prices and increasing the likelihood of being selected in the market.

☐ Potential market power issue



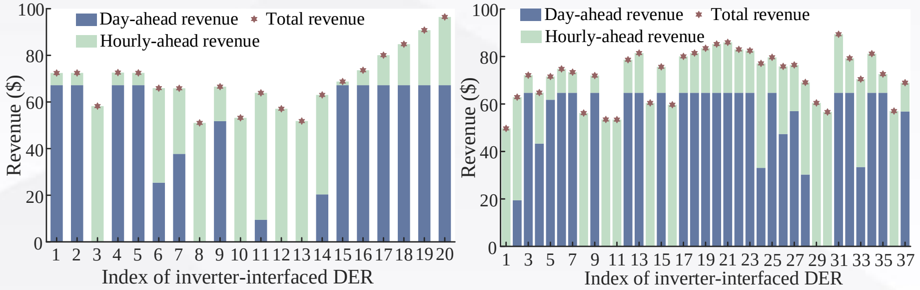
(a) With a day-ahead Var reserve contract



(b) Without a day-ahead Var reserve contract

- ➢ Robust day-ahead Var reserve contract prevents DERs from gaining market power and manipulating reactive market prices.

☐ Revenue from Var ancillary service trading



(a) 69-bus testing system (b) 123-bus testing system

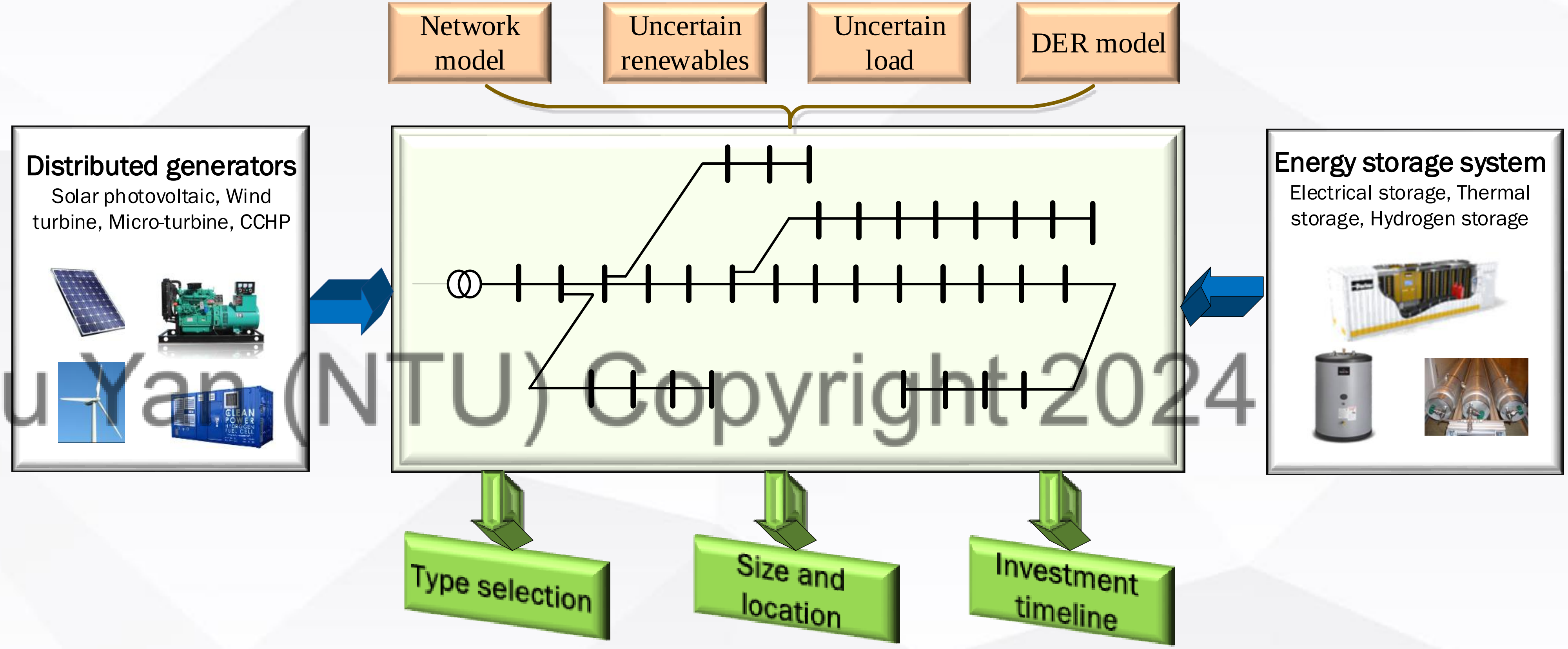
- ➢ DERs are incentivized to participate in both day-ahead and hourly-ahead trading, thereby providing operational support for distribution systems.

☐ Scalability

Distribution network (DN)		33-bus DN	69-bus DN	123-bus DN
Participants in the reactive power ancillary service trading		1 DSO & 9 DERs	1 DSO & 20 DERs	1 DSO & 37 DERs
Day-ahead problem	Algorithm	C&CG	C&CG	C&CG
	No. of iterations	5	4	3
	Solution time	108.2s	120.3s	236.6s
Hourly-ahead problems	Algorithm	Algorithm 1	Algorithm 1	Algorithm 1
	No. of iterations	113	261	165
	Solution time	39.8s	110.4s	129.2s
	Parallel solution time	4.0s	5.3s	3.4s

- ➢ The framework and methods are highly scalable.

Optimal Planning of DERs in Microgrid


Network model
Uncertain renewables
Uncertain load
DER model

Distributed generators
Solar photovoltaic, Wind turbine, Micro-turbine, CCHP

Energy storage system
Electrical storage, Thermal storage, Hydrogen storage

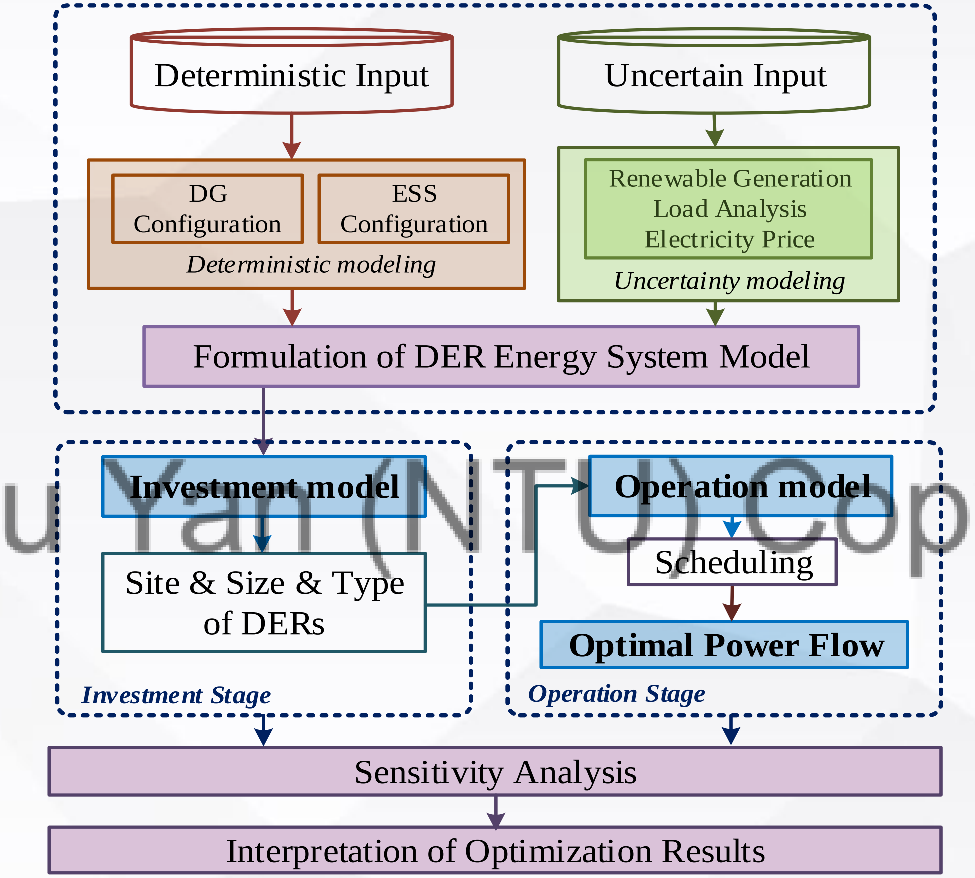
Type selection
Size and location
Investment timeline

Objective: Minimize total investment costs
Constraints: operational limits
network constraints
component constraints, etc.
Variables: size, site, type, installation year, etc.

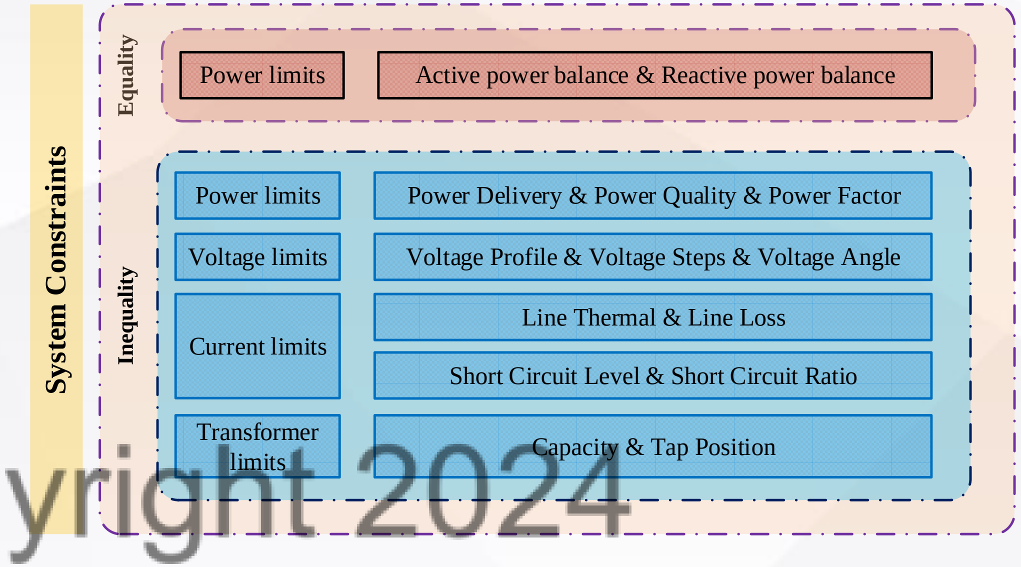
Stochastic programming
Robust optimization
Probability-weighted robust optimization
…

1. REIDS Project
2. Control
1) Islanded mode
2) Grid-tied mode
3. Operation
1) Energy dispatch
2) Volt/Var regulation
4. Hierarchy coordination
5. Trading
1) Review
2) Centralized trading
3) P2P trading
6. Planning
1) DG planning
2) ESS planning
3) Joint planning
NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

▪ Optimal Planning of DERs in Microgrid


Deterministic Input
Uncertain Input
DG Configuration
ESS Configuration
Deterministic modeling
Renewable Generation
Load Analysis
Electricity Price
Uncertainty modeling
Formulation of DER Energy System Model
Investment model
Site & Size & Type of DERs
Investment Stage
Operation model
Scheduling
Optimal Power Flow
Operation Stage
Sensitivity Analysis
Interpretation of Optimization Results

Two-stage framework of the DER planning

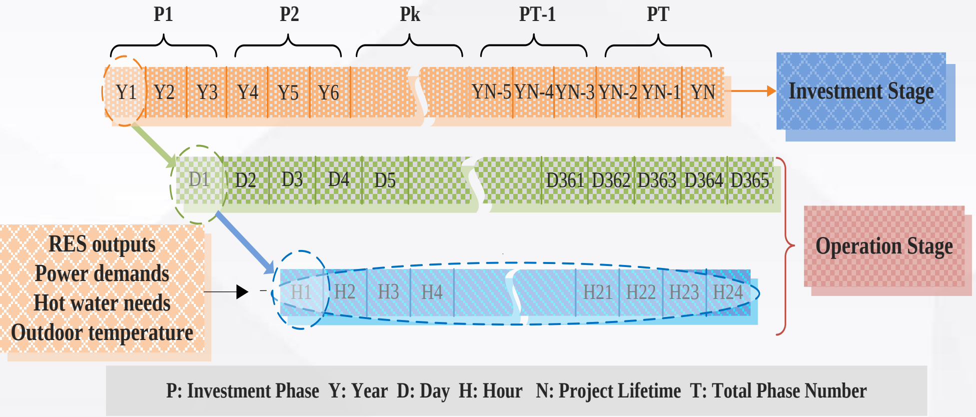

System Constraints
Equality
Power limits
Active power balance & Reactive power balance
Inequality
Power limits
Power Delivery & Power Quality & Power Factor
Voltage limits
Voltage Profile & Voltage Steps & Voltage Angle
Current limits
Line Thermal & Line Loss
Short Circuit Level & Short Circuit Ratio
Transformer limits
Capacity & Tap Position

The constraints of distributed generator planning

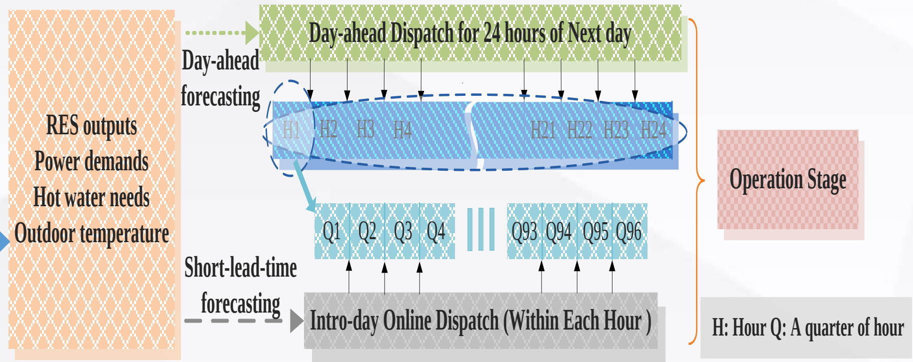
	Objective
Technical	• Maximization of system reliability • Minimization in system losses • Minimization of voltage deviation • Minimization of absolute active power flow
Economical	• Maximization of social welfare • Maximization of system annual profit • Minimization of investment and operation cost
Environmental	• Minimization of gas emissions

R. Leng, Z. Li, and Y. Xu, “A comprehensive literature review for optimal planning of distribution energy resources in distribution grid,” *Proc. IEEE ISGT-Asia 2022*, 1-5 Nov. Singapore.

Optimal Placement of Heterogeneous Distributed Generators



Proposed two-stage DG placement method



Sub-stages for system operation

$$NPV_s = \max_{z\in CF_z, x\in CG_x} \{ \underbrace{-F(z)}_{\text{Investment Stage}} + \underset{\text{Operation Stage}}{G(x)} \}$$

$$\begin{aligned} &\text{Min } G(x|c) = \min_{w}\{S(w|c) + E[Q(w|c,\omega)]\} \\ &\text{s.t.} \quad w \in CS_w \mid z \\ &\qquad Q(w|c,\omega) = \min_{y} L(y|c) \\ &\qquad y \in CL(w,\omega) \end{aligned}$$

System multi-stage operation model

Year/Bus	3	6	9	12	18	22	25	27	30	33
CCHP unit：Cap-65										
1-4	65	195	65	130	0	0	130	65	0	65
5-8	65	195	65	195	0	65	130	65	65	65
9-12	65	195	65	195	65	65	130	65	65	130
Electric boiler: A										
1-4	123.2	96	90.7	0	146.8	41.5	167.8	92.9	0	0
5-8	123.2	96	128.1	0	146.8	88.5	214.8	92.9	0	0
9-12	138.5	96	129.6	0	146.8	120.4	216.2	92.9	0	0
Electric boiler: B										
9-12	0	0	0.0	57.1	0	66.7	74.1	0	0	0
Electric chiller:A										
1-4	200.2	0	68.4	0	105.8	0.0	141.3	0	0	48.25
Electric chiller: B										
1-4	0	0	25.0	0	0	50.7	74.3	0	0	0
5-8	0	0	50.3	0	0	103.8	115.2	0	0	0
9-12	0	0	90.9	0	0	143.0	115.2	0	0	0
Photovaltics: B										
1-12	137.6	137.6	136.2	122.2	118.9	137.7	181.6	181.6	177.8	169
Wind turbine: A										
1-12	80	0	0	0	0	80	80	0	80	0
Wind turbine: B										
1-12	0	240	120	0	240	0	240	0	120	0

Z. Li and **Y. Xu***, "Optimal Placement of Heterogeneous Distributed Generators in a Grid-Connected Multi-Energy Microgrid under Uncertainties," *IET Renewable Power Generation, 2019.*

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

5. Trading
1) Review
2) Centralized trading
3) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) Joint planning

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

Probability-Weighted Robust Optimization (PRO) for DG Planning

Problems identification: Robust optimization only considers the worst case under a single day profile, while stochastic programming cannot cover full spectrum of uncertainties and thus full operational robustness.

Our aims: to ensure a full robustness for the short-term operation under the uncertainties over the long-term planning horizon.

Probability-Weighted Uncertainty Sets

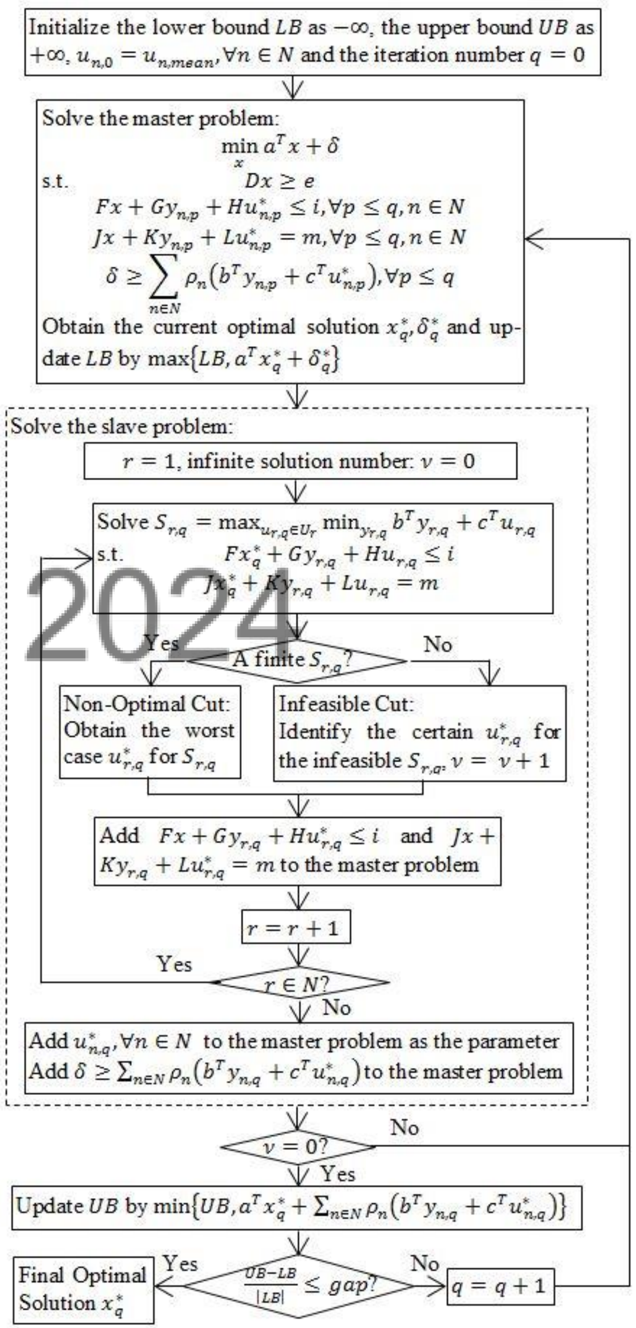
$$U_v^D = \{\underline{\mu}_{y,v}^D \le \sum_{t\in T}\sum_{i\in I} h \times P_{i,t,y,v}^D \le \overline{\mu}_{y,v}^D, \forall y,$$
$$\underline{P}_{i,t,y,v}^D \le P_{i,t,y,v}^D \le \overline{P}_{i,t,y,v}^D, \forall i,t,y\} \text{ with } \rho_v, \forall v = 1,2,\ldots,n_v$$

PRO Formulation

$$\min_x a^T x + \sum_{n\in N} \rho_n \left(\max_{u_n \in U_n} \min_{y_n} b^T y_n + c^T u_n \right)$$
$$\text{s.t.} \quad Dx \ge e$$
$$Fx + Gy_n + Hu_n \le i, \forall n$$
$$Jx + Ky_n + Lu_n = m, \forall n$$

C. Zhang, **Y. Xu***, Z.Y. Dong, "Probability-Weighted Robust Optimization for Distributed Generation Planning in Microgrids," ***IEEE Trans. Power Syst.*, 2018**.

Solution Algorithm



Initialize the lower bound LB as $-\infty$, the upper bound UB as $+\infty$, $u_{n,0} = u_{n,mean}, \forall n \in N$ and the iteration number $q = 0$

Solve the master problem:
$$\min_x a^T x + \delta$$
$$\text{s.t.} \quad Dx \ge e$$
$$Fx + Gy_{n,p} + Hu_{n,p}^* \le i, \forall p \le q, n \in N$$
$$Jx + Ky_{n,p} + Lu_{n,p}^* = m, \forall p \le q, n \in N$$
$$\delta \ge \sum_{n\in N} \rho_n \left(b^T y_{n,p} + c^T u_{n,p}^*\right), \forall p \le q$$
Obtain the current optimal solution x_q^*, δ_q^* and update LB by $\max\{LB, a^T x_q^* + \delta_q^*\}$

Solve the slave problem:

$r = 1$, infinite solution number: $v = 0$

Solve $S_{r,q} = \max_{u_{r,q}\in U_r} \min_{y_{r,q}} b^T y_{r,q} + c^T u_{r,q}$
$$\text{s.t.} \quad Fx_q^* + Gy_{r,q} + Hu_{r,q} \le i$$
$$Jx_q^* + Ky_{r,q} + Lu_{r,q} = m$$

A finite $S_{r,q}$?

Yes

No

Non-Optimal Cut: Obtain the worst case $u_{r,q}^*$ for $S_{r,q}$

Infeasible Cut: Identify the certain $u_{r,q}^*$ for the infeasible $S_{r,q}$, $v = v + 1$

Add $Fx + Gy_{r,q} + Hu_{r,q}^* \le i$ and $Jx + Ky_{r,q} + Lu_{r,q}^* = m$ to the master problem

$r = r + 1$

$r \in N$?

Yes

No

Add $u_{n,q}^*, \forall n \in N$ to the master problem as the parameter
Add $\delta \ge \sum_{n\in N} \rho_n \left(b^T y_{n,q} + c^T u_{n,q}^*\right)$ to the master problem

$v = 0$?

No

Yes

Update UB by $\min\{UB, a^T x_q^* + \sum_{n\in N} \rho_n \left(b^T y_{n,q} + c^T u_{n,q}^*\right)\}$

$\frac{UB-LB}{|LB|} \le gap$?

Yes

No

Final Optimal Solution x_q^*

$q = q + 1$

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

5. Trading
1) Review
2) Centralized trading
3) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) Joint planning

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

▪ Probability-Weighted Robust Optimization (PRO) for DG Planning

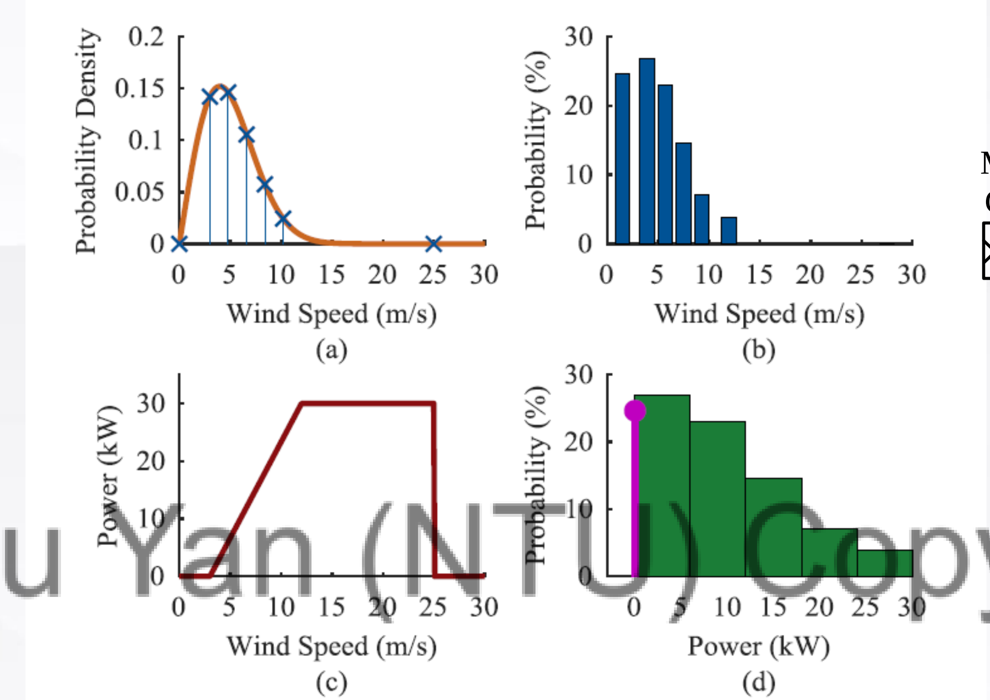
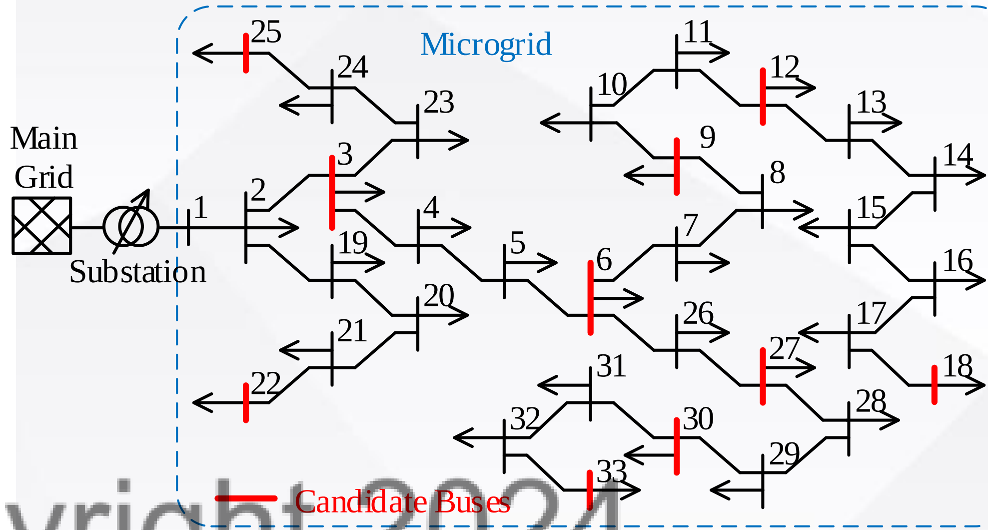


Fig. 3 (a) Wind speed probability density; (b) Wind speed probability; (c) Wind power generation function; (d) Wind power probability.



COMPARISON BETWEEN DIFFERENT METHODS

DG Planning Method	PRO	RO			
Uncertainty Profile Case	N/A	1	2	3	4
Voltage Violation Rate	0%	8.12%	0%	3.12%	11.44%
Profit in NPV (M$)	23.51	24.71	23.43	24.50	24.74

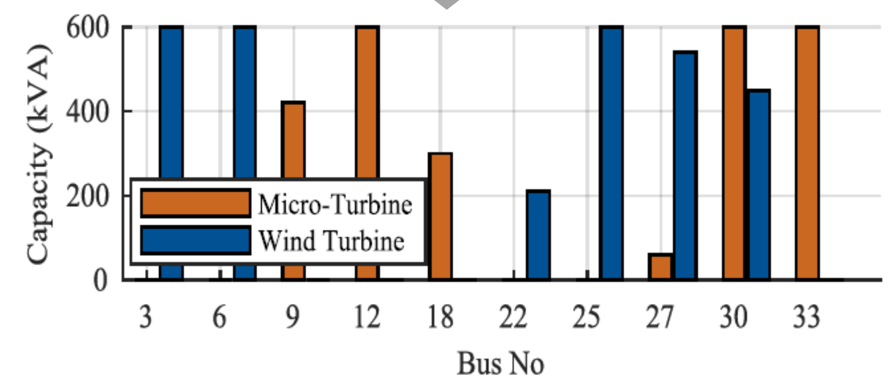
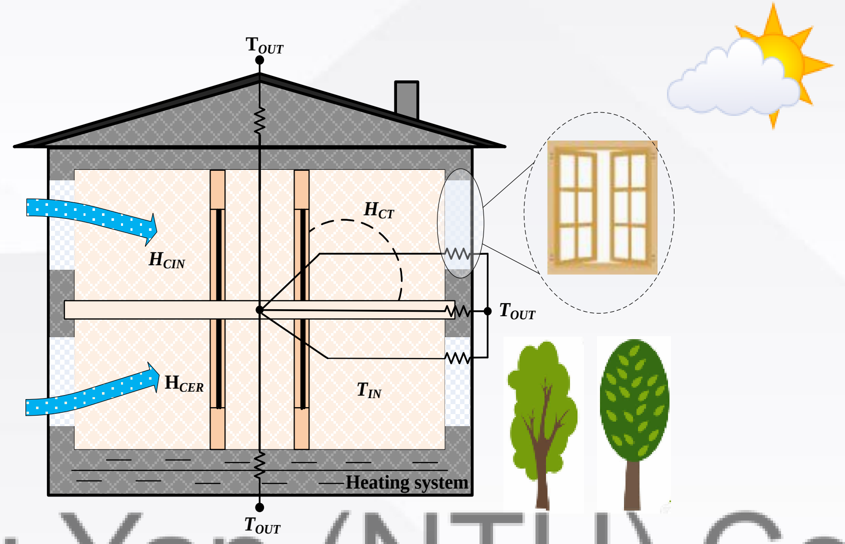


Fig. 4 DG planning decisions.

C. Zhang, **Y. Xu***, Z.Y. Dong, "Probability-Weighted Robust Optimization for Distributed Generation Planning in Microgrids," ***IEEE Trans. Power Syst.*, 2018**.

Optimal Deployment of Heterogeneous Energy Storage



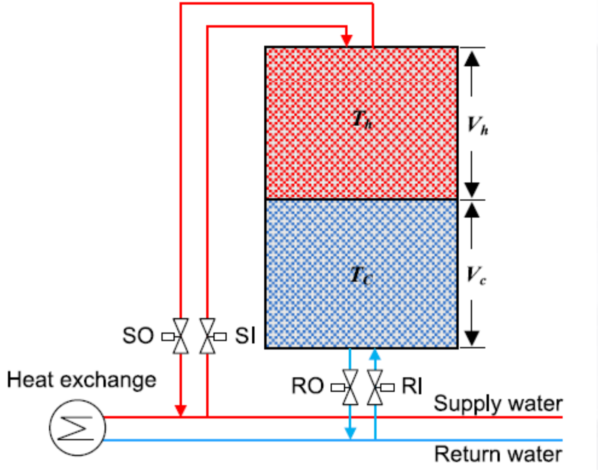
Typical structure of a room in a residential building

$$\max_{z\in Z, x\in X, \eta_{VaR}\in\Re} [C_{EDP} - \rho_{RK} CVaR_\alpha(C_{EDP})]$$

$$\text{s.t.,}\ C_{EDP} = \frac{1}{365\times N_P}\cdot\frac{dr(1+dr)^{N_P}}{(1+dr)^{N_P}-1}\cdot\Big[\underbrace{-F(z)}_{\text{Investment Stage}} + \underbrace{G(x)}_{\text{Operation Stage}}\Big]$$

$$CVaR_\alpha(C_{EDP}) = \eta_{VaR} + \frac{1}{1-\alpha_{CL}} E \times [\max(C_{EDP} - \eta_{VaR}, 0)]$$

Risk-averse objective function



Structure of the thermal storage

$$\underset{x}{Min}\, G(x) = \underset{w,y_1,y_2...,y_q}{Min}\,[S(w) + \sum_{q\in N_Q} c_q L(y_q)]$$

$$s.t. \quad w \in CS_w \mid z$$

$$y_q \in CL(w,\omega_q), \forall q$$

Proposed multi-stage stochastic deployment model

Z. Li and **Y. Xu***, “Optimal Stochastic Deployment of Heterogeneous Energy Storage in a Residential Multi-Energy Microgrid with Demand-Side Management,” *IEEE Transactions on Industrial Informatics*, 2020. **Web-of-Science Highly Cited Paper**

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

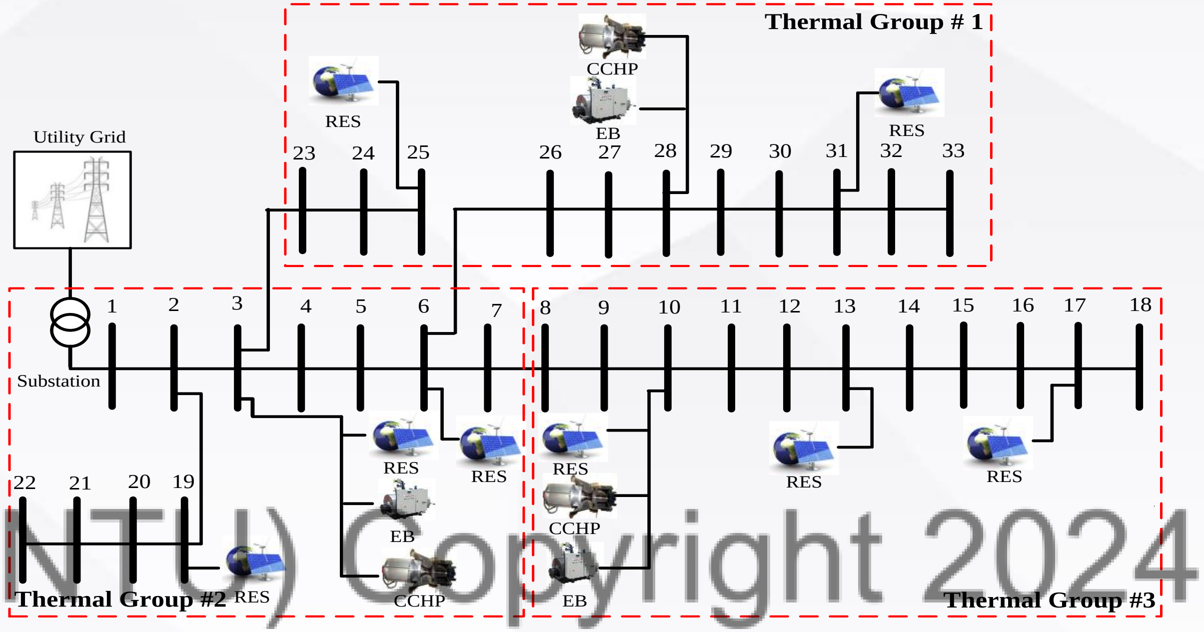
4. Hierarchy coordination

5. Trading
1) Review
2) Centralized trading
3) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) Joint planning

NANYANG TECHNOLOGICAL UNIVERSITY
SINGAPORE

Planning results



Deployment Results For Battery Storage (kWh)

Year/Bus	3	6	18	22	25	27	30	33
1-3	1500	0	0	1500	1500	0	0	0
4-6	1500	466.0	101.7	1500	1500	0	0	473.2
7-9	1500	466.0	101.7	1500	1500	378.0	81.19	473.2

Deployment Results For Thermal Storage (kWh)

Year 1-9	Group 1	Group2	Group3
Cooling storage tank	0	0	0
Heat storage tank	1800	1800	1800

Z. Li and **Y. Xu***, "Optimal Stochastic Deployment of Heterogeneous Energy Storage in a Residential Multi-Energy Microgrid with Demand-Side Management," *IEEE Transactions on Industrial Informatics*, 2020. **Web-of-Science Highly Cited Paper**

Joint Planning of Utility-Owned Distributed Energy Resources in an Unbalanced Active Distribution Network Considering Asset Health Degradation

Research motivation: DERs asset health will degrade along with the service period. The asset health degradation of DER will cause nameplate capacity decrease and incur the extra cost of operation and maintenance.

Our aims: proposes a new planning method for utility-owned distributed generators and energy storage systems in an unbalanced active distribution network considering asset health degradation.

- *WT blade erosion*

- *PV module degradation*

- *DG capacity drop modeling by Wiener model:*

$$\Gamma_{cap}^{q,y} = \Gamma_{cap}^{q,y-\Delta y} + \lambda_{cap}^{q} a(y-\Delta y)^{a-1}\Delta y + \sigma_{cap}^{q} Y\sqrt{\Delta y}$$

- *DG O&M cost increase modeling by Wiener model:*

$$\chi_{om}^{q,y,d,t} = \chi_{om}^{q,y,d,t-\Delta t} + \lambda_{om}^{q} b(t-\Delta t)^{b-1}\Delta t + \sigma_{om}^{q} Y\sqrt{\Delta t}$$

Proposed DG health degradation model based on the Wiener model

- **The linearized three-phase power flow**

Active power balance:

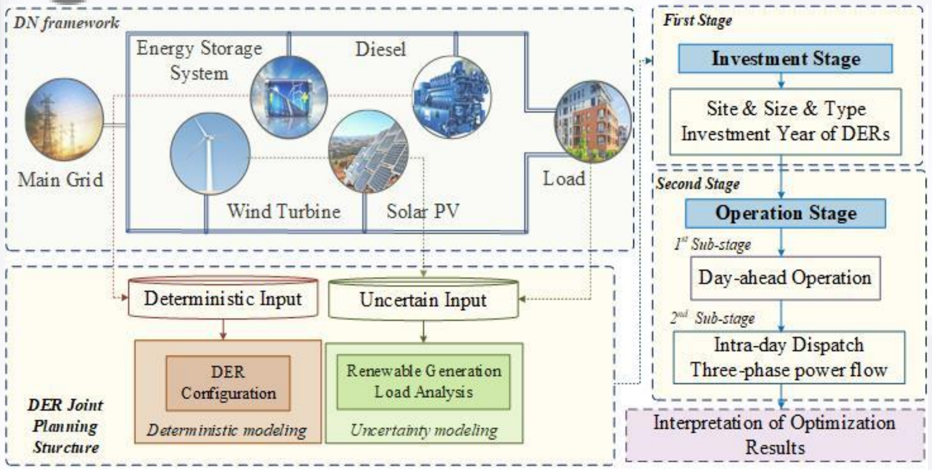
$$P_{flw}^{p,y,d,t,br+1} = P_{flw}^{p,y,d,t,br} - P_{flw}^{p,y,d,t,0,br+1} - P_{LD}^{p,y,d,t,i} + P_{DE}^{p,y,d,t,i} + P_{PV}^{p,y,d,t,i} + P_{WT}^{p,y,d,t,i} + P_{BSD}^{p,q,y,d,t,i} - P_{BSC}^{p,q,y,d,t,i}$$

Reactive power balance:

$$Q_{flw}^{p,y,d,t,br+1} = Q_{flw}^{p,y,d,t,br} - Q_{flw}^{p,y,d,t,0,br+1} - Q_{LD}^{p,y,d,t,i} + Q_{WT,PV}^{p,y,d,t,i}$$

Voltage Constraint:

$$\begin{bmatrix} V_a^{y,d,t,i+1} \\ V_b^{y,d,t,i+1} \\ V_c^{y,d,t,i+1} \end{bmatrix} = \begin{bmatrix} V_a^{y,d,t,br} \\ V_b^{y,d,t,br} \\ V_c^{y,d,t,br} \end{bmatrix} - \bar{Z}_{i\to j} \begin{bmatrix} P_{flw,a}^{y,d,t,br} - jQ_{flw,a}^{y,d,t,br} \\ P_{flw,b}^{y,d,t,br} - jQ_{flw,b}^{y,d,t,br} \\ P_{flw,c}^{y,d,t,br} - jQ_{flw,c}^{y,d,t,br} \end{bmatrix} - \bar{Z}_{i\to j}^{*} \begin{bmatrix} P_{flw,a}^{y,d,t,br} + jQ_{flw,a}^{y,d,t,br} \\ P_{flw,b}^{y,d,t,br} + jQ_{flw,b}^{y,d,t,br} \\ P_{flw,c}^{y,d,t,br} + jQ_{flw,c}^{y,d,t,br} \end{bmatrix}$$



The proposed DERs joint planning framework

R. Leng, Z. Li, **Y. Xu***, Joint Planning of Utility-Owned Distributed Energy Resources in an Unbalanced Active Distribution Network Considering Asset Health Degradation[J]. *IEEE Transactions on Smart Grid, 2024*.

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

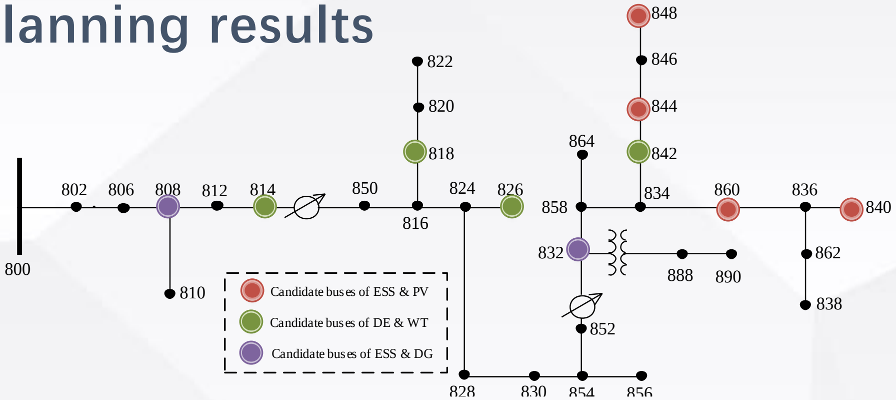
5. Trading
1) Review
2) Centralized trading
3) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) Joint planning

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

Joint Planning of Utility-Owned Distributed Energy Resources in an Unbalanced Active Distribution Network Considering Asset Health Degradation

- Planning results



IEEE 34-bus distribution system topology

DERs deployment results

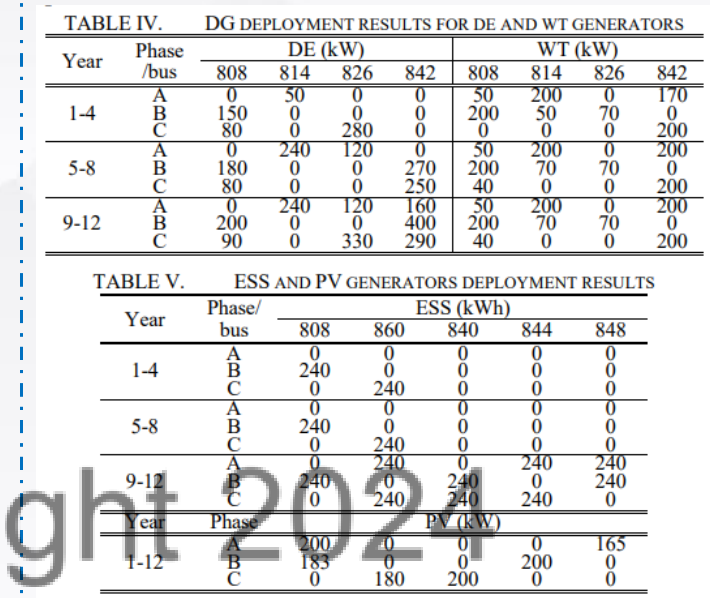
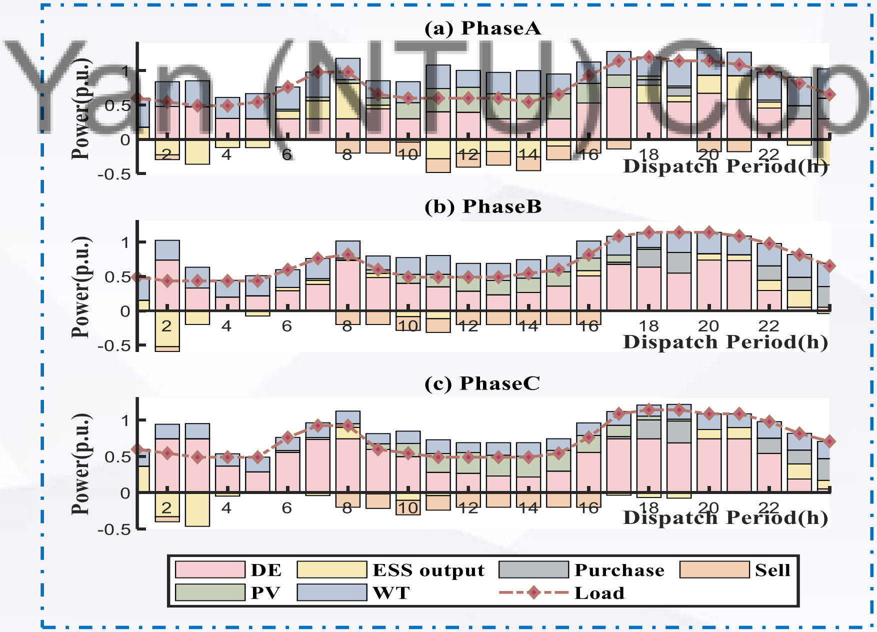


TABLE IV. DG DEPLOYMENT RESULTS FOR DE AND WT GENERATORS

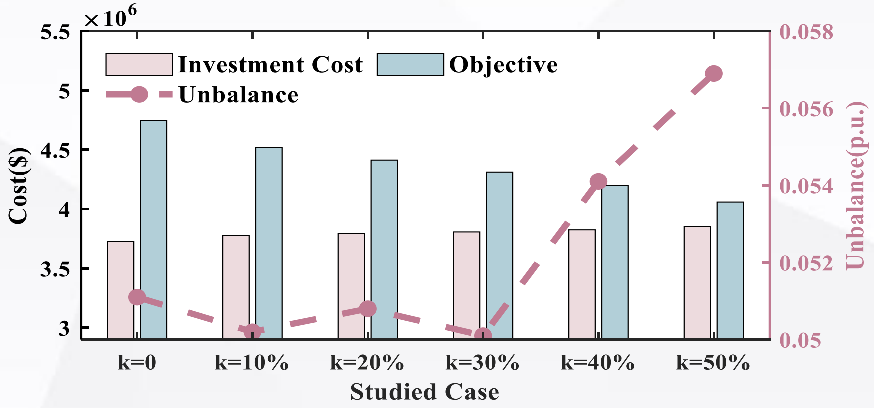
Year	Phase /bus	DE (kW) 808	DE (kW) 814	DE (kW) 826	DE (kW) 842	WT (kW) 808	WT (kW) 814	WT (kW) 826	WT (kW) 842
1-4	A	0	50	0	0	50	200	0	170
	B	150	0	0	0	200	50	70	0
	C	80	0	280	0	0	0	0	200
5-8	A	0	240	120	0	50	200	0	200
	B	180	0	0	270	200	70	70	0
	C	80	0	0	250	40	0	0	200
9-12	A	0	240	120	160	50	200	0	200
	B	200	0	0	400	200	70	70	0
	C	90	0	330	290	40	0	0	200

TABLE V. ESS AND PV GENERATORS DEPLOYMENT RESULTS

Year	Phase/ bus	ESS (kWh) 808	ESS (kWh) 860	ESS (kWh) 840	ESS (kWh) 844	ESS (kWh) 848
1-4	A	0	0	0	0	0
	B	240	0	0	0	0
	C	0	240	0	0	0
5-8	A	0	0	0	0	0
	B	240	0	0	0	0
	C	0	240	0	0	0
9-12	A	0	240	0	240	240
	B	240	0	240	0	240
	C	0	240	240	240	0
Year	Phase	PV (kW)				
1-12	A	200	0	0	0	165
	B	183	0	0	200	0
	C	0	180	200	0	0



Simulation results for operation stage in year 2034-Spring/Fall



Comparison results for different degradation parameters

R. Leng, Z. Li, **Y. Xu***, Joint Planning of Utility-Owned Distributed Energy Resources in an Unbalanced Active Distribution Network Considering Asset Health Degradation[J]. *IEEE Transactions on Smart Grid, 2024*.

Real-Option Based Planning of Utility-Owned Distributed Energy Resources for Islanded Distribution Networks in Southeast Asia

Research challenges and contributions in this paper

DERs planning for islanded DNs in Southeast Asia

	Weather		Location
Featured Challenge	High Temperature	Variable Weather	Geographical isolation
Technical Contribution	Detailed stationary ESS thermal model	PV inverter oversizing with lifetime reduction	Supply chain risks Real option theory based planning
Research Contribution	ESS cooling load estimation	Enhance reactive power support	Defer option for managing supply chain risk
Users	Distribution grid operators, microgrid owners, DER asset investors		

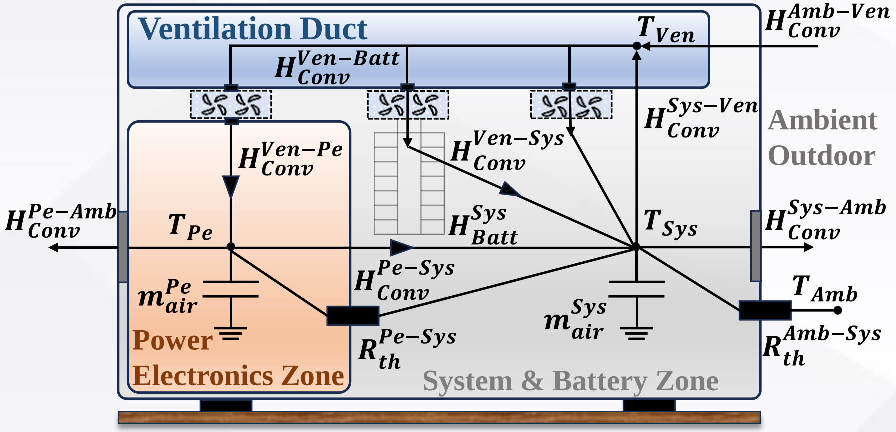


Illustration of the ESS container system thermal management

Supply Chain Risk Model

Supply chain risk degree:

$$\Theta_{Ma}^{q}=\frac{y_q\left[\Upsilon+(n-1)(1+\varpi\delta_q^2)\right]}{2\mu_{Ma}^{q}\left[2\Upsilon+(n-1)(1+\varpi\delta_q^2)\right]\left[\Upsilon+n(1+\varpi\delta_q^2)\right](2+\varepsilon)}$$

Warehouse disruption risk degree:

$$\lambda_{wa}^{q,d}=\max\{0,[\lambda_{wa}^{q,d-1}+\min\{(1-\lambda_{wa}^{q,d-1}),(\frac{1}{\partial^{q,d}})\}]\cdot[1-\Lambda^{q,d}\frac{\psi^{q,d}}{100}]\}$$

Real option valuation:

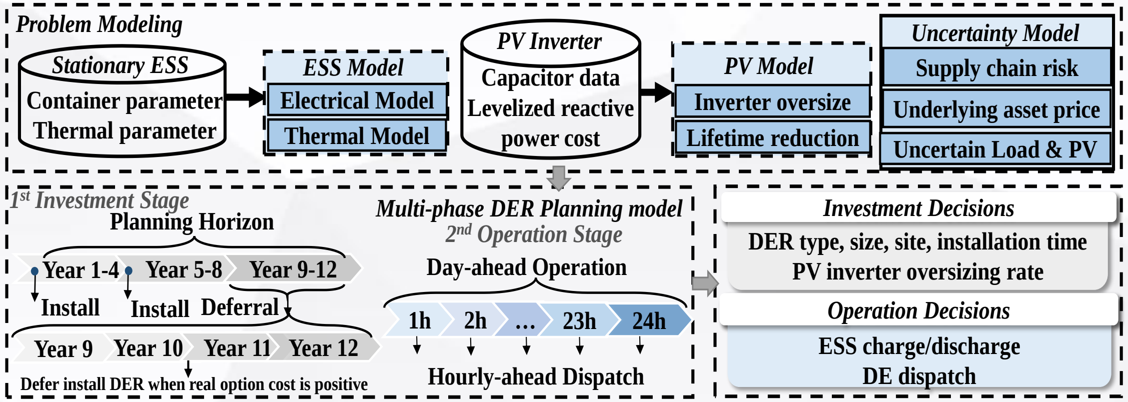
$$C_{DERopt}^{y}=S_{DER}^{y}\cdot N(d_1)-K_{DER}^{y}\cdot e^{-r_f T}\cdot N(d_1-\sigma_{DER}\sqrt{T})$$

$$d_1=\ln(S_{DER}^{y}/K_{DER}^{y})+(r_f+0.5\sigma_{DER}^2)T/\sigma_{DER}\sqrt{T}$$

$$S_{DER}^{y}(t+\Delta t)=S_{DER}^{y}(t)+\mu_{DER}t+\sigma_B Y\sqrt{\Delta t}$$

Multistage and multiphase framework for DER joint planning:

In the investment stage, the entire planning period is divided into multiple planning sub-horizons. The operation stage involves the day-ahead operation and hourly ahead dispatch.



The proposed DER planning framework

R. Leng, **Y. Xu***, Real-Option Based Planning of Utility-Owned Distributed Energy Resources for Islanded Distribution Networks in Southeast Asia[J].*IEEE Transactions on Smart Grid, 2024*.

1. REIDS Project

2. Control
1) Islanded mode
2) Grid-tied mode

3. Operation
1) Energy dispatch
2) Volt/Var regulation

4. Hierarchy coordination

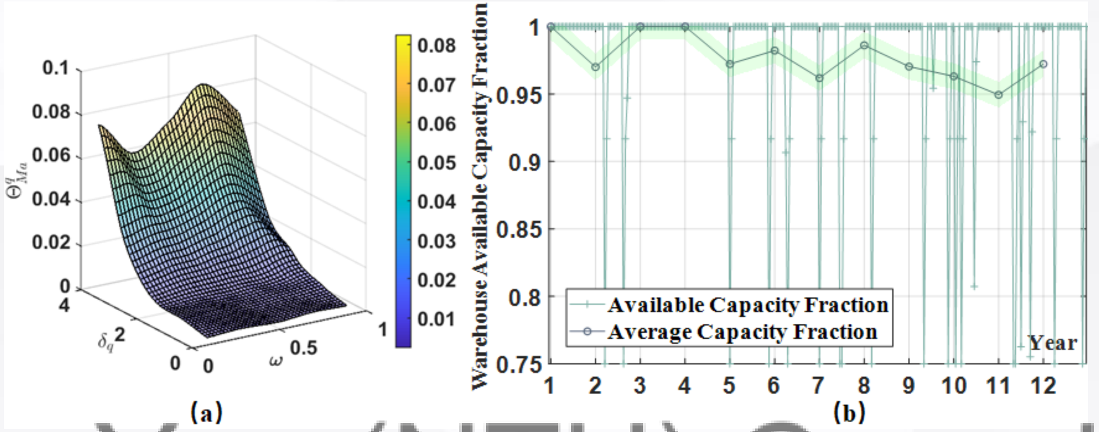
5. Trading
1) Review
2) Centralized trading
3) P2P trading

6. Planning
1) DG planning
2) ESS planning
3) Joint planning

NANYANG TECHNOLOGICAL UNIVERSITY
SINGAPORE

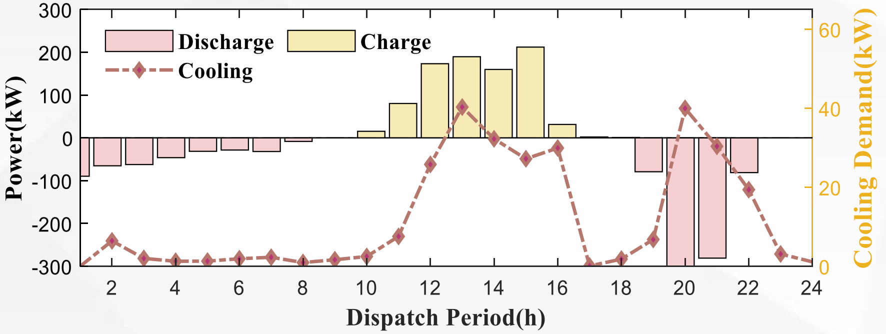
Real-Option Based Planning of Utility-Owned Distributed Energy Resources for Islanded Distribution Networks in Southeast Asia

Simulation results



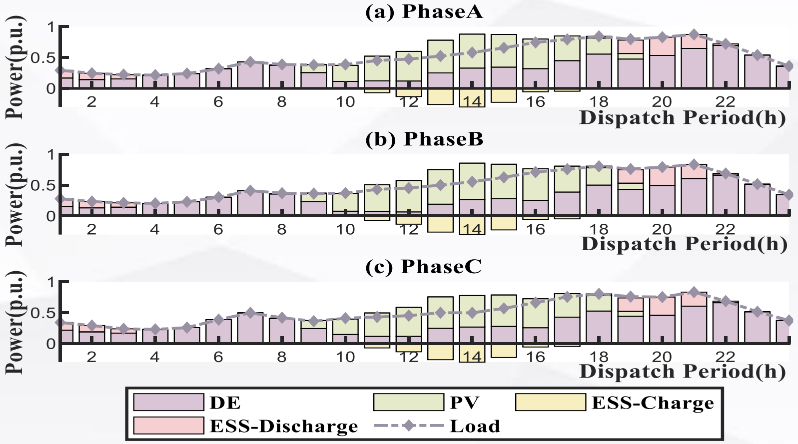
Supply chain risk parameters. (a) Joint impact of ϖ, δ_q and supply risk degree Θ^q_{Ma} at n=4. (b) Warehouse Capacity Fraction Curve for 12 years.

ESS cooling curve associated with ESS charge and discharge

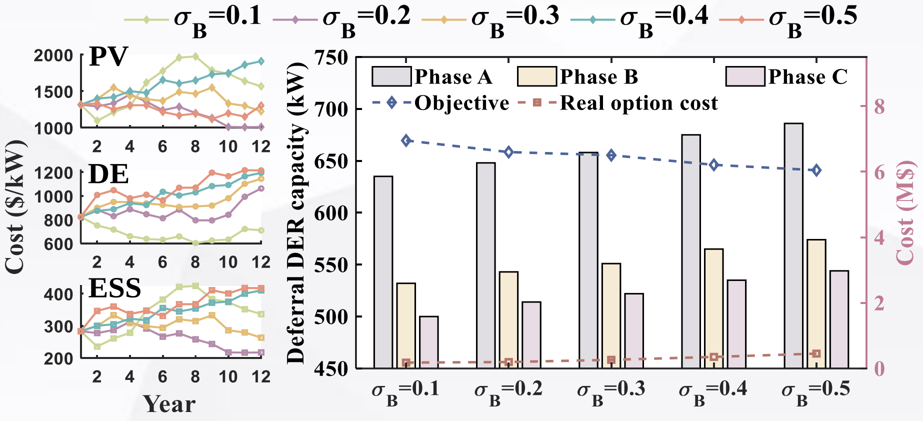


PV inverter oversizing results in the final planning year

Phase A		Phase B		Phase C	
Bus	OS%	Bus	OS%	Bus	OS%
808	28%	808	60%	808	60%
860	49%	840	23%	860	19%
840	60%	848	60%	844	60%
848	60%	832	42%	832	60%



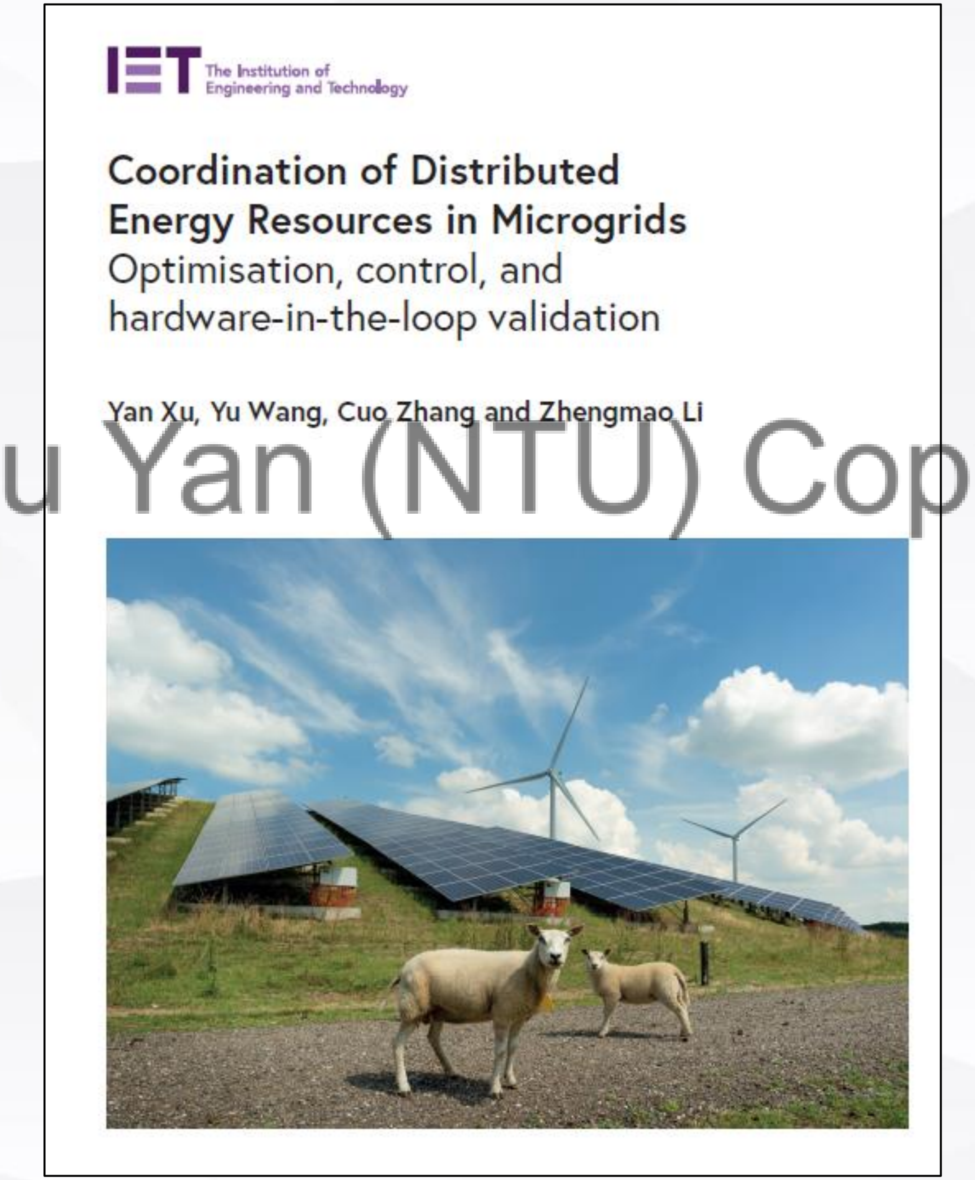
Simulation results for the operation stage in June 2035



Sensitivity results for different volatility values

R. Leng, **Y. Xu***, Real-Option Based Planning of Utility-Owned Distributed Energy Resources for Islanded Distribution Networks in Southeast Asia[J].*IEEE Transactions on Smart Grid, 2024*.

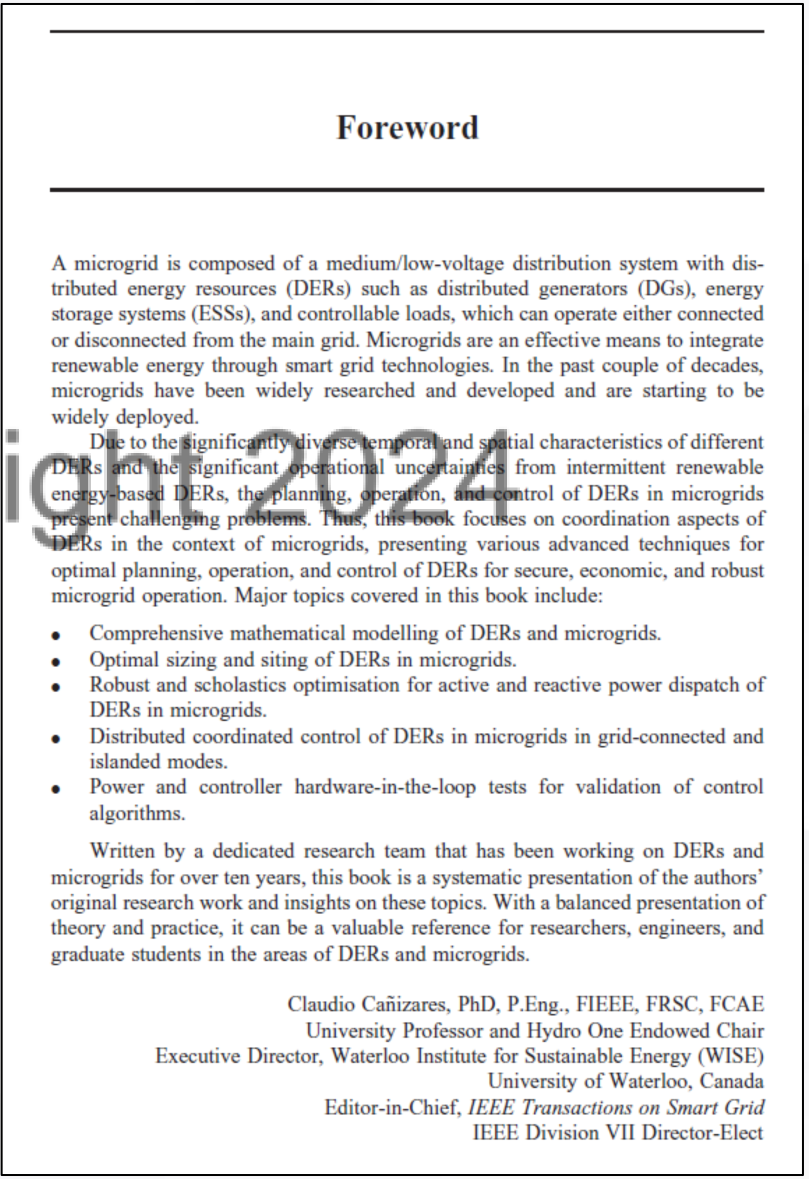
Y. Xu, Y. Wang, C. Zhang, and Z. Li, "Coordination of Distributed Energy Resources in Microgrids: Optimisation, control, and hardware-in-the-loop validation," IET Press, 2021



IET The Institution of Engineering and Technology

Coordination of Distributed Energy Resources in Microgrids
Optimisation, control, and hardware-in-the-loop validation

Yan Xu, Yu Wang, Cuo Zhang and Zhengmao Li



Foreword

A microgrid is composed of a medium/low-voltage distribution system with distributed energy resources (DERs) such as distributed generators (DGs), energy storage systems (ESSs), and controllable loads, which can operate either connected or disconnected from the main grid. Microgrids are an effective means to integrate renewable energy through smart grid technologies. In the past couple of decades, microgrids have been widely researched and developed and are starting to be widely deployed.

Due to the significantly diverse temporal and spatial characteristics of different DERs and the significant operational uncertainties from intermittent renewable energy-based DERs, the planning, operation, and control of DERs in microgrids present challenging problems. Thus, this book focuses on coordination aspects of DERs in the context of microgrids, presenting various advanced techniques for optimal planning, operation, and control of DERs for secure, economic, and robust microgrid operation. Major topics covered in this book include:

- Comprehensive mathematical modelling of DERs and microgrids.
- Optimal sizing and siting of DERs in microgrids.
- Robust and scholastics optimisation for active and reactive power dispatch of DERs in microgrids.
- Distributed coordinated control of DERs in microgrids in grid-connected and islanded modes.
- Power and controller hardware-in-the-loop tests for validation of control algorithms.

Written by a dedicated research team that has been working on DERs and microgrids for over ten years, this book is a systematic presentation of the authors' original research work and insights on these topics. With a balanced presentation of theory and practice, it can be a valuable reference for researchers, engineers, and graduate students in the areas of DERs and microgrids.

Claudio Cañizares, PhD, P.Eng., FIEEE, FRSC, FCAE
University Professor and Hydro One Endowed Chair
Executive Director, Waterloo Institute for Sustainable Energy (WISE)
University of Waterloo, Canada
Editor-in-Chief, *IEEE Transactions on Smart Grid*
IEEE Division VII Director-Elect

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

Publications Microgrid Control

1. W. Yao, Y. Wang, **Y. Xu***, and C. Dong, "Small-Signal Stability Analysis and Lead-Lag Compensation Control for DC Networked-Microgrid under Multiple Time Delays," ***IEEE Trans. Power Syst.*, 2022.**
2. W. Yao, Y. Wang, **Y. Xu***, and C. Deng, "Cyber-Resilient Control of an Islanded Microgrid Under Latency Attacks and Random DoS Attacks," ***IEEE Trans. Industrial Informatics*, 2022.**
3. Y. Wang, S. Mondal, C. Deng, K. Satpathi, **Y. Xu*** and S. Dasgupta, "Cyber-Resilient Cooperative Control of Bidirectional Interlinking Converters in Networked AC/DC Microgrids," ***IEEE Trans. Ind. Electronics*, 2021.**
4. Y. Wang, S. Mondal, K. Satpathi, **Y. Xu***, S. Dasgupta, A. Gupta, "Multi-Agent Distributed Power Management of a DC Shipboard Power System for Optimal Fuel Efficiency," ***IEEE Trans. Transp. Electrification*, 2021.**
5. W. Yao, Y. Wang, **Y. Xu*,** C. Deng, and Q. Wu, "Distributed Weight-Average-Prediction Control and Stability Analysis for an Islanded Microgrid with Communication Time Delay," ***IEEE Trans. Power Syst.*, 2021.**
6. Y. Wang, C. Deng, D. Liu, **Y. Xu***, and J. Dai, "Unified Real Power Sharing of Generator and Storage in Islanded Microgrid via Distributed Dynamic Event-Triggered Control," ***IEEE Trans. Power Syst.*, 2021.**
7. C. Deng, Y. Wang, C. Wen, **Y. Xu**, and P. Lin, "Distributed Resilient Control for Energy Storage Systems in Cyber-Physical Microgrids," ***IEEE Trans. Ind. Informatics*, 2021 – Web-of-Science Highly Cited Paper**
8. T. L. Nguyen, Y. Wang, Q. T. Tran, R. Caire, **Y. Xu** and C. Gavriluta, "A Distributed Hierarchical Control Framework in Islanded Microgrids and Its Agent-based Design for Cyber-Physical Implementations," ***IEEE Trans. Industrial Electronics*, 2021.**
9. Y. Wang, T.L. Nguyen, **Y. Xu*,** Q.T. Tran, and R. Caire, "Peer-to-Peer Control for Networked Microgrids: Multi-Layer and Multi-Agent Architecture Design," ***IEEE Trans. Smart Grid*, 2020.**

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

Publications Microgrid Control

10. Y. Wang, T.L. Nguyen, M. Syed, **Y. Xu*,** E. Guillo-Sansano, V.H. Nguye, G. Burt, and Q.T. Tran, “A Distributed Control Scheme of Microgrids in Energy Internet Paradigm and Its Multisite Implementation,” ***IEEE Trans. Industrial Informatics,*** **2020. – Web-of-Science Highly Cited Paper**
11. Y. Wang, M.H. Syed, E. Guillo-Sansano, **Y. Xu*,** and G.M. Burt, “Inverter-based Voltage Control of Distribution Networks: A Three-Level Coordinated Method and Power Hardware-in-the-Loop Validation,” ***IEEE Trans. Sustainable Energy,*** **2020.**
12. Q. Xu, **Y. Xu**, C. Zhang, and P. Wang, “A Robust Droop-based Autonomous Controller for Decentralized Power Sharing in DC Microgrid Considering Large Signal Stability,” ***IEEE Trans. Indus. Info.,*** **2020.**
13. Y. Wang, Y. Tang, **Y. Xu*,** et al, “A Distributed Control Scheme of Thermostatically Controlled Loads for Building-Microgrid Community,” ***IEEE Trans. Sust. Energy,*** **2019. – Web-of-Science Highly Cited Paper**
14. Y. Wang, T. Zhao, C. Ju, **Y. Xu***, P. Wang “Two-Level Distributed Voltage/Var Control of Aggregated PV Inverters in Distribution Networks,” ***IEEE Trans. Power Delivery,*** **2019**.
15. Y. Wang, **Y. Xu**, and Y. Tang, “Distributed Aggregation Control of Grid-Interactive Smart Buildings for Power System Frequency Support,” ***Applied Energy,*** **2019.**
16. Y. Wang, T.L. Nguyen, **Y. Xu***, et al, “Cyber-Physical Design and Implementation of Distributed Event-Triggered Secondary Control in Islanded Microgrids,” ***IEEE Trans. Industry Applications,*** **2019.**
17. Y. Wang, **Y. Xu**, Y. Tang, et al “Aggregated Energy Storage for Power System Frequency Control: A Finite-Time Consensus Approach,” ***IEEE Trans. Smart Grid,*** **2018.**
18. Y. Wang, **Y. Xu*,** Y. Tang, et al, “Decentralized-Distributed Hybrid Voltage Regulation of Power Distribution Networks Based on Power Inverters,” ***IET Gen. Trans. & Dist.,*** **2018.**

▪ Publications Microgrid Operation and Energy Trading

1. Y. Zou, **Y. Xu*,** and J. Li, “Aggregator-Network Coordinated Peer-to-Peer Multi-Energy Trading via Adaptive Robust Stochastic Optimization,” ***IEEE Trans. Power Syst.*, 2024.**
2. Y. Zou, **Y. Xu***, and C. Zhang, “A Risk-Averse Adaptive Stochastic Optimization Method for Transactive Energy Management of a Multi-Energy Microgrid,” ***IEEE Trans. Sustainable Energy*, 2023.**
3. D. Liu, C. Zhang, **Y. Xu**, Z. Dong and Y. Chi, "Sensitivity Region-Based Optimization for Maximizing Renewable Generation Hosting Capacity of An Islanded Microgrid," ***IEEE Trans. Smart Grid*, 2023.**
4. Z. Li, L. Wu, **Y. Xu**, et al, “Distributed tri-layer risk-averse stochastic game approach for energy trading among multi-energy microgrids,” ***Applied Energy*, 2023. - Web of Science highly cited paper**
5. Y. Zou, **Y. Xu***, X. Feng, and H.D. Nguyen, “Peer-to-Peer Transactive Energy Trading of a Reconfigurable Multi-Energy Network,” ***IEEE Trans. Smart Grid*, 2022.**
6. R. Xu, C. Zhang, **Y. Xu**, Z.Y. Dong, and R. Zhang, “Multi-Objective Hierarchically-Coordinated Volt/Var Control for Active Distribution Networks with Droop-Controlled PV Inverters,” ***IEEE Trans. Smart Grid*, 2022.**
7. Z. Li, L. Wu, **Y. Xu** and X. Zheng, "Stochastic-Weighted Robust Optimization Based Bilayer Operation of a Multi-Energy Building Microgrid Considering Practical Thermal Loads and Battery Degradation," ***IEEE Trans. Sustainable Energy*, 2022.**
8. Z. Li, L. Wu, **Y. Xu**, S. Moazeni, and Z. Tang, “Multi-Stage Real-time Operation of A Multi-energy Microgrid With Electrical and Thermal Energy Storage Assets: A Data-Driven MPC-ADP Approach,” ***IEEE Trans. Smart Grid*, 2022. - Web of Science highly cited paper**
9. Q. Chai, C. Zhang, **Y. Xu**, and Z.Y. Dong, “PV Inverter Reliability-Constrained Volt/Var Control of Distribution Networks,” ***IEEE Trans. Sustainable Energy*, 2021.**
10. Z. Li, L. Wu, and **Y. Xu**, “Risk-Averse Coordinated Operation of a Multi-energy Microgrid Considering Voltage/Var Control and Thermal Flow: An Adaptive Stochastic Approach,” ***IEEE Trans. Smart Grid*, 2021.**

Publications Microgrid Operation and Energy Trading

11. Z. Li, **Y. Xu***, L. Wu, and X. Zheng, "A Risk-Averse Adaptively Stochastic Optimization Method for Multi-Energy Ship Operation Under Diverse Uncertainties," ***IEEE Trans. Power Syst.*, 2021. - Web of Science highly cited paper**
12. C. Zhang and **Y. Xu***, **"**Hierarchically-Coordinated Voltage/VAR Control of Distribution Networks using PV Inverters," ***IEEE Trans. Smart Grid*, 2020. – 2021 IEEE Trans. Smart Grid Outstanding Paper Award**
13. C. Zhang, **Y. Xu***, Z.Y. Dong, and R. Zhang, "Multi-Objective Adaptive Robust Voltage/VAR Control for High-PV Penetrated Distribution Networks," ***IEEE Trans. Smart Grid*, 2020.**
14. Q. Xu, **Y. Xu***, Z. Xu, L. Xie, F. Blaabjerg, "A Hierarchically Coordinated Operation and Control Scheme for DC Microgrid Clusters under Uncertainty," ***IEEE Trans. Sustainable Energy*, 2020.**
15. Q. Xu, T. Zhao, **Y. Xu***, Z. Xu, P. Wang, and F. Blaabjerg, "A Distributed and Robust Energy Management System for Networked Hybrid AC/DC Microgrids," ***IEEE Trans. Smart Grid*, 2020.**
16. Y. Chen, X. Feng, Z. Li, **Y. Xu***, and A. Miragha, "Multi-stage coordinated operation of a multi-energy microgrid with residential demand response under diverse uncertainties", ***IET Energy Conversion & Economics*, 2020**. **– IET Premium Award (Best Paper)**
17. C. Zhang, **Y. Xu***, and Z.Y. Dong, "Robustly Coordinated Operation of a Multi-Energy Micro-Grid in Grid-Connected and Islanded Modes under Uncertainties," ***IEEE Trans. Sustainable Energy*, 2020.**
18. Z. Li and **Y. Xu*,** "Temporally-Coordinated Optimal Operation of a Multi-energy Microgrid under Diverse Uncertainties," ***Applied Energy*, 2019.**
19. C. Zhang, **Y. Xu***, Z.Y. Dong, "Robustly Coordinated Operation of a Multi-Energy Micro-Grid in Grid-Connected and Islanded Modes under Uncertainties," ***IEEE Trans. Sustainable Energy*, 2019.**
20. S. Sharma, **Y. Xu***, A. Verma**,** et al, "Time-Coordinated Multi-Energy Management of Smart Buildings under Uncertainties," ***IEEE Trans. Industrial Informatics*, 2019.**

Publications Microgrid Operation and Energy Trading

21. Y. Chen, **Y. Xu***, et al, "Optimally Coordinated Dispatch of Combined-Heat-and-Electrical Network," ***IET Gen. Trans. & Dist.*, 2019.**
22. R. Xu, C. Zhang, **Y. Xu***, Z.Y. Dong, "Rolling Horizon Based Multi-Objective Robust Voltage/VAR Regulation with Conservation Voltage Reduction in High PV-Penetrated Distribution Networks," ***IET Gen. Trans. & Dist.*, 2019.**
23. **Y. Xu***, Z.Y. Dong, et al, "Multi-timescale coordinated voltage/var control of high renewable-penetrated distribution networks," ***IEEE Trans. Power Syst.*, 2018.**
24. Z. Li and **Y. Xu***, "Optimal coordinated energy dispatch for a multi-energy microgrid in grid-connected and islanded modes," ***Applied Energy*, 2018. – Web-of-Science Highly Cited Paper & "2018 Applied Energy Highly Cited Paper Award"**
25. C. Zhang, **Y. Xu*,** Z.Y. Dong, et al, "Robustly Coordinated Operation of A Multi-Energy Microgrid with Flexible Electric and Thermal Loads," ***IEEE Trans. Smart Grid*, 2018.**
26. C. Zhang, **Y. Xu***, Z.Y. Dong, "Three-Stage Robust Inverter-Based Voltage/Var Control for Distribution Networks with High PV," ***IEEE Trans. Smart Grid*, 2017. – Web-of-Science Highly Cited Paper**
27. C. Zhang, **Y. Xu*,** Z.Y. Dong , et al, "Robust operation of Microgrids via two-stage coordinated energy storage and direct load control," ***IEEE Trans. Power Syst.*, 2017.**
28. C. Zhang, **Y. Xu**, Z.Y. Dong, "Robust Coordination of Distributed Generation and Price-Based Demand Response in Microgrids," ***IEEE Trans. Smart Grid*, 2017. – Web-of-Science Highly Cited Paper**
29. W. Zhang, **Y. Xu***, Z.Y. Dong, "Robust SCOPF using multiple microgrids for corrective control under uncertainty," ***IEEE Trans. Industrial Informatics*, 2017.**
30. C. Ju, P. Wang, L. Goel, and **Y. Xu***, "A two-layer energy management system for microgrids with hybrid energy storage considering degradation costs," ***IEEE Trans. Smart Grid*, 2017. – Web-of-Science Highly Cited Paper**

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

Publications Microgrid Planning

1. R. Leng and **Y. Xu*,** Real-Option Based Planning of Utility-Owned Distributed Energy Resources for Islanded Distribution Networks in Southeast Asia," ***IEEE Trans. Smart Grid, 2024.***
2. R. Leng, Z. Li, and **Y. Xu*,** "Joint Planning of Utility-Owned Distributed Energy Resources in an Unbalanced Active Distribution Network Considering Asset Health Degradation," ***IEEE Trans. Smart Grid, 2024.***
3. Z. Li, **Y. Xu***, et al, "Optimal Deployment of Heterogeneous Energy Storage System in a Residential Multi-Energy Microgrid with Demand Side Management," ***IEEE Trans. Industrial Informatics, 2020.*** **– Web-of-Science Highly Cited Paper**
4. Z. Yan, T. Zhao, **Y. Xu***, et al, "Data-driven Robust Planning of Electric Vehicle Charging Infrastructure for Urban Residential Carparks," ***IET Gen. Trans. & Dist., 2020.***
5. Z. Li, **Y. Xu*,** et al, "Optimal Placement of Heterogeneous Distributed Generators in a Grid-Connected Multi-Energy Microgrid under Uncertainties," ***IET Renewable Power Generation, 2019.***
6. C. Zhang, **Y. Xu*,** Z.Y. Dong, et al, "Probability-Weighted Robust Optimization for Distributed Generation Planning in Microgrids," ***IEEE Trans. Power Syst., 2018.***
7. **Y. Xu**, Z.Y. Dong, K.P. Wong, et al, "Optimal capacitor placement to distribution transformers for power loss reduction in radial distribution systems," ***IEEE Trans. Power Systems, 2013.***

***Corresponding author**

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

NANYANG
TECHNOLOGICAL
UNIVERSITY
SINGAPORE

Thank You!