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

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0. Outline

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

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1 **REIDS Project**

Timescale

	Topic	Items	Timescale
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 Planning	Distributed generation units Energy storage systems	years ~ decades

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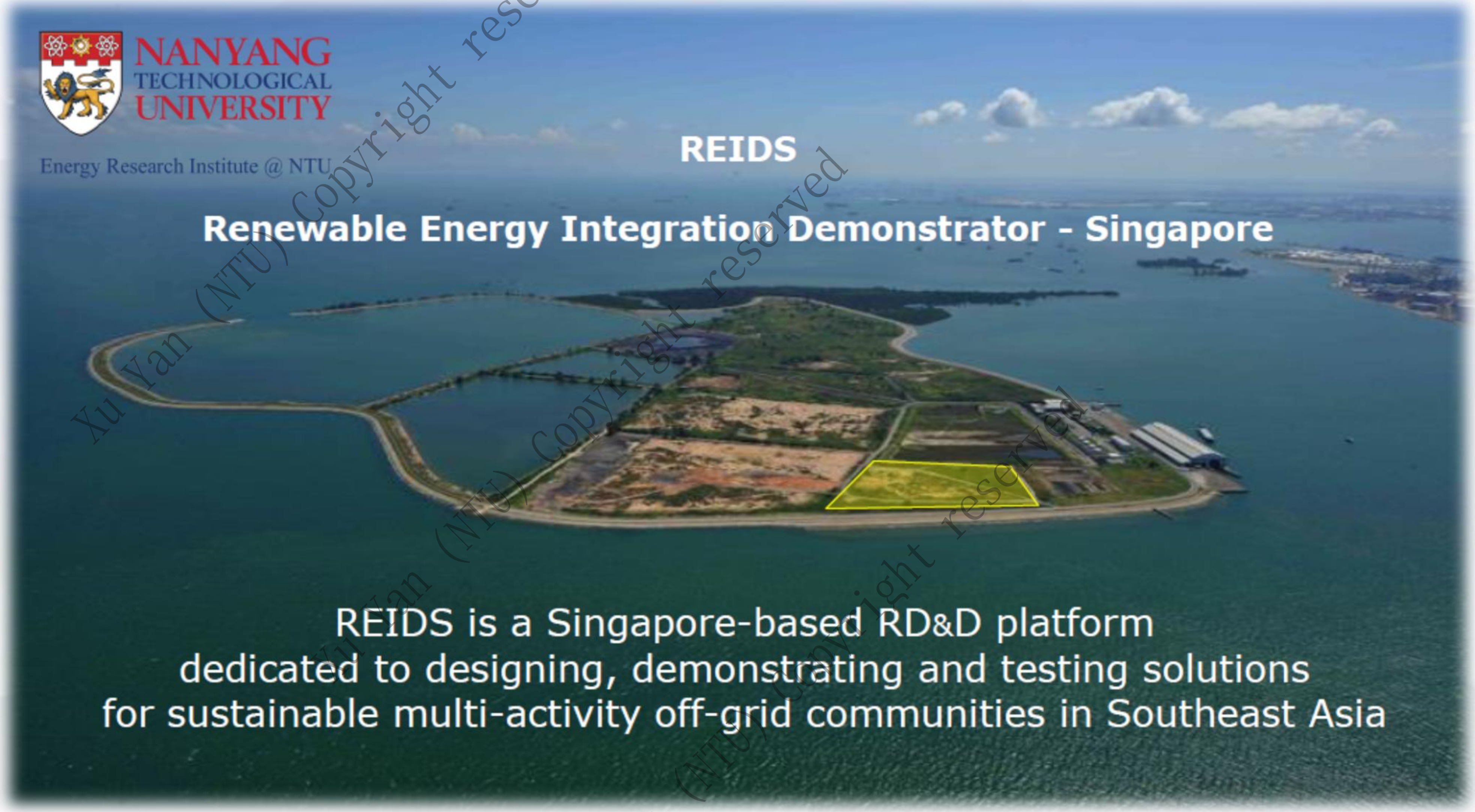
- *Renewable Energy Integration Demonstrator – Singapore* (REIDS)



REIDS

Renewable Energy Integration Demonstrator - Singapore

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

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

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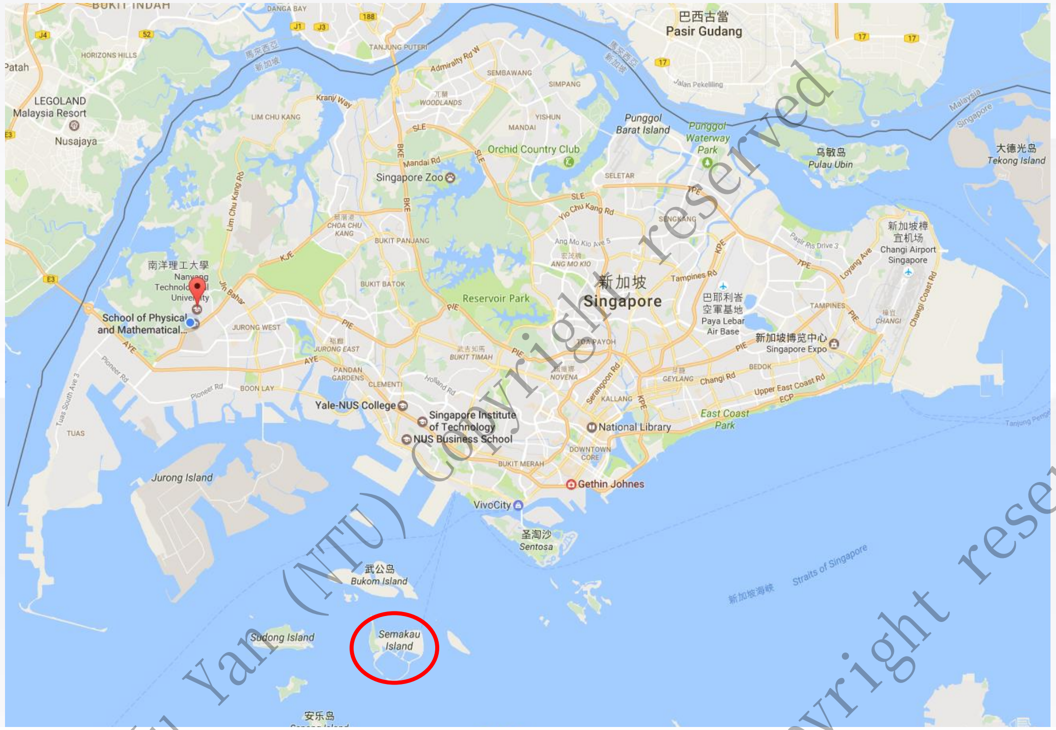

REIDS Partners

accenture
adaro POWER
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ENGIE
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NORTIS ENERGY
REC
Rolls-Royce
Schneider Electric
SEAS Sustainable Energy Association of Singapore
sembcorp
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Trinasolar
VDE RENEWABLES
Vestas

Research Leader

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Supporting Agencies

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

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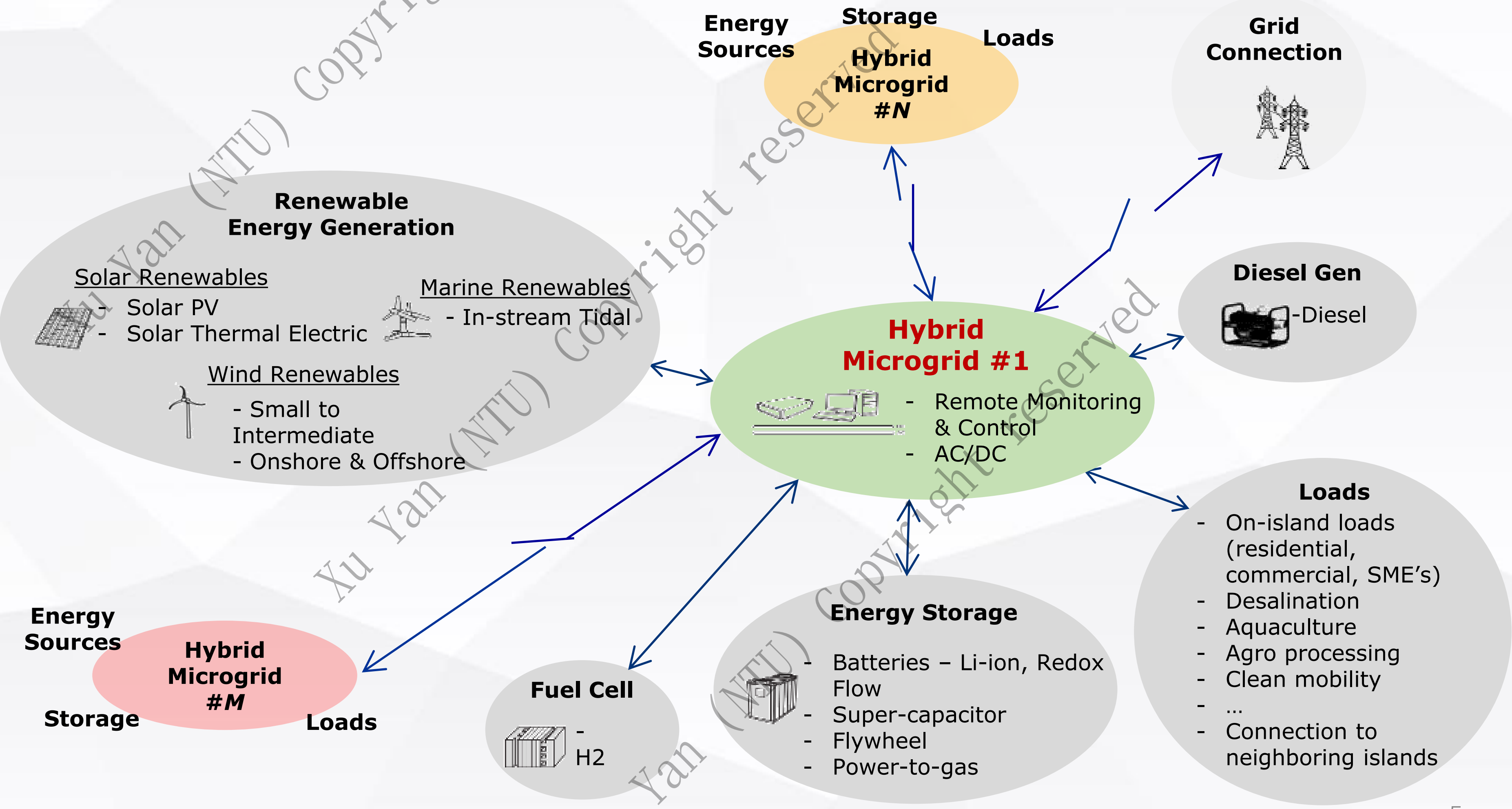
▪ REIDS Roadmap and Framework

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



Energy Sources **Storage** **Loads**
Hybrid Microgrid *#N*

Grid Connection

Renewable Energy Generation

Solar Renewables
- Solar PV
- Solar Thermal Electric

Marine Renewables
- In-stream Tidal

Wind Renewables
- Small to Intermediate
- Onshore & Offshore

Diesel Gen
-Diesel

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

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

Energy Sources **Storage** **Loads**
Hybrid Microgrid *#M*

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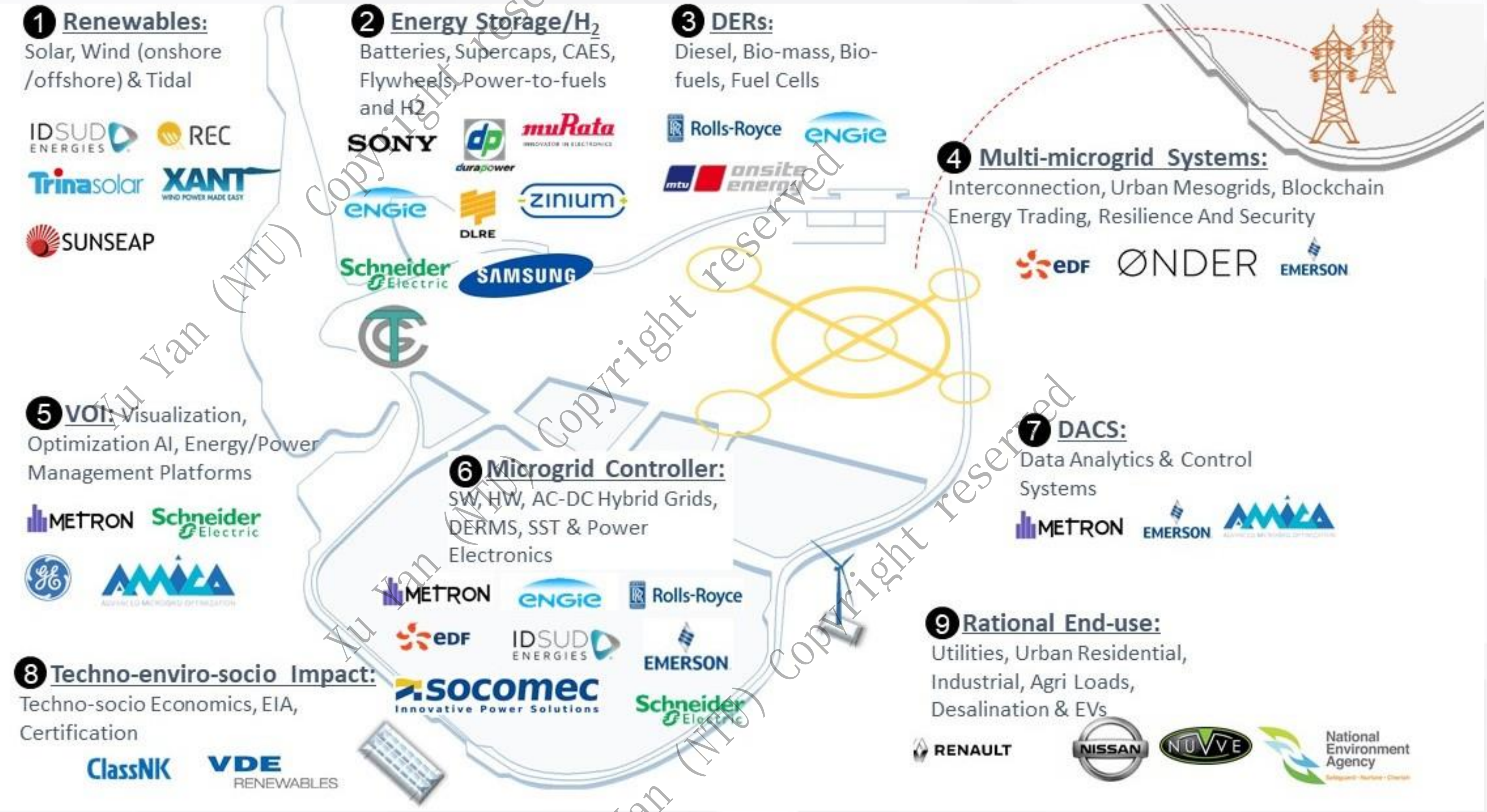
▪ Onboard Industry Collaborators



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

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

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

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

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

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

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

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

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

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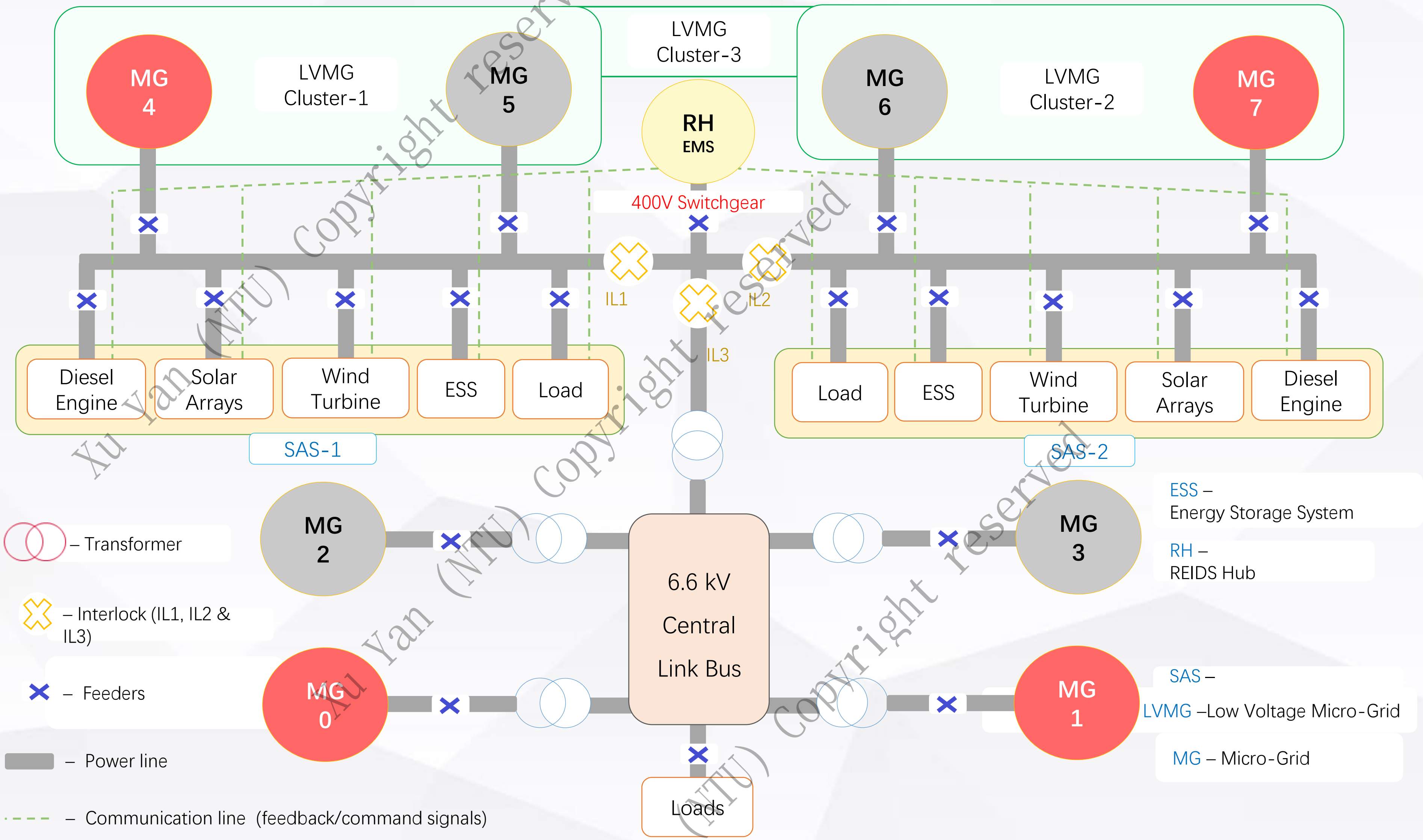
REIDS Electrical Structure



– Transformer

– Interlock (IL1, IL2 & IL3)

– Feeders

– Power line

– Communication line (feedback/command signals)

ESS – Energy Storage System

RH – REIDS Hub

SAS –

LVMG –Low Voltage Micro-Grid

MG – Micro-Grid

LVMG Cluster-1	Operating MG4 and /or MG5 with RH & shared assets set -1
LVMG Cluster-2	Operating MG6 and /or MG7 with RH & shared assets set -2
LVMG Cluster-3	Operating Clusters 1 & 2 with RH & shared assets set 1 & 2

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Onsite pictures

MG0 Test & Commissioning - March 2017

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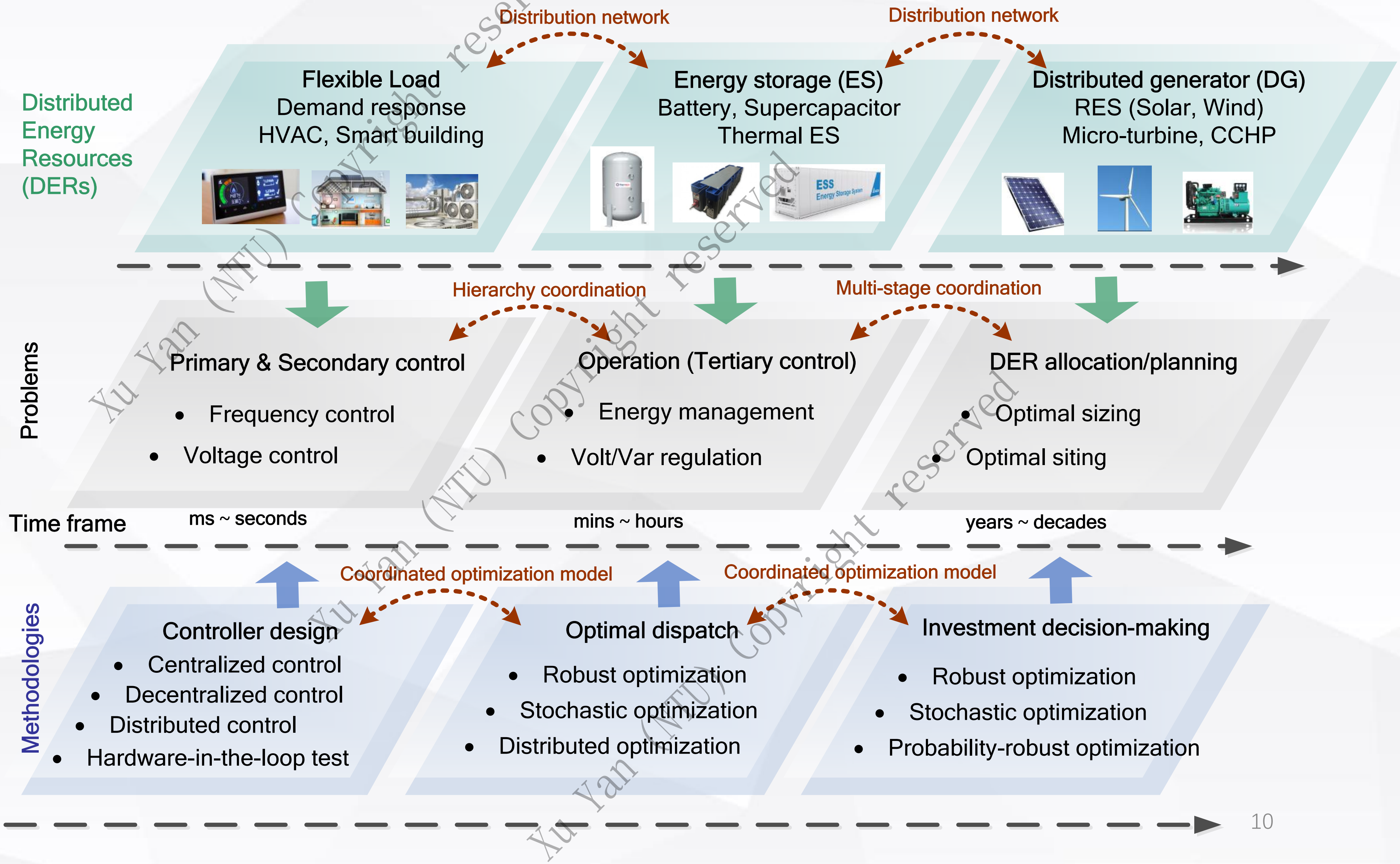
- Onsite pictures

▪ Our research Framework: system-level coordination of DERs



Distributed Energy Resources (DERs)

Distribution network

Distribution network

Flexible Load
Demand response
HVAC, Smart building

Energy storage (ES)
Battery, Supercapacitor
Thermal ES

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

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

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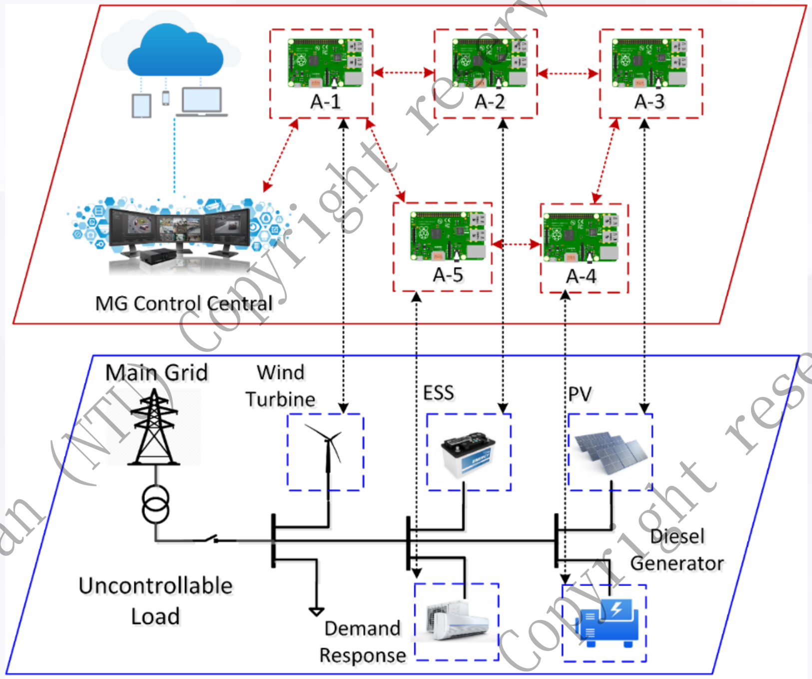
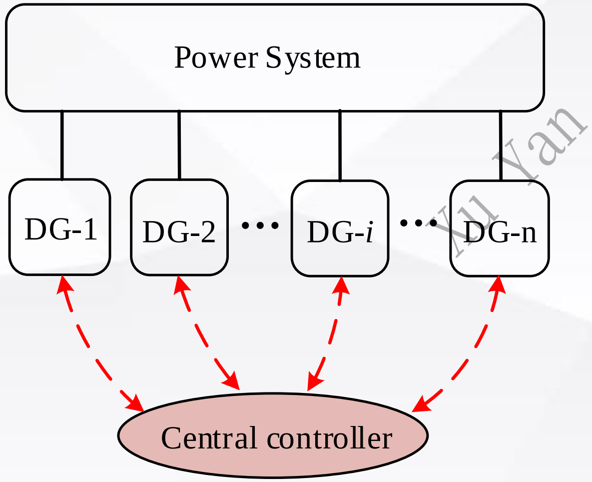
Control of DERs in Microgrids

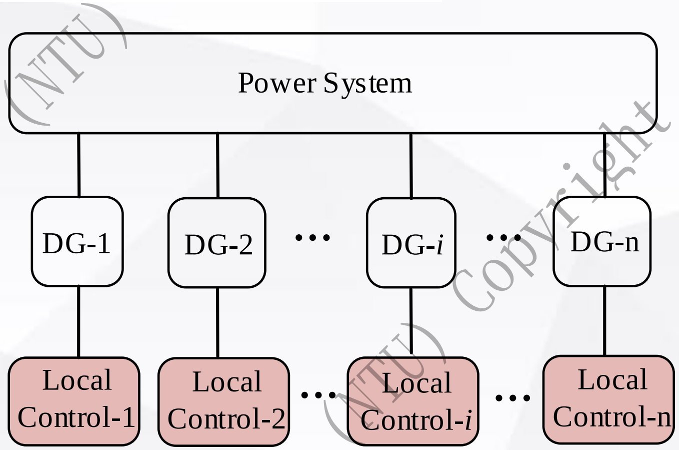


1. **Islanded mode:**
   - Distributed control (event-triggered, finite-time)
   - Hardware-in-the-Loop (Hil) validation

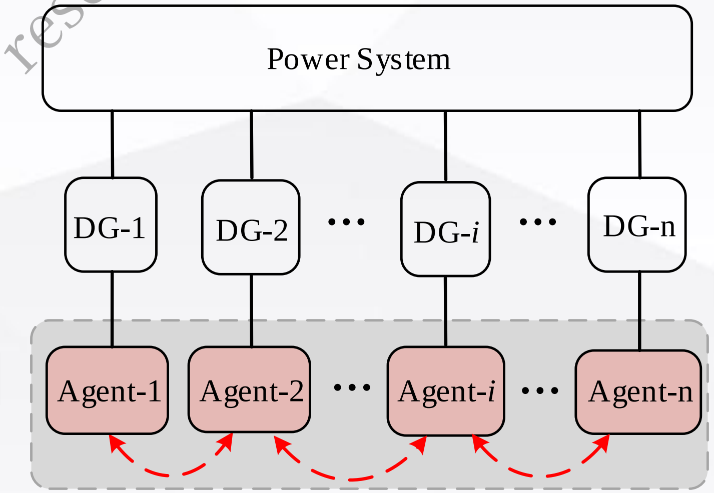
2. **Grid-connected mode:**
   - DER for *f* support
   - DER for *V* support



(a) Centralized control



(b) Decentralized control



(c) Distributed control

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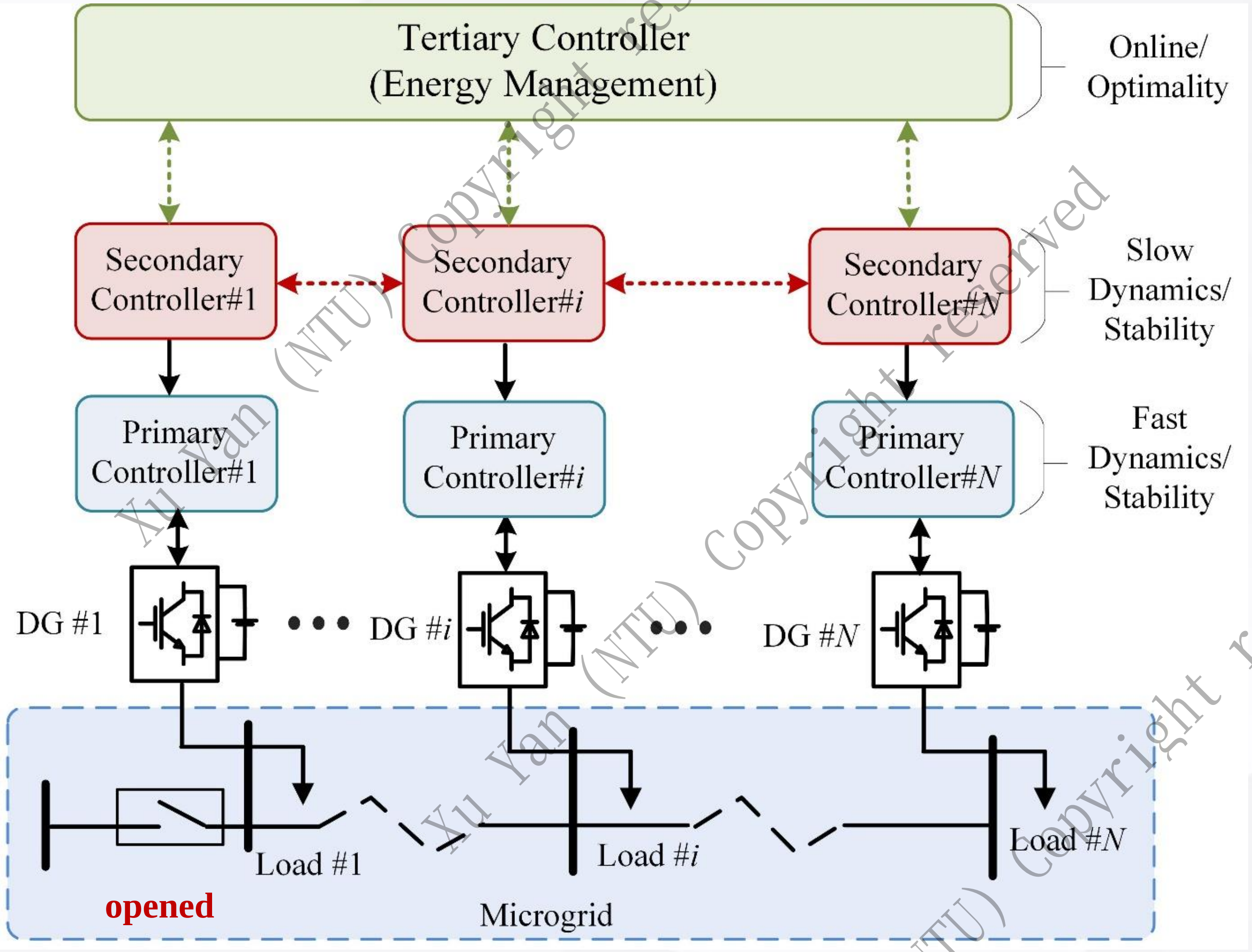
Hierarchical control of an islanded microgrid



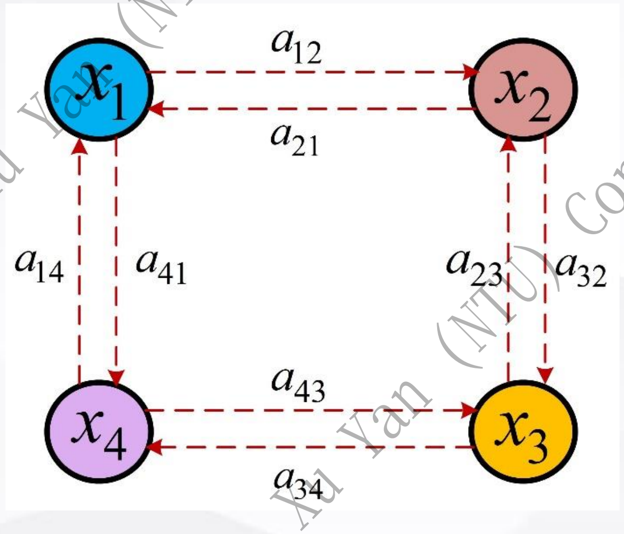
Hierarchical control framework of islanded microgrids

- ➢ 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

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

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

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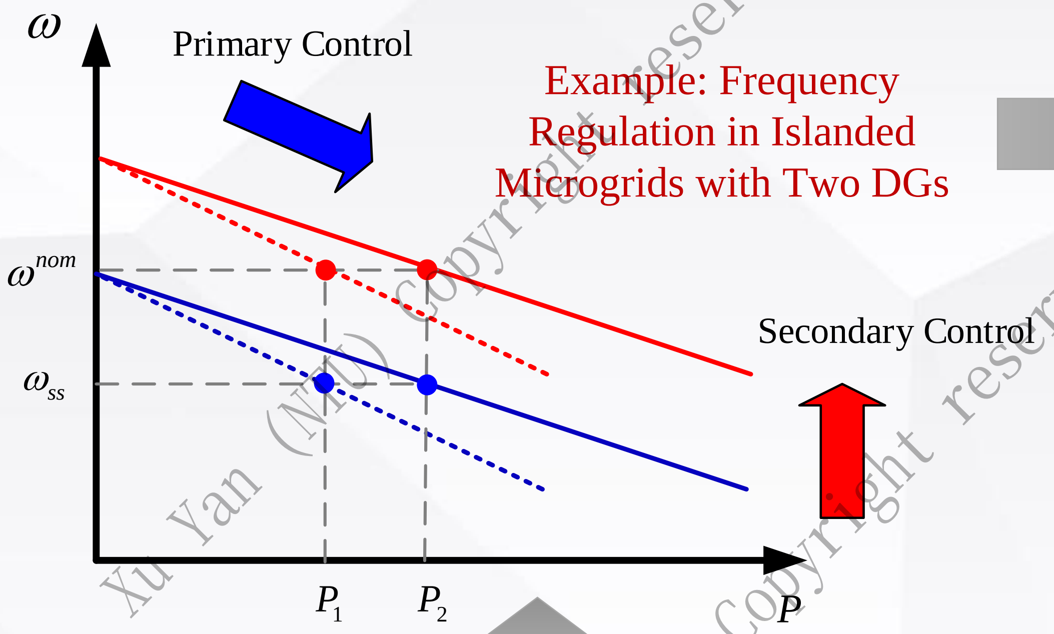
Secondary Controller Design – Principle



Example: Frequency Regulation in Islanded Microgrids with Two DGs

Droop control

$$\omega_i = \omega_i^{\mathrm{nom}} - m_i^P P_i$$

$$V_i = V_i^{\mathrm{nom}} - m_i^Q Q_i$$

Taking Derivative

$$\dot{\omega}_i = \dot{\omega}_i^{\mathrm{nom}} - m_i^P \dot{P}_i$$

$$\dot{V}_i = \dot{V}_i^{\mathrm{nom}} - m_i^Q \dot{Q}_i$$

Problem formulation

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

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

Apply consensus control rule

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

$$u_i^{p} = \sum_{j=1}^{N} a_{ij}(m_j^P P_j - m_i^P P_i)$$

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

$$u_i^{Q} = \sum_{j=1}^{N} a_{ij}(m_j^Q Q_j - m_i^Q Q_i)$$

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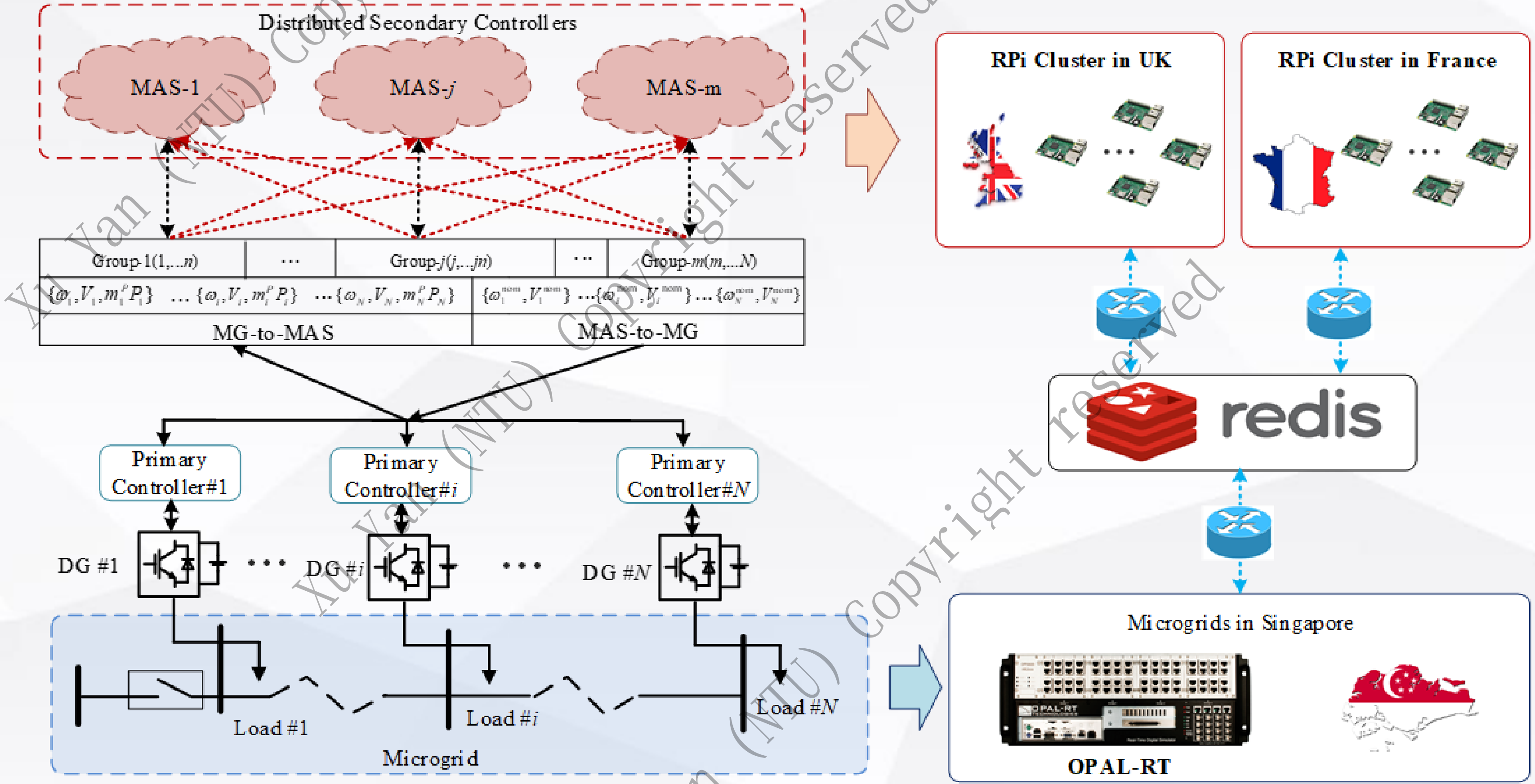
- Cross-national hardware-in-the-loop (HiL) testbed

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.

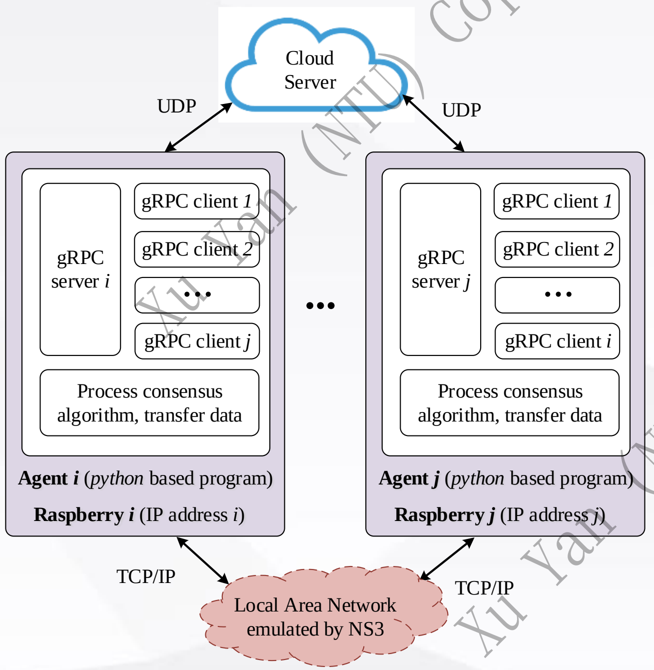


Y. Wang, T. L. Nguyen, M. H. Syed, **Y. Xu***. "A Distributed Control Scheme of Microgrids in Energy Internet and Its Multi-Site Implementation." ***IEEE Transactions on Industrial Informatics*, 2020.**

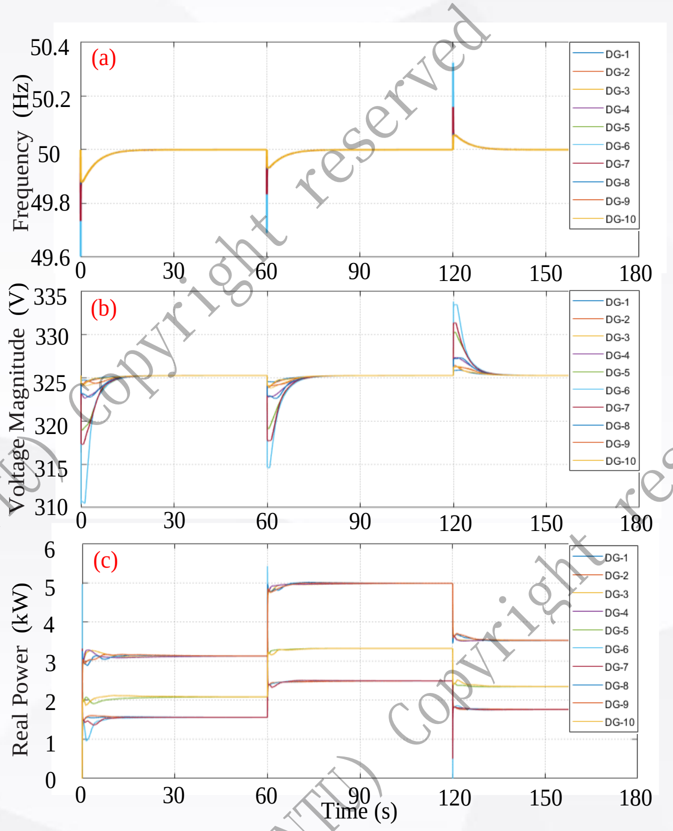
HiL Validation Results – Controller performance

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

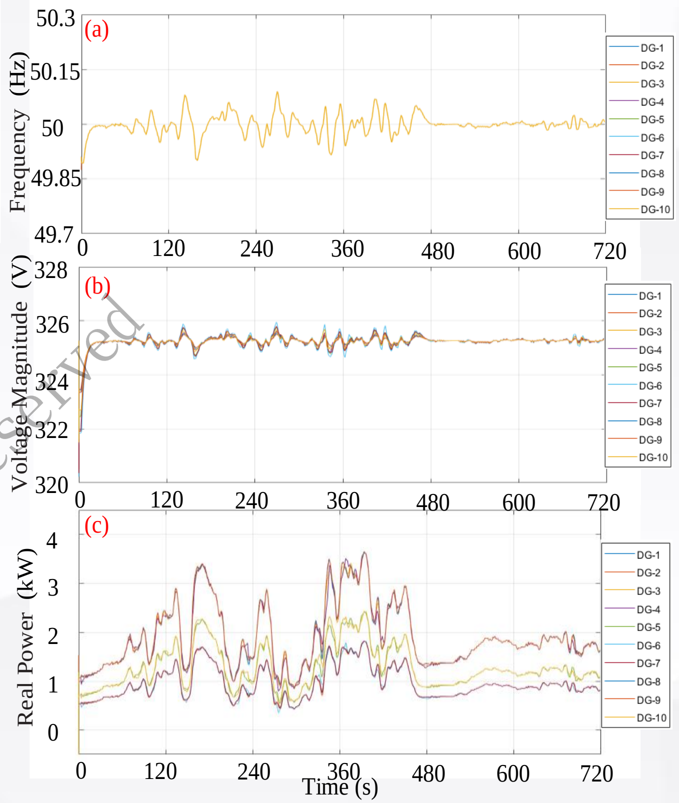
Structure of each agent based on gRPC



a) step load change case



b) Real PV and load profile case



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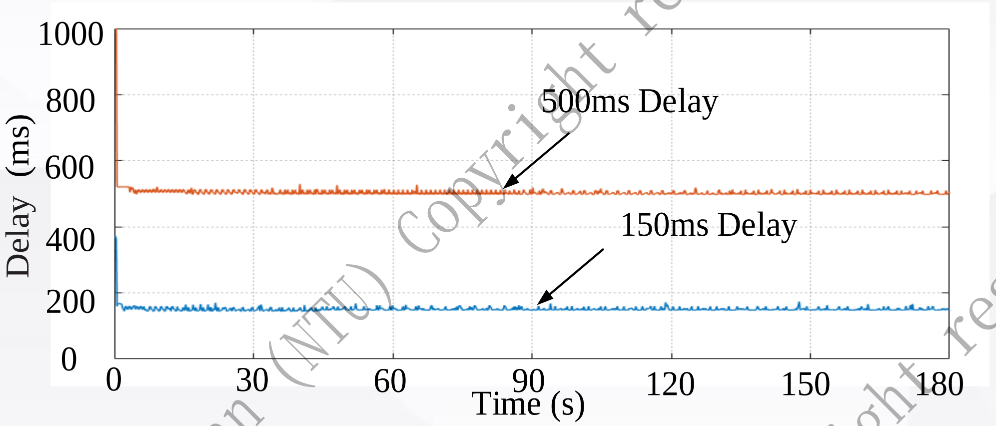
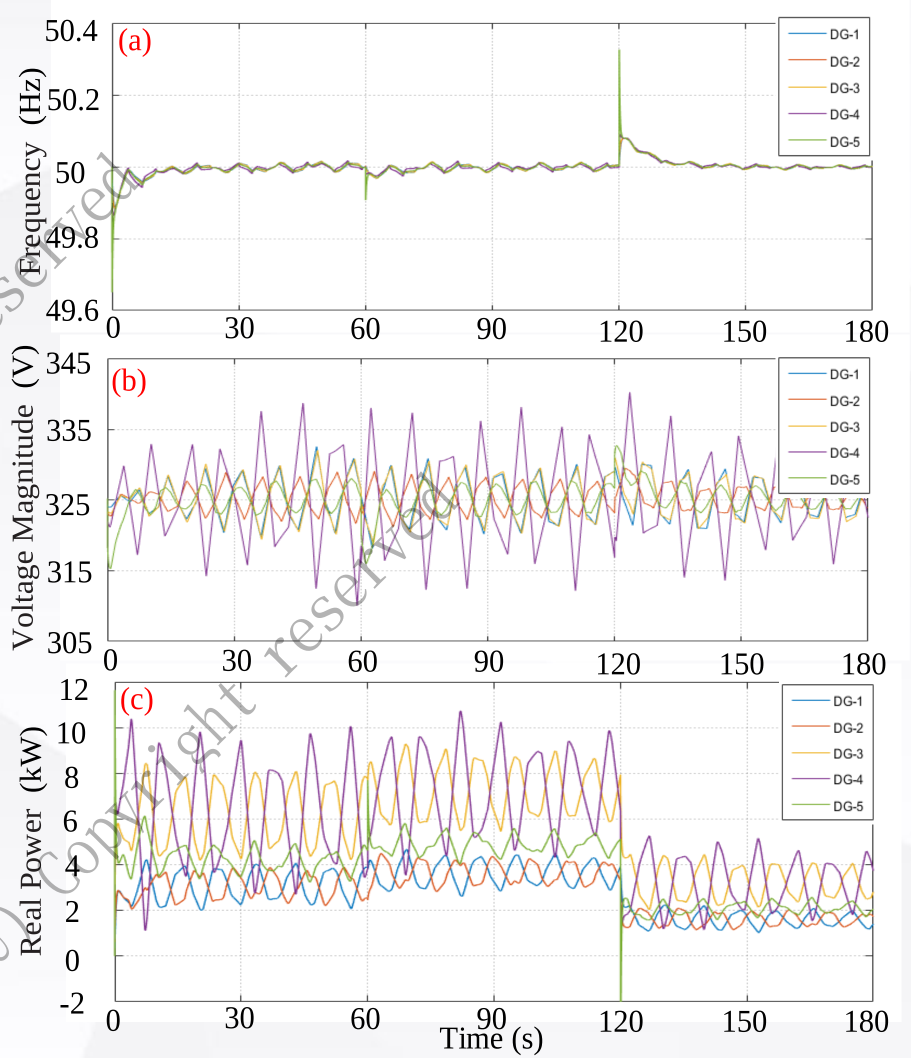
▪ HiL Validation Results – Communication delay

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

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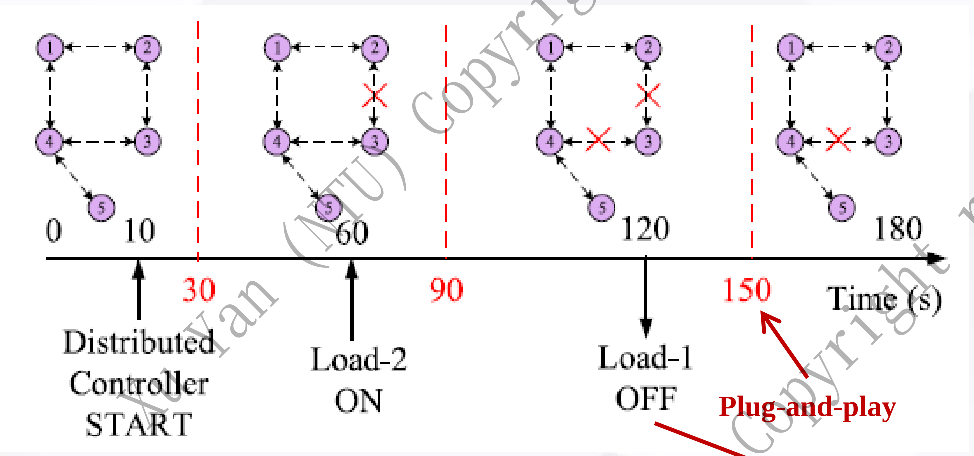
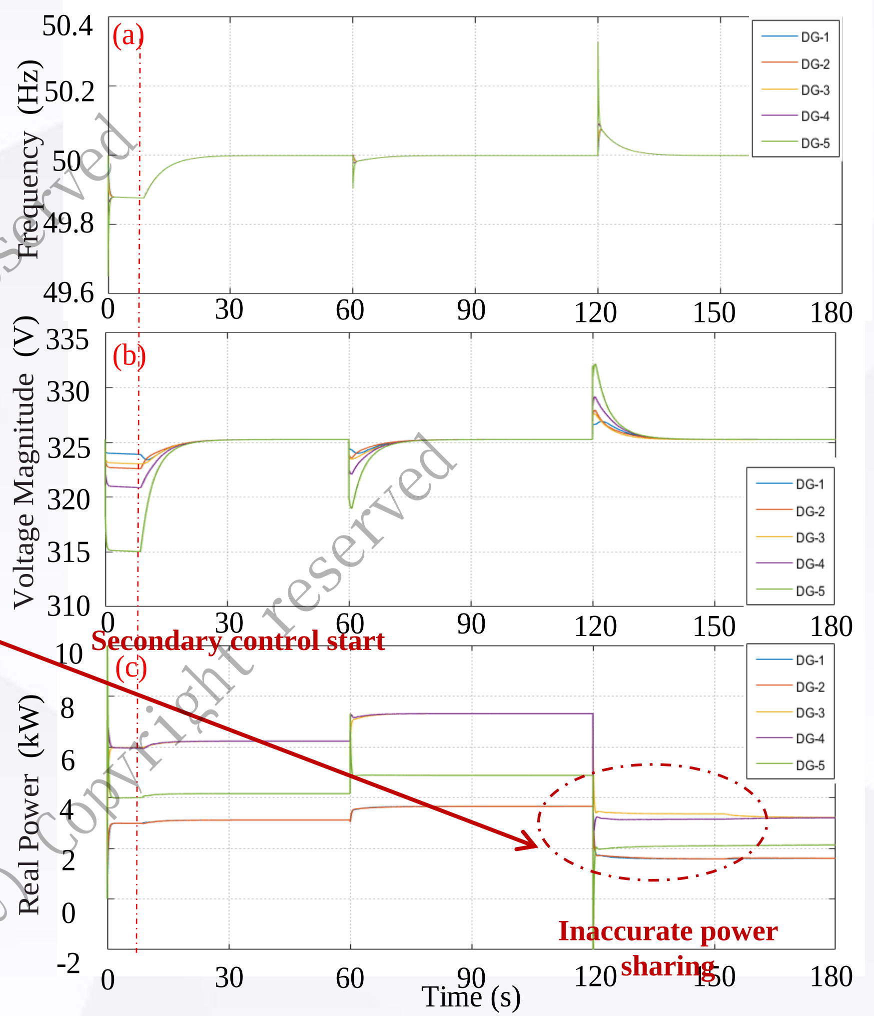
HiL Validation Results – Communication failures

Communication failures



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



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

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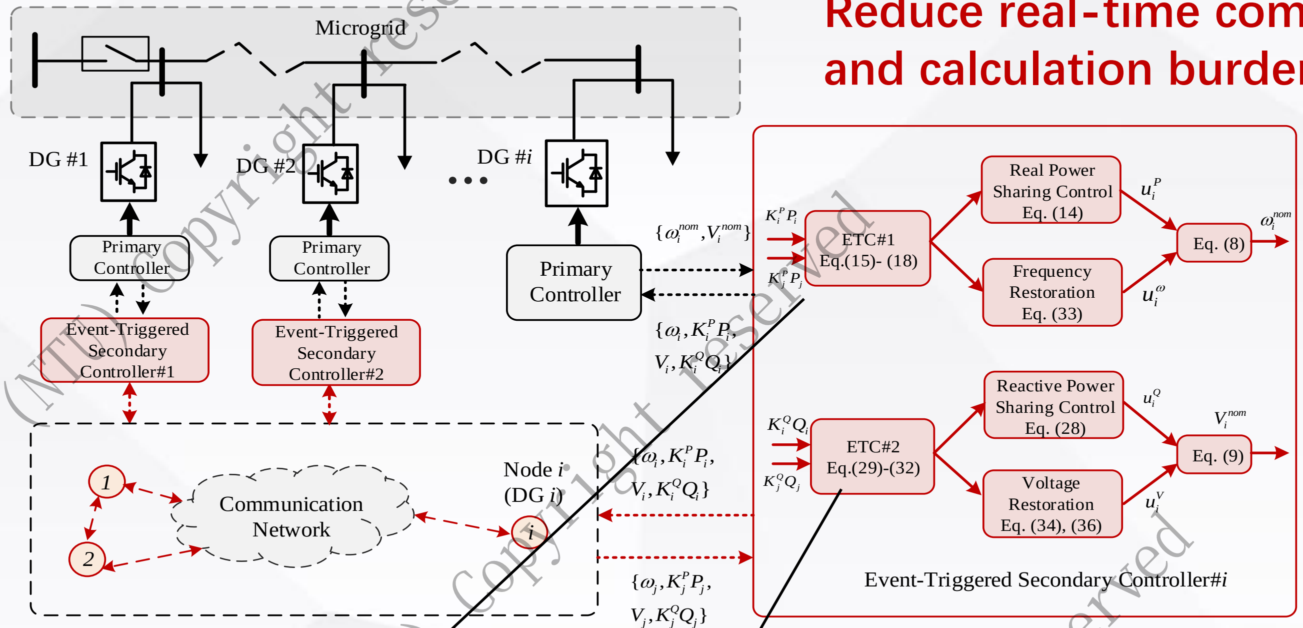
▪ Event-Triggered Distributed Control of Islanded Microgrids

Reduce real-time communication and calculation burden



Event-Trigger Condition for *f* and P:

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

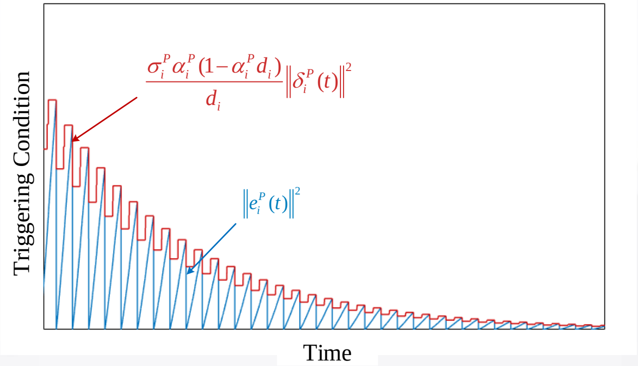
$$t_k^{Pi} = \inf\{t > t_{k-1}^{Pi} \mid f_i^P(t) = 0\}$$

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**.

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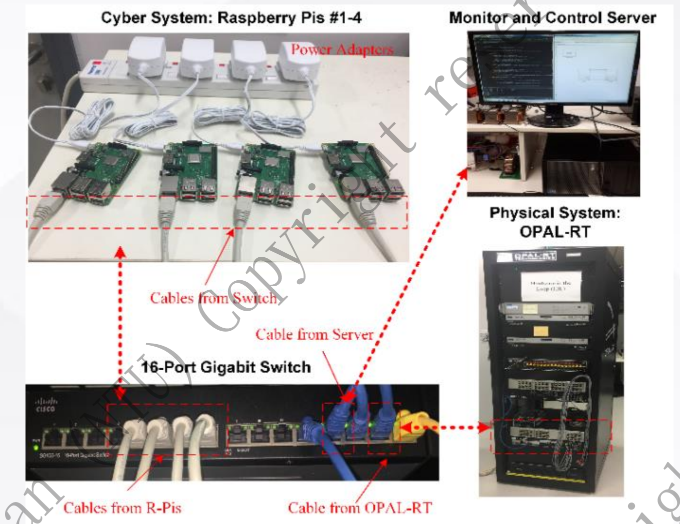
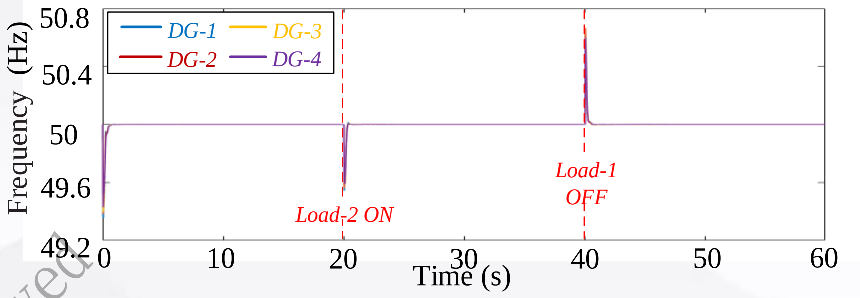
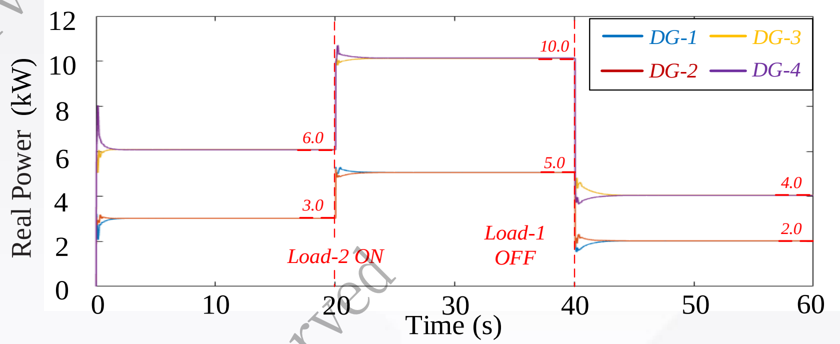
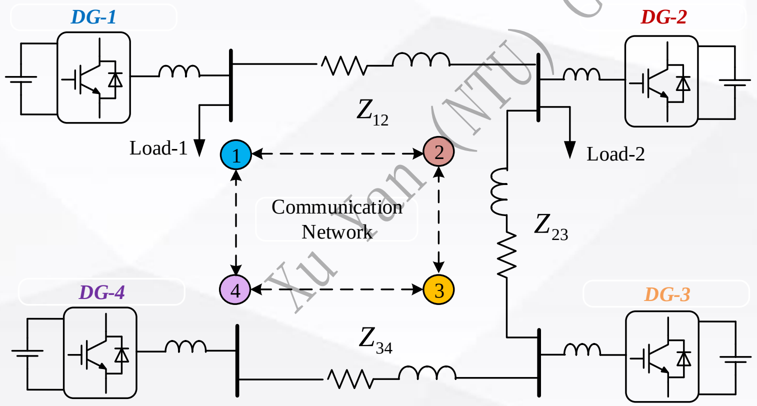
▪ Controller Hardware-in-the-Loop (CHil) Test



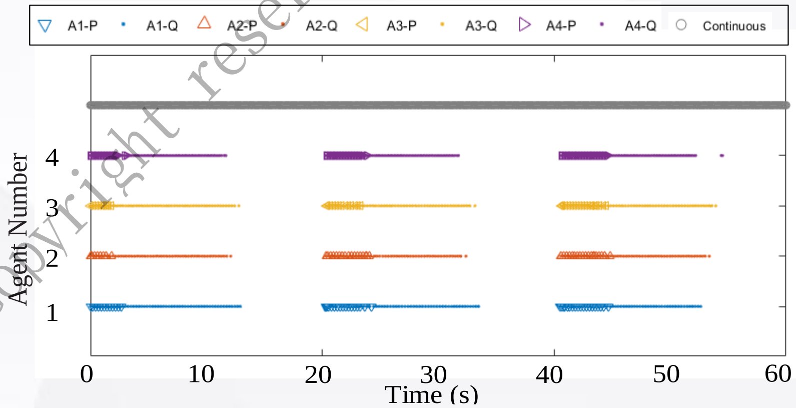
HiL testbed with Raspberry Pi and OPAL-RT







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**.

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

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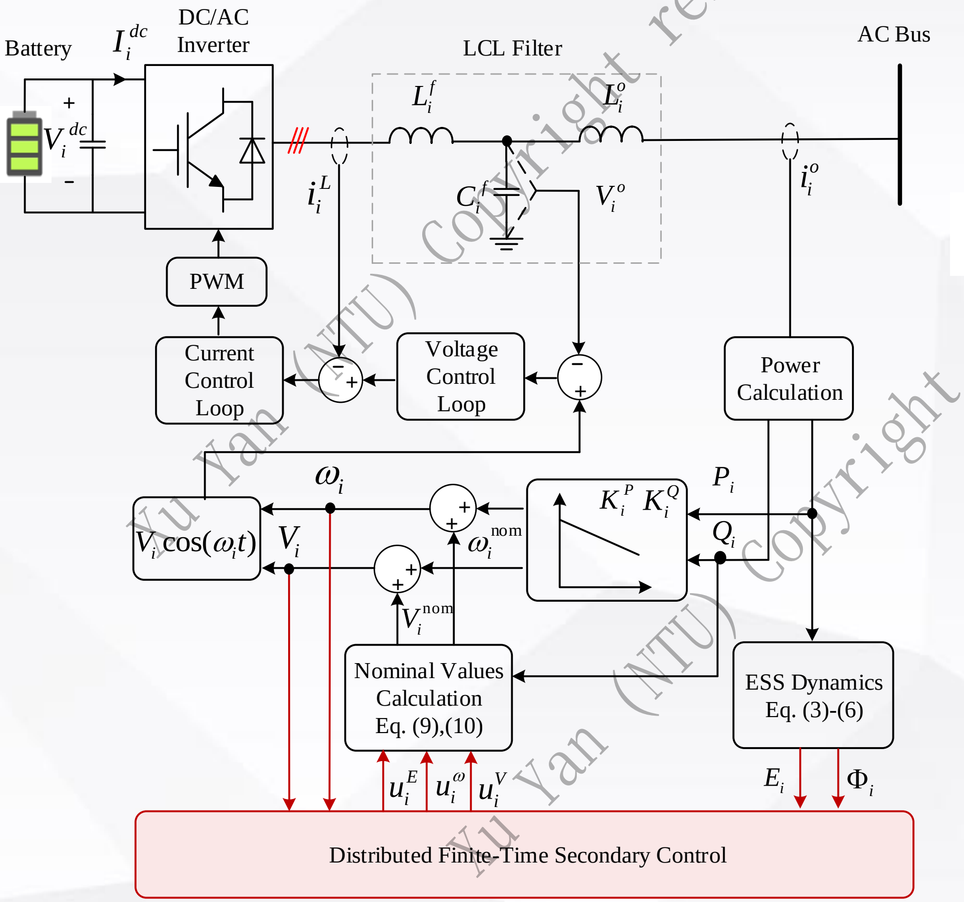
Finite-Time Distributed Control of Energy Storage Systems



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

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

$$\Phi_i(t) = \Phi_j(t), E_i(t) = E_j(t) \forall t \geq T^E$$

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

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

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.**

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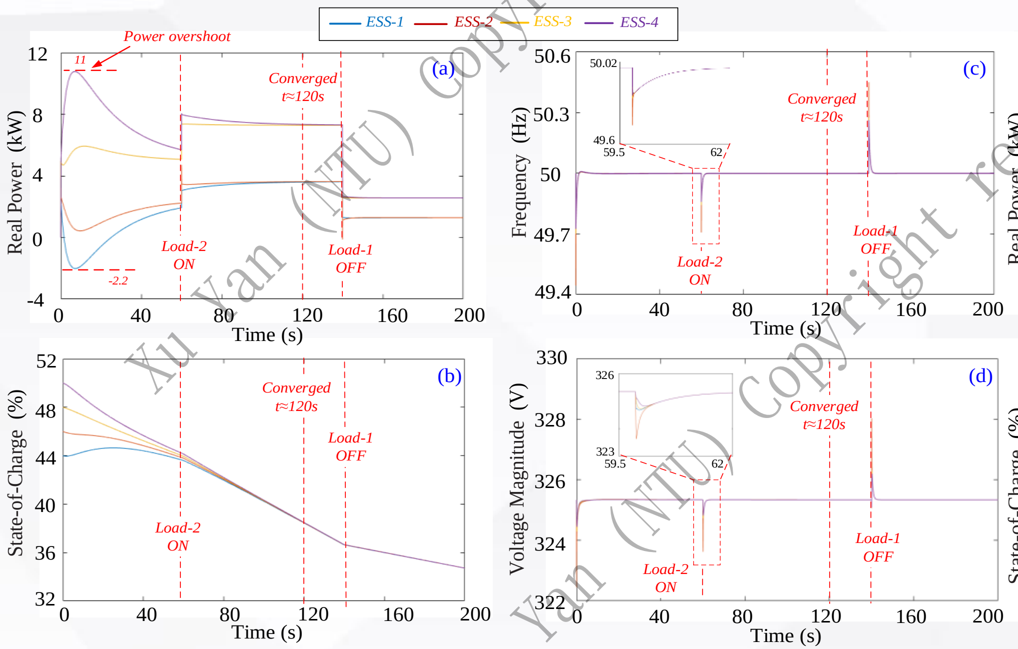
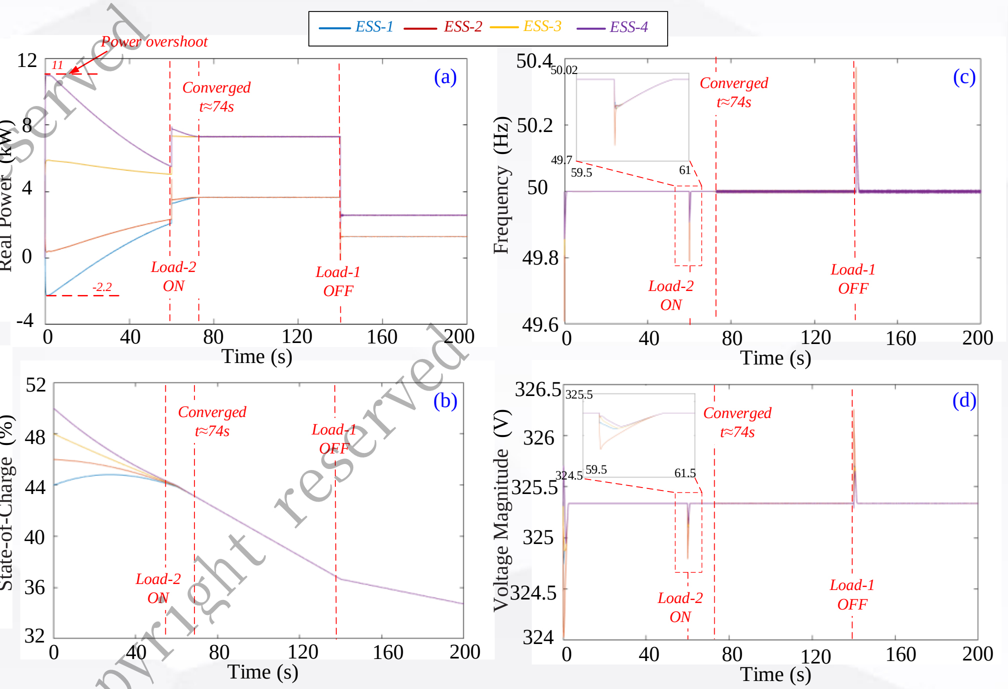
▪ Finite-Time Distributed Control of Energy Storage Systems

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.***

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Grid-connected mode of Microgrids (DER support)

Voltage control support:

mitigate voltage deviation

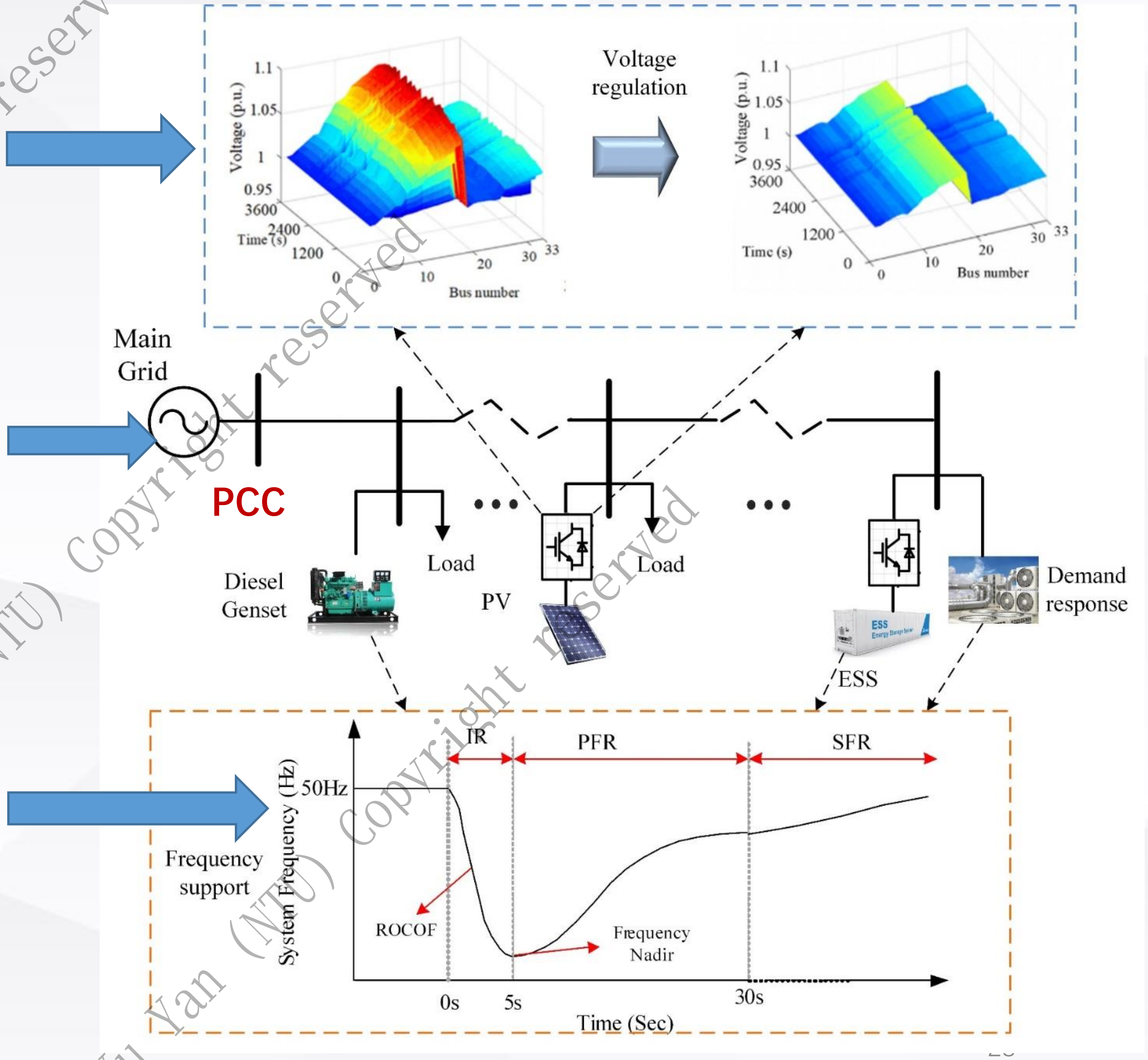
(seconds to minutes)

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

Frequency control support:

mitigate frequency variation

(ms to seconds)



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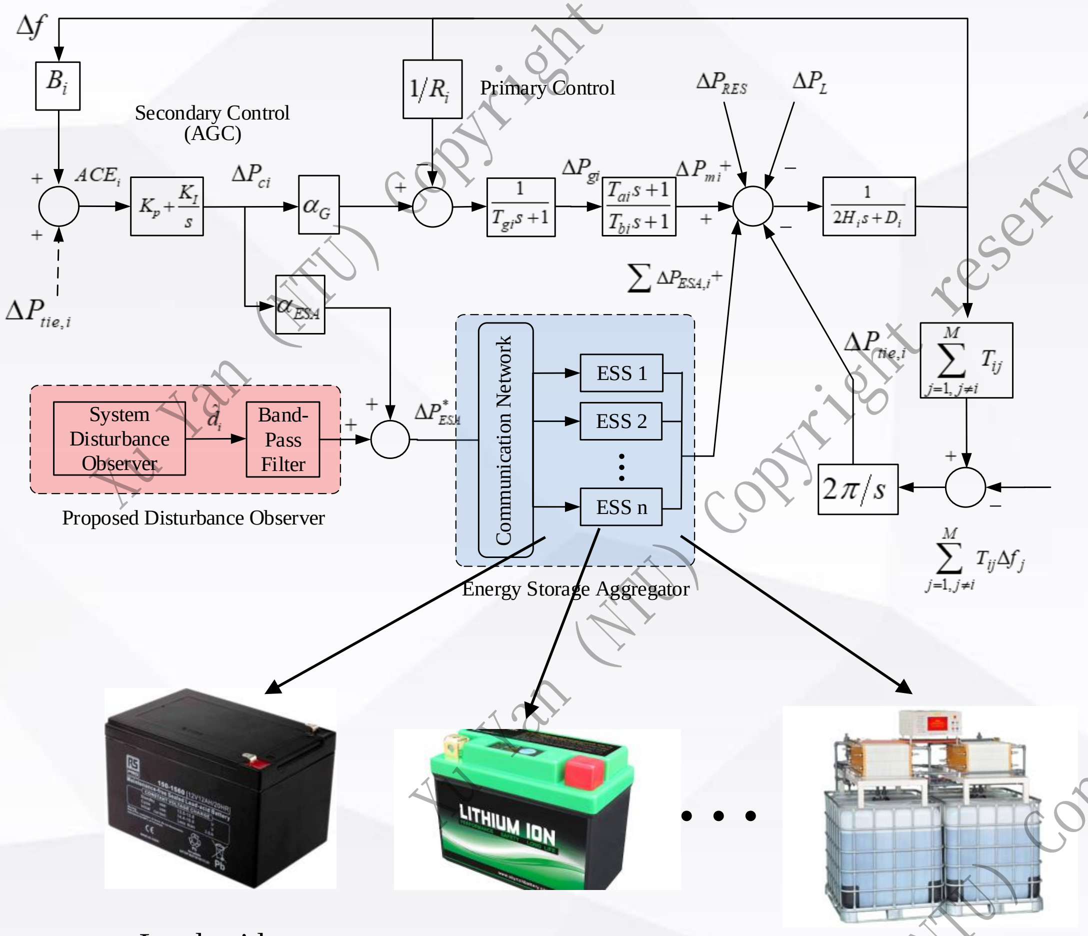
▪ Frequency Support from Aggregated Energy Storage

Proposed load frequency control (LFC) framework



Lead acid battery

Lithium ion battery

Vanadium redox battery

LFC with primary control

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

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

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

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

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,

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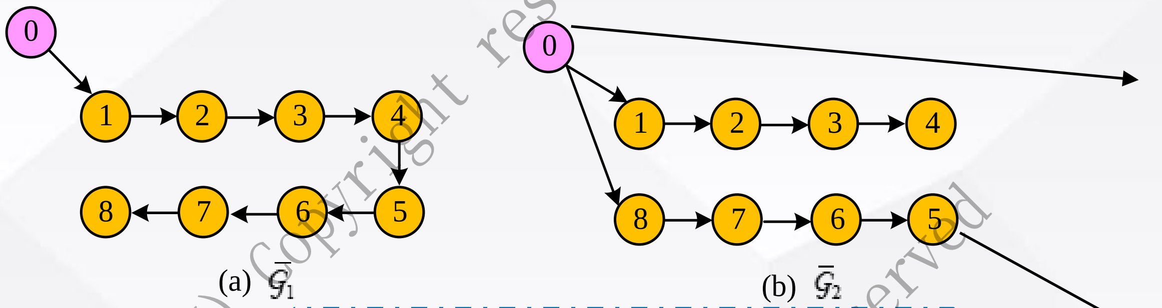
▪ Frequency Support from Aggregated Energy Storage

Communication topologies of ESSs



Leader model

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

LFC power reference

ESS model (follower)

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

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 Law

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

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

Control Objectives: achieve LFC power reference with consensus SOC

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

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

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,**

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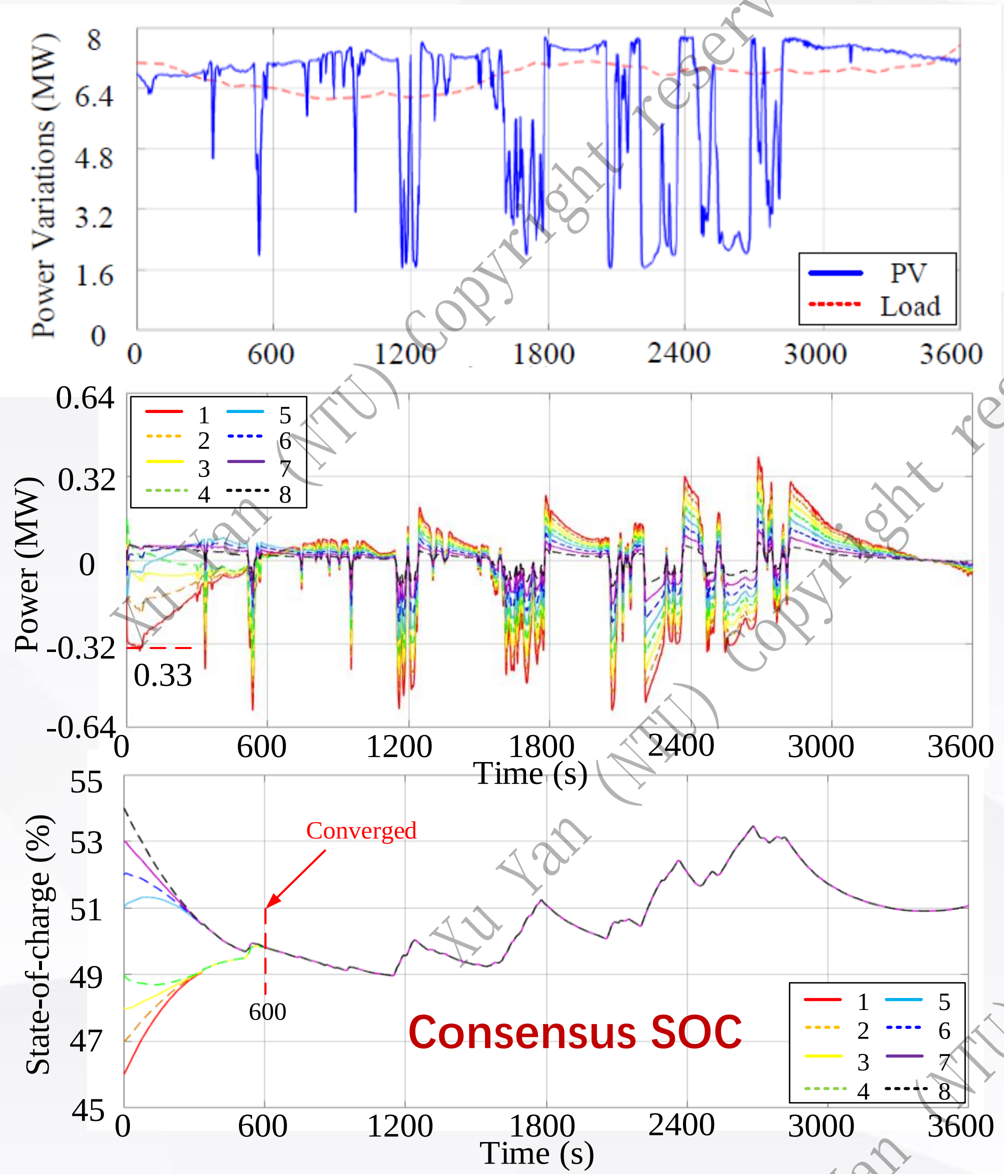
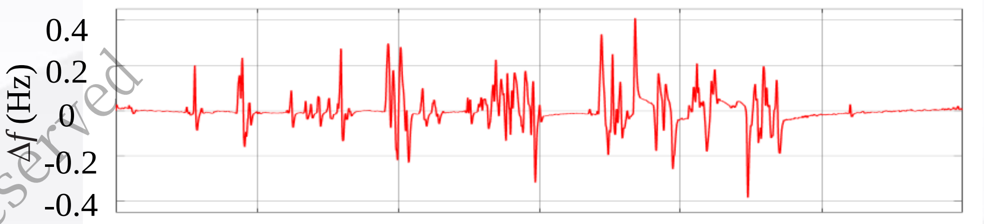
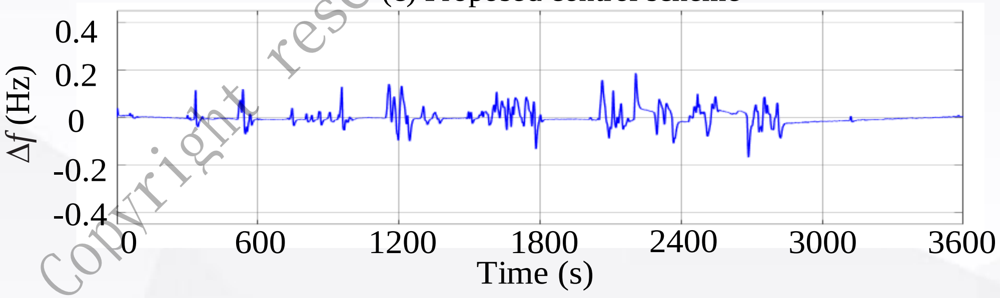
- Simulation Results



Consensus SOC


(a) Conventional LFC scheme


(b) LFC with ESA w/o observer


(c) Proposed control scheme

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.**

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Thermostatically Controlled Loads (TCLs) for frequency support

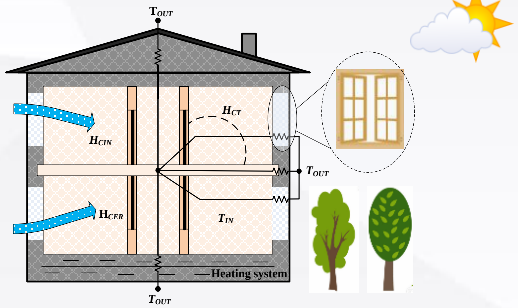
Temperature dynamics of TCL:

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

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:

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

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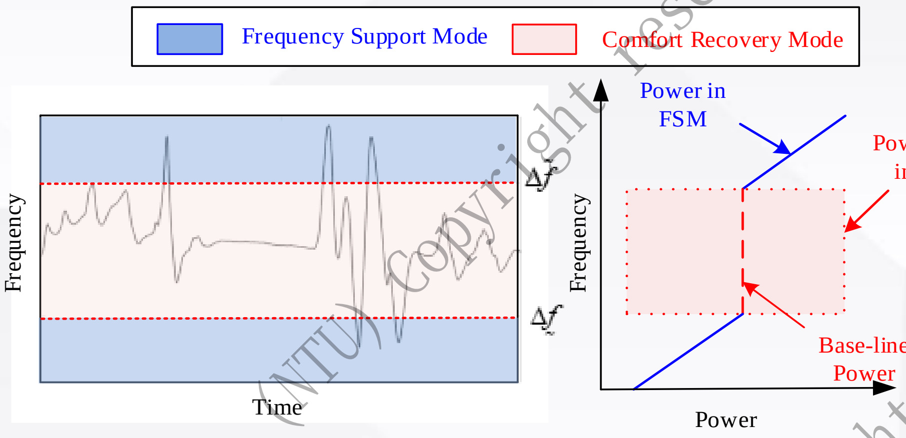
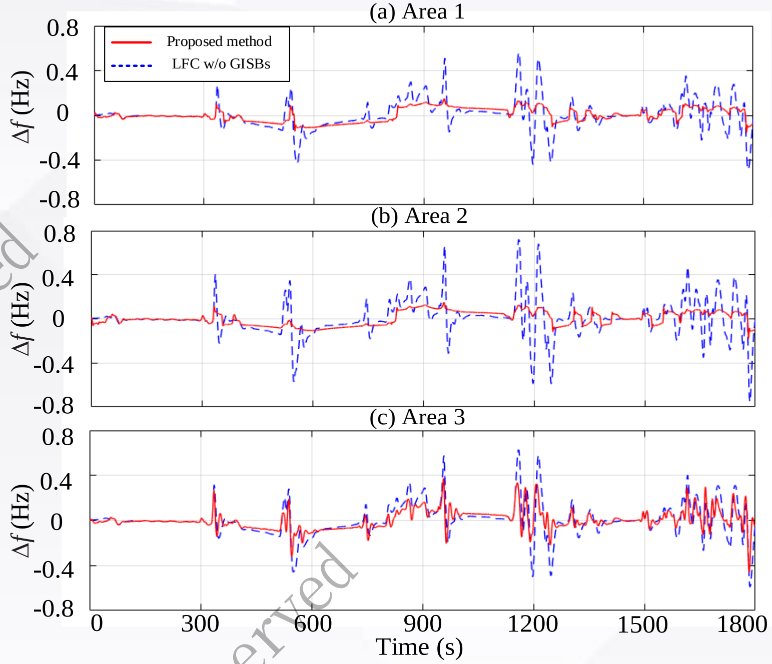
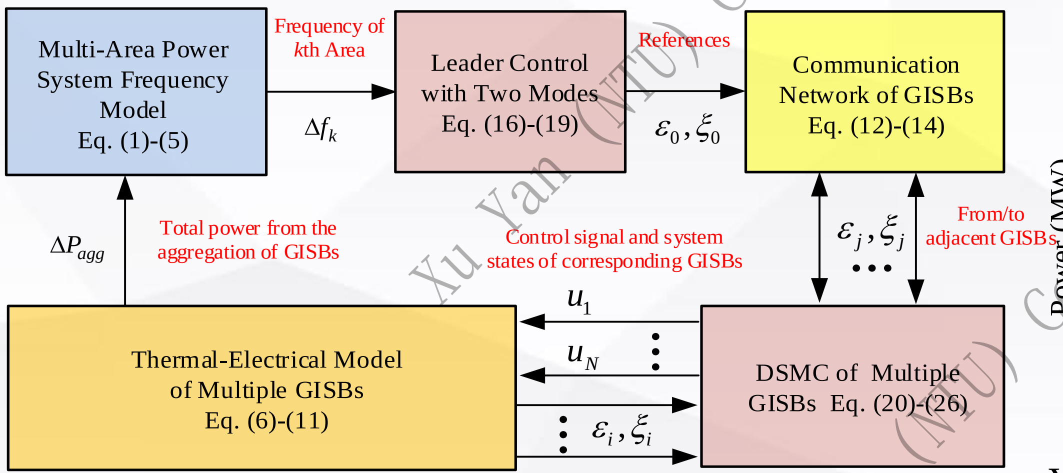
Thermostatically Controlled Loads (TCLs) for frequency support



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





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

Frequency of kth 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

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

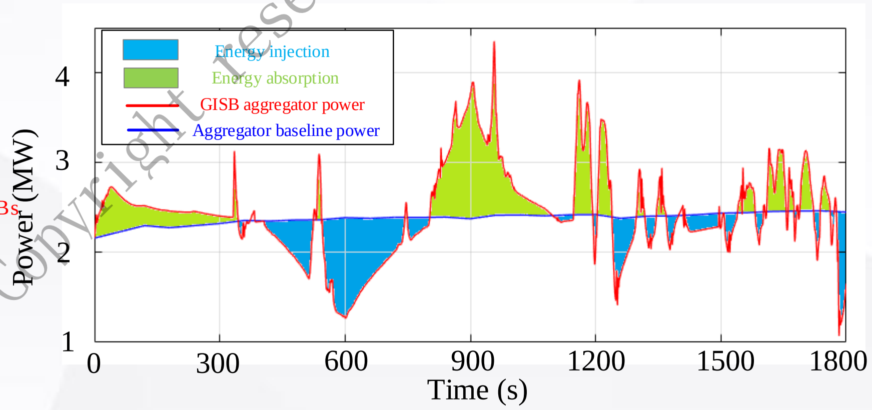
u_1

u_N

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.**

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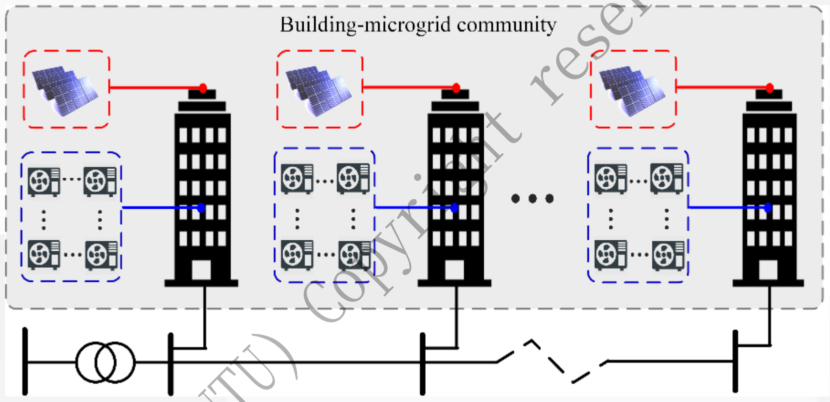
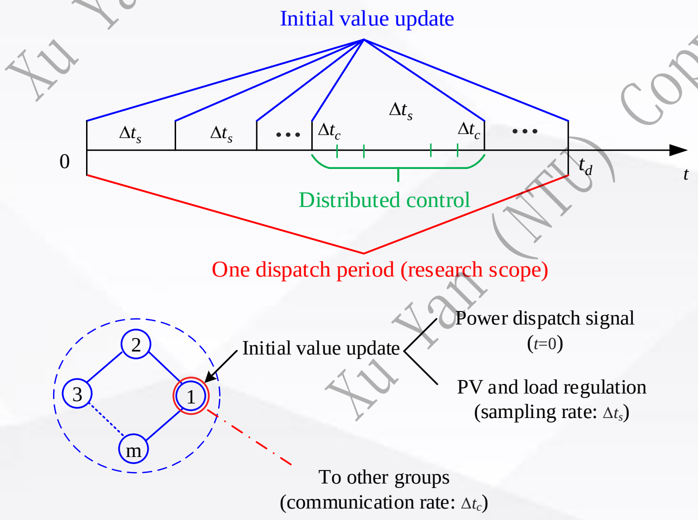
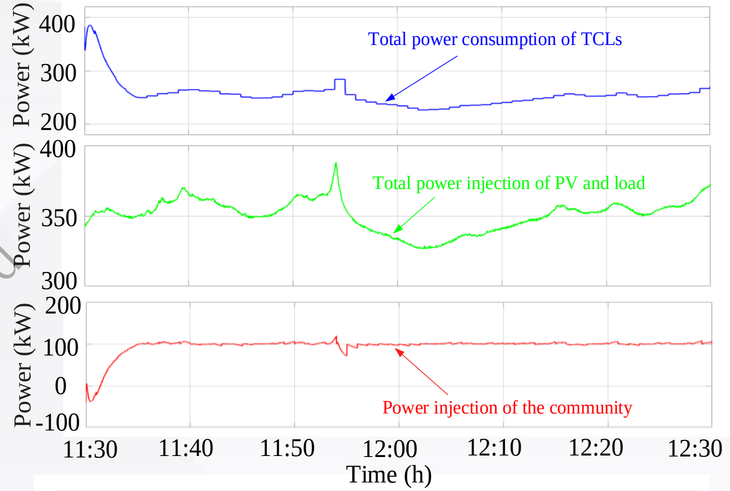
Ancillary Service Support from Smart Building Community

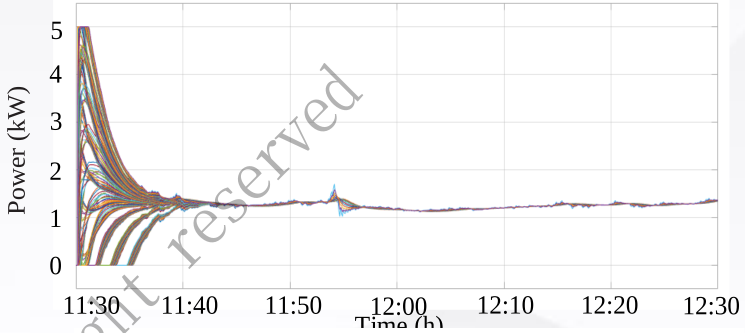


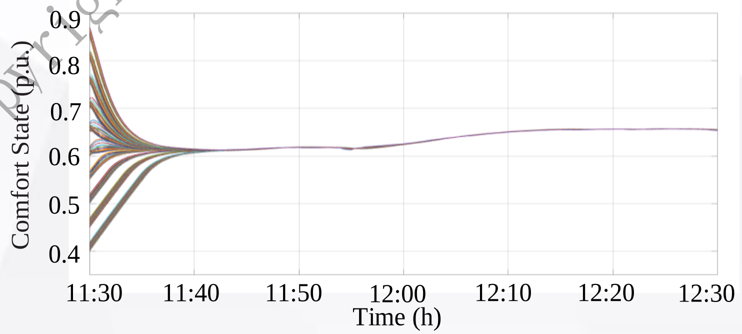
Smart building community: TCLs+PVs



Initial value updating scheme



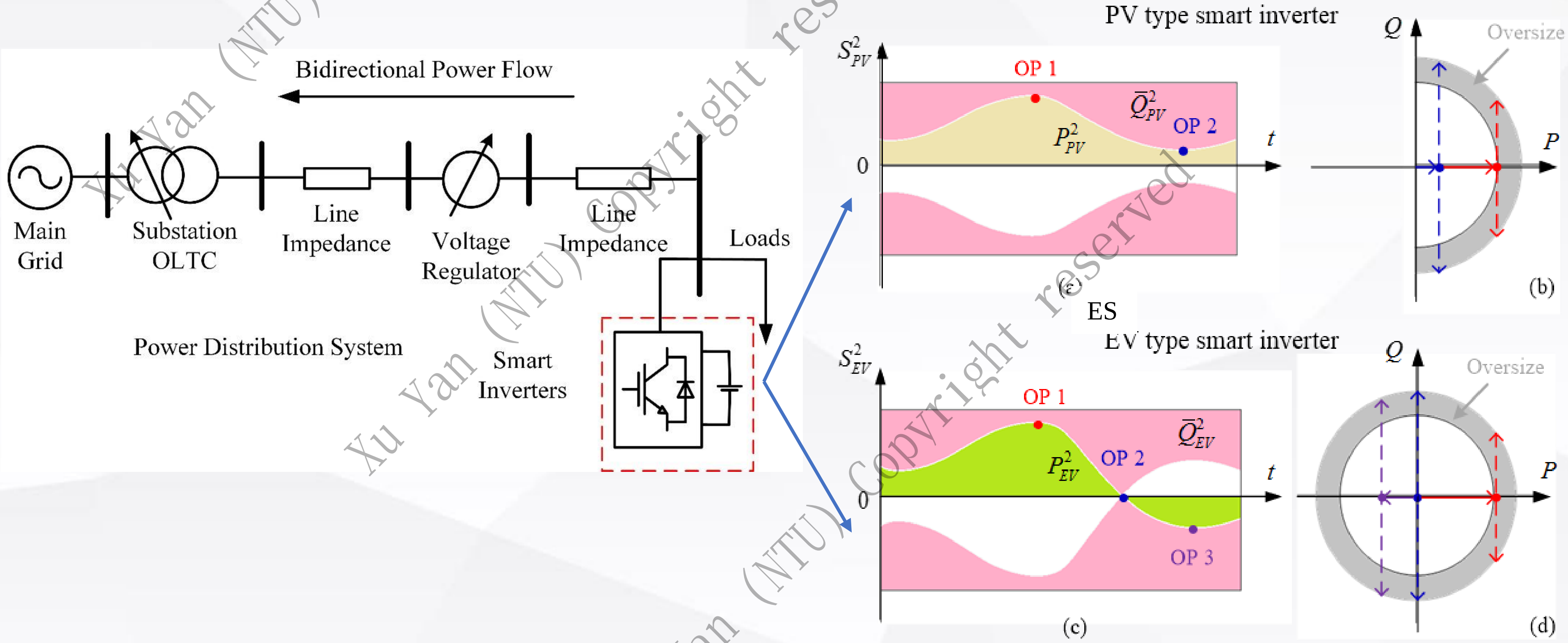




Y. Wang, Y. Tang, **Y. Xu***, et al, “A Distributed Control Scheme of Thermostatically Controlled Loads for Building-Microgrid Community,” ***IEEE Trans. Sustainable Energy*, 2019**.

- 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



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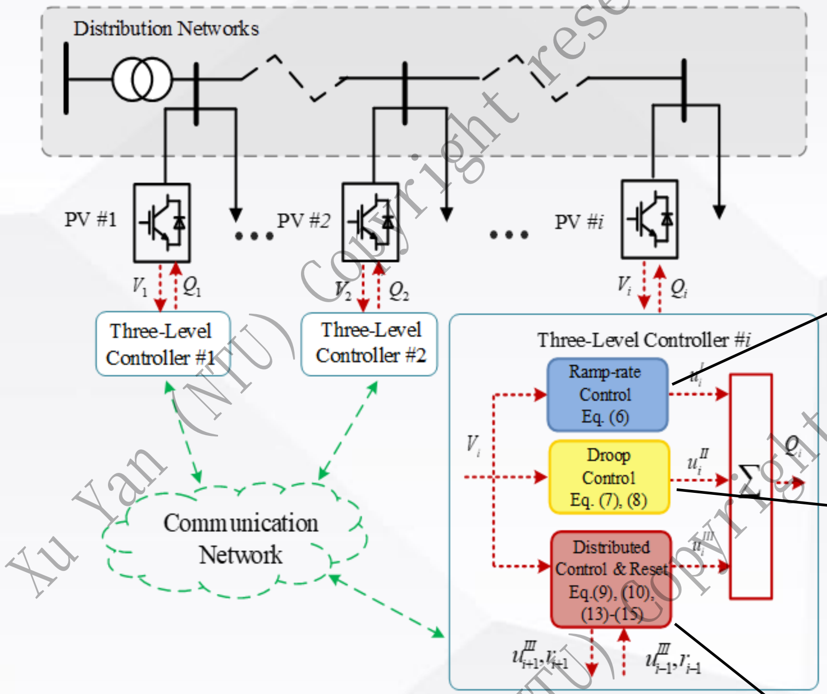
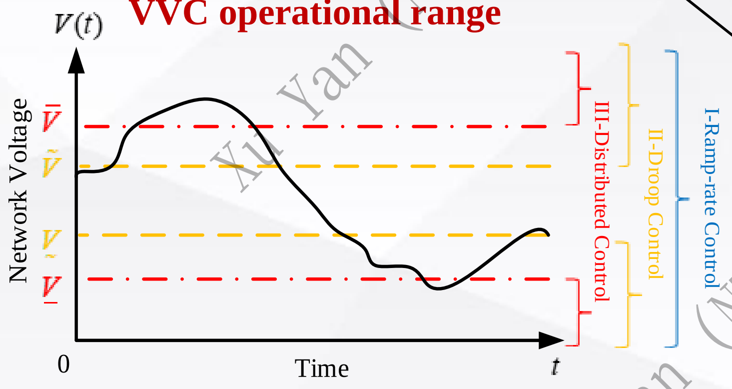
Real-Time Coordinated Voltage/Var Control Controller




VVC operational range

Controller design:

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

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

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

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

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

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**.

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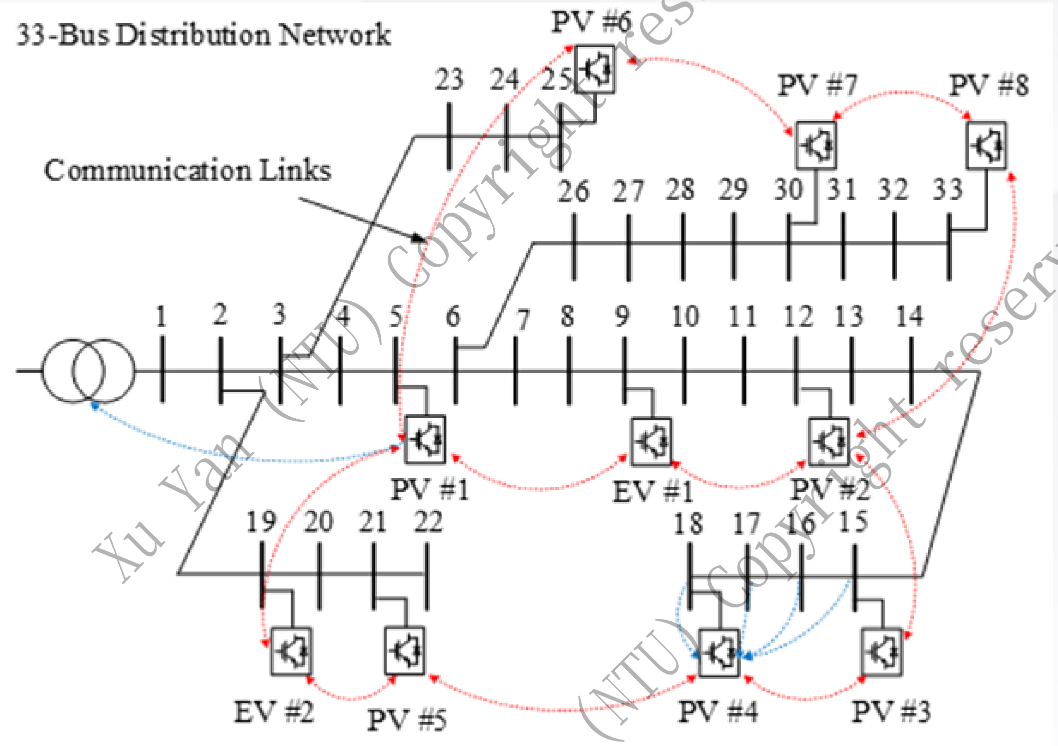
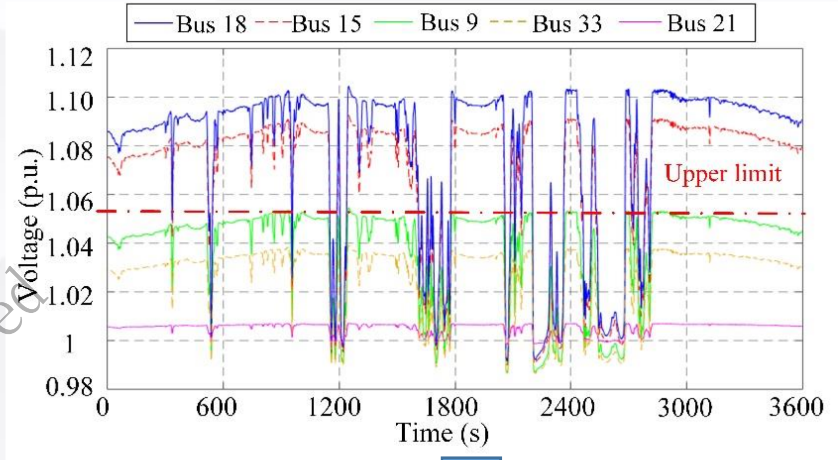
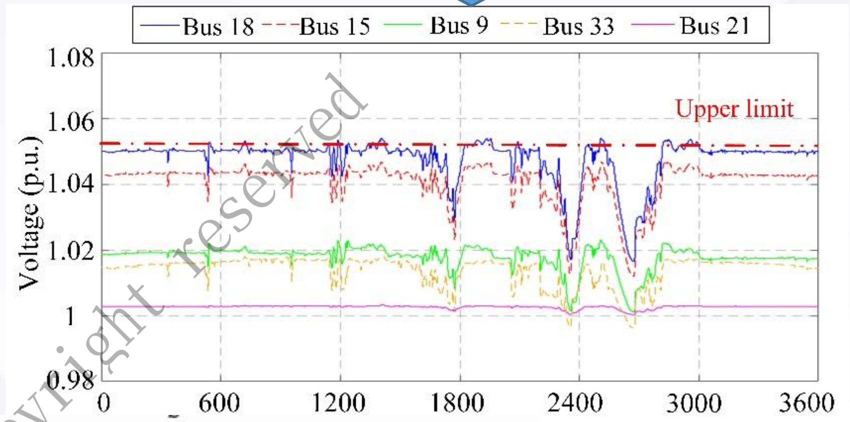
Simulation Tests

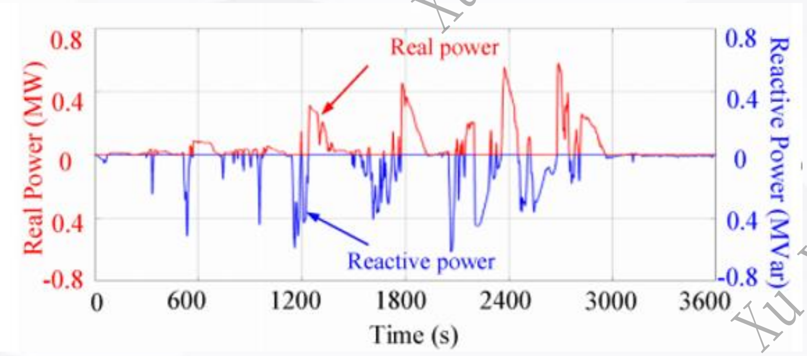


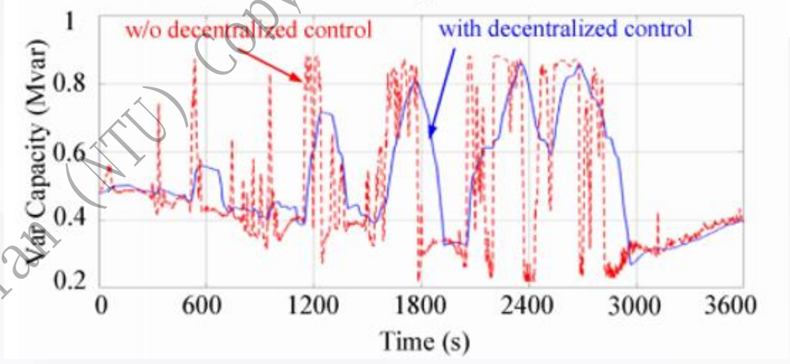
Real-time voltage/var control from inverters





Effectiveness of ramp-rate control





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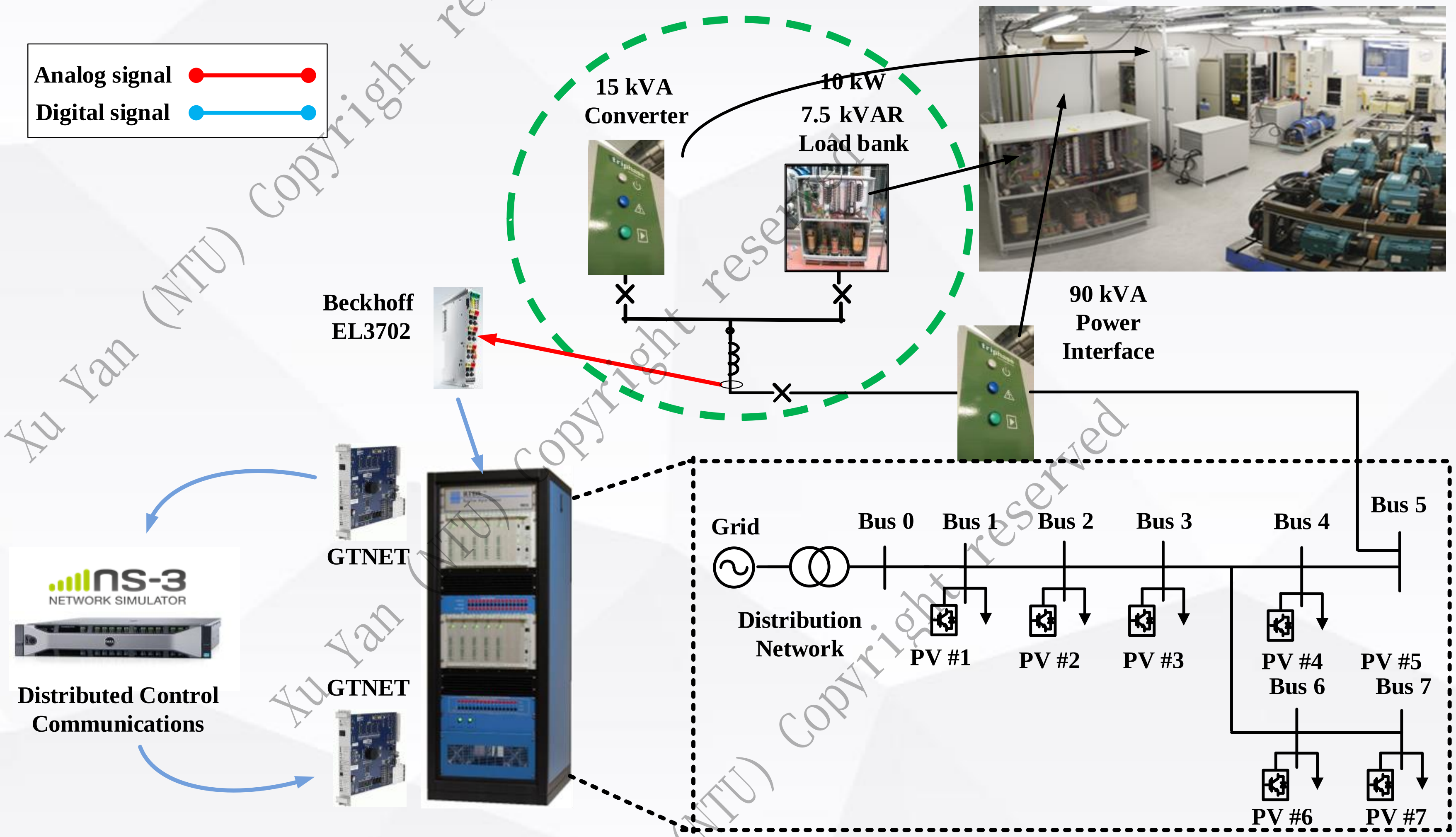
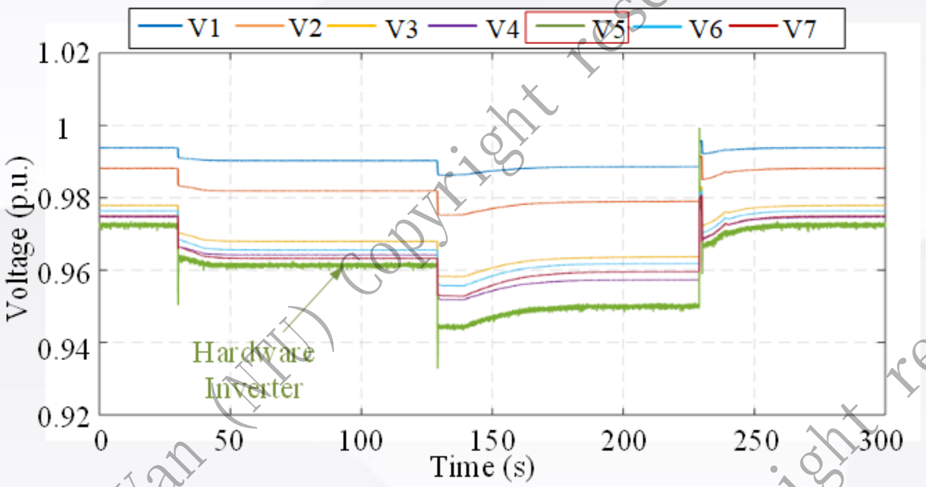
▪ Power Hardware-in-the-Loop (PHiL) Test

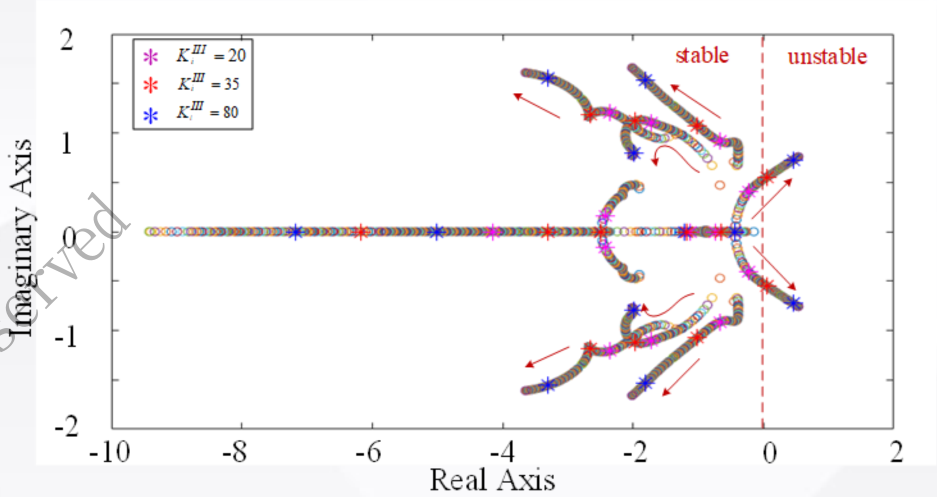


Y. Wang, M. H. Syed, E. Guillo-Sansano, **Y. Xu***, and G. Burt "Inverter-Based Voltage Control of Distribution Networks: A Three-Level Coordinated Method and Power Hardware-in-the-Loop Validation," ***IEEE Transactions on Sustainable Energy*, 2019**.

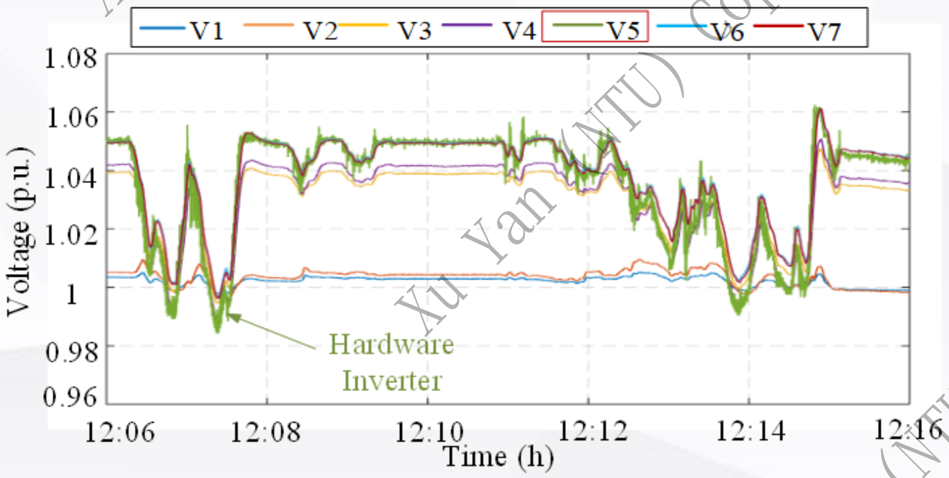
- Power HiL Results and Eigenvalues



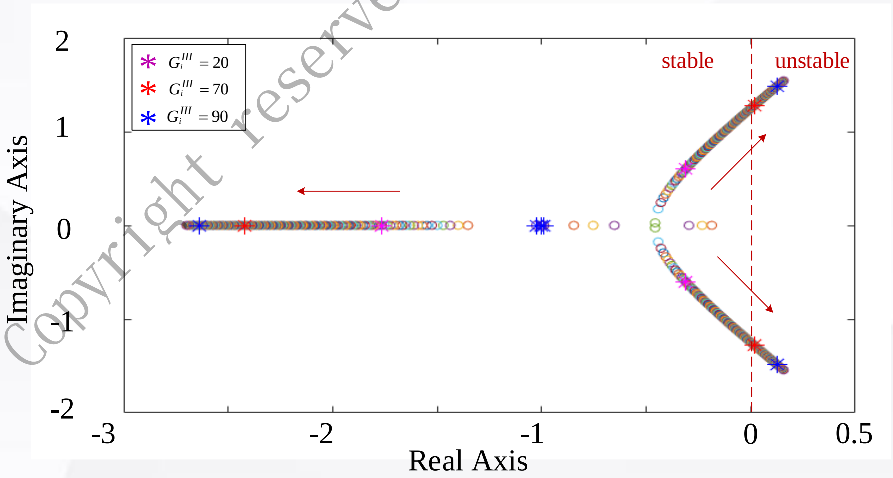
Voltage profiles under step load changes



Trace of eigenvalues under different control gains



Voltage profiles under real PV and load data



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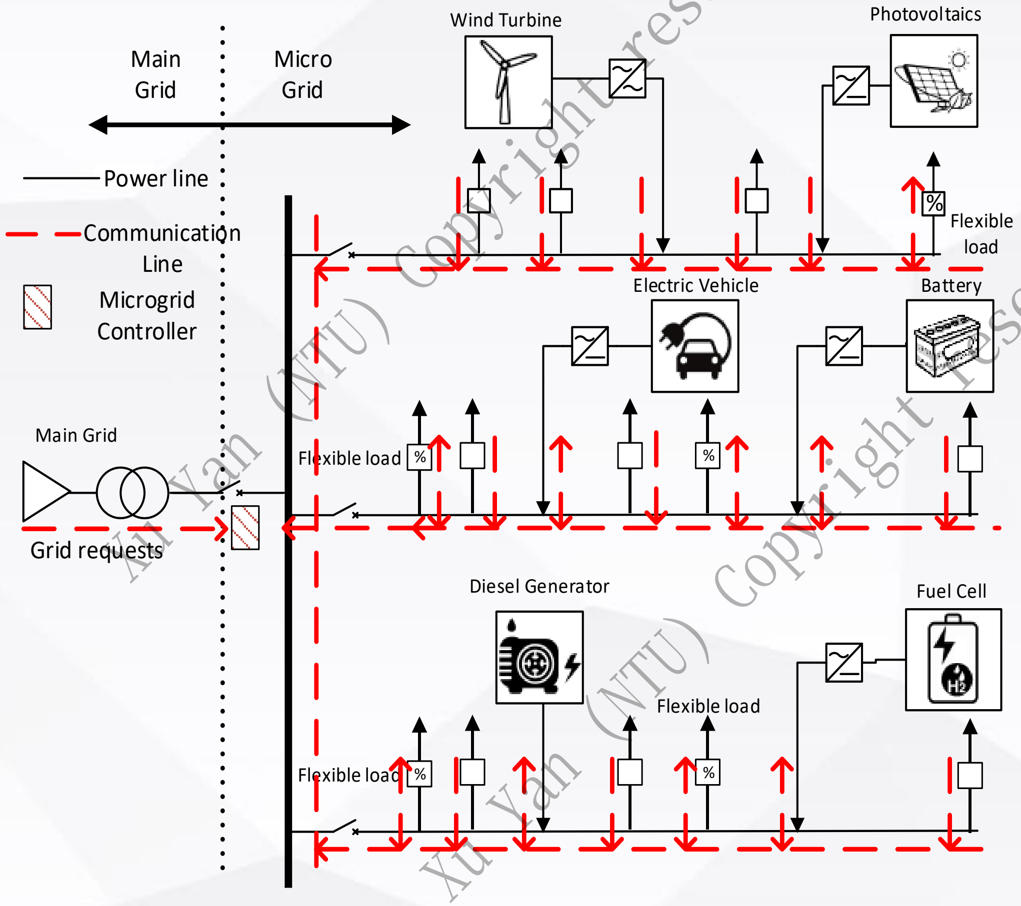
Operation of DER - Energy Dispatch & Volt/Var Regulation in Microgrid



- Network model:
1) Linearized Dist-Flow
2) Second-order cone model

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

1)–3) Active power resource

4)–6) Reactive power resource

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

1)–3) Uncertain

- State variables:
1) Bus voltage
2) Branch power flow
3) Power exchange with main grid

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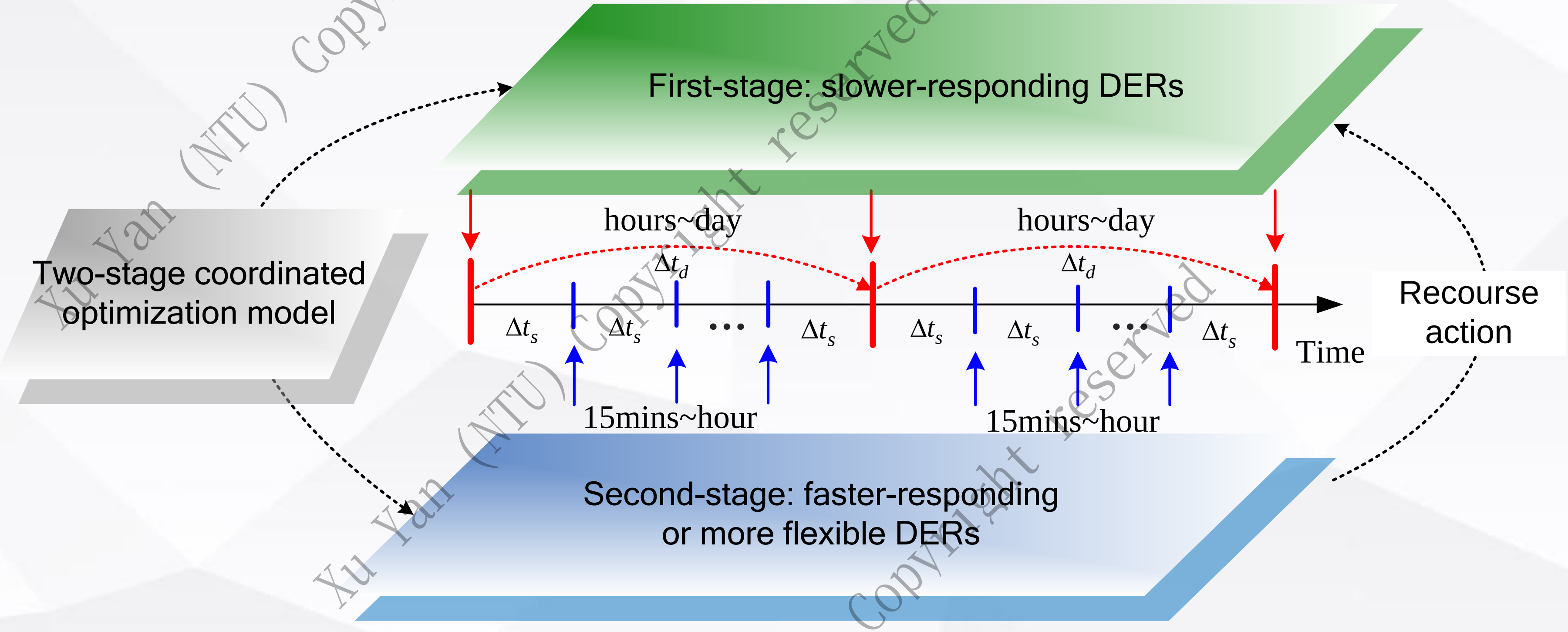
Two-stage coordinated operation – Temporal Coordination of DERs

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.

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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 $\min_{x\in F} \{f(x) + E[Q(x,\ \xi)]\}$	Optimize under worst case $\min_{\boldsymbol{x}} \left(\boldsymbol{c}^T\boldsymbol{x} + \max_{\boldsymbol{d}\in\mathcal{D}} \min_{\boldsymbol{y}\in\Omega(\boldsymbol{x},\boldsymbol{d})} \boldsymbol{b}^T\boldsymbol{y} \right)$
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

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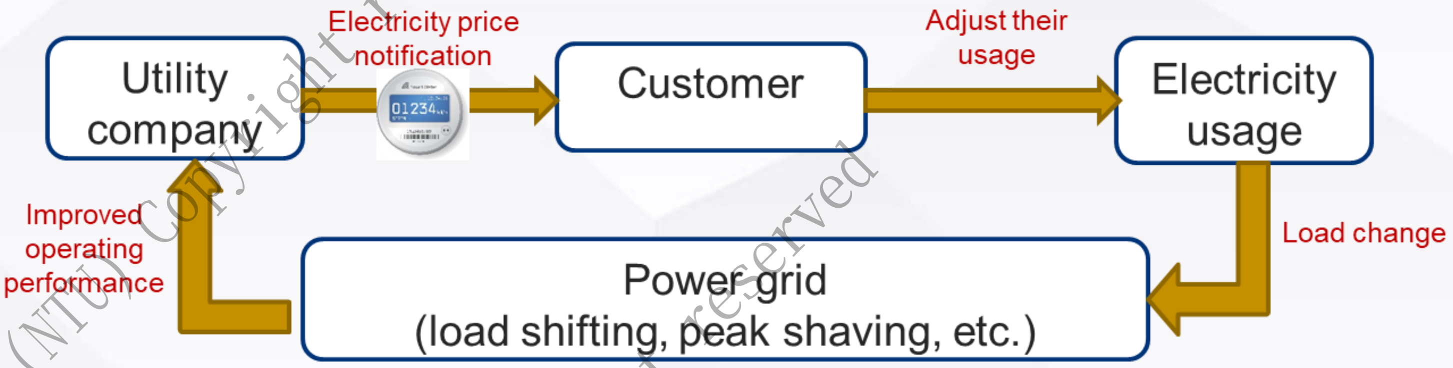
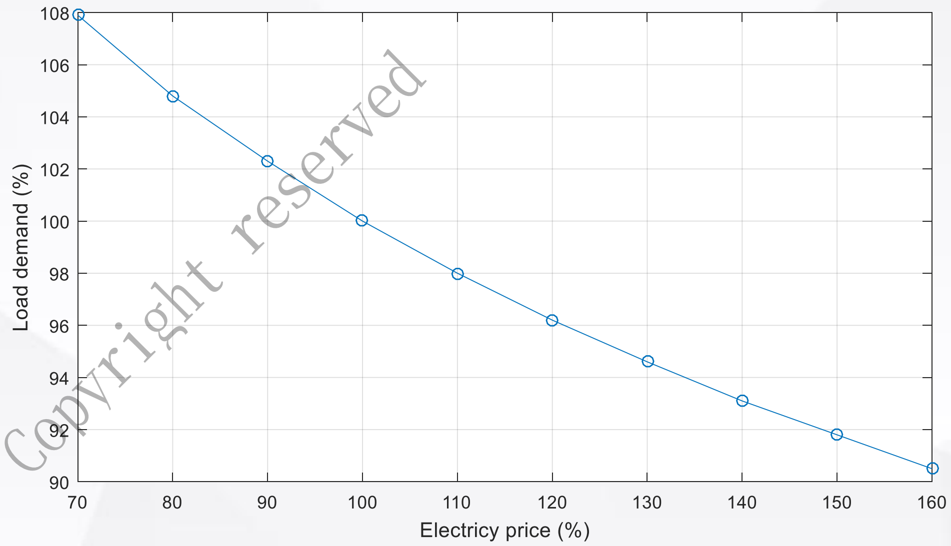
▪ Robustly Coordinated Energy Management

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



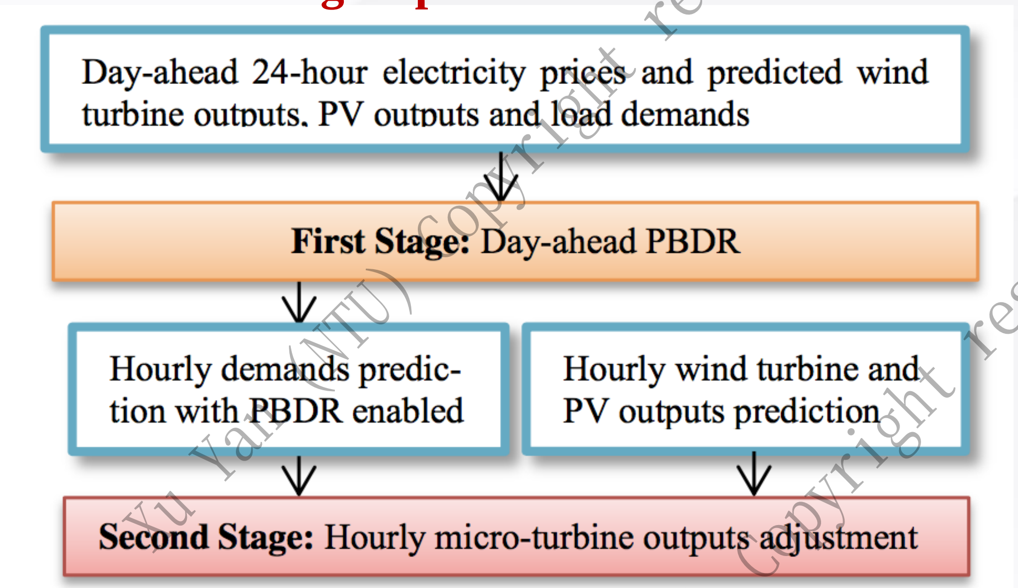
$$P_t^D = A\,Pr_t^{\varepsilon}$$

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.

▪ 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.

$$Ax \geq \mathrm{b}$$

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

$$u \in U$$

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**

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▪ Robustly Coordinated Energy Management

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

Modelling for Price-based DR

$$C_{rev} = C_{rev}^{pr} + C_{rev}^{unc} \tag{9}$$

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

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

$$\alpha_{j,t} \in \{0,1\}, \forall j,t \tag{12}$$

$$\sum_{j \in J} \alpha_{j,t} = 1, \forall t \tag{13}$$

$$\sum_{t \in T} \sum_{i \in N_D} P_{D,i,t}^{pr} \sum_{j \in J} \alpha_{j,t} L_{j,t} Pr_{j,t} \leq \sum_{t \in T} \sum_{i \in N_D} P_{D,i,t}^{pr} Pr_{0,t} \tag{14}$$

$$\sum_{t \in T} \sum_{i \in N_D} P_{D,i,t}^{pr} \sum_{j \in J} \alpha_{j,t} L_{j,t} \geq \sum_{t \in T} \sum_{i \in N_D} P_{D,i,t}^{pr} \tag{15}$$

- 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.

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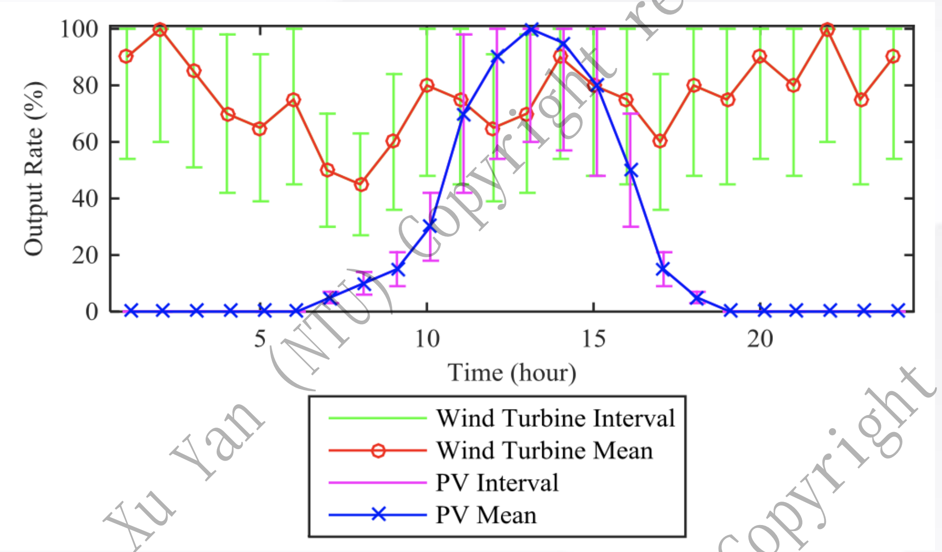
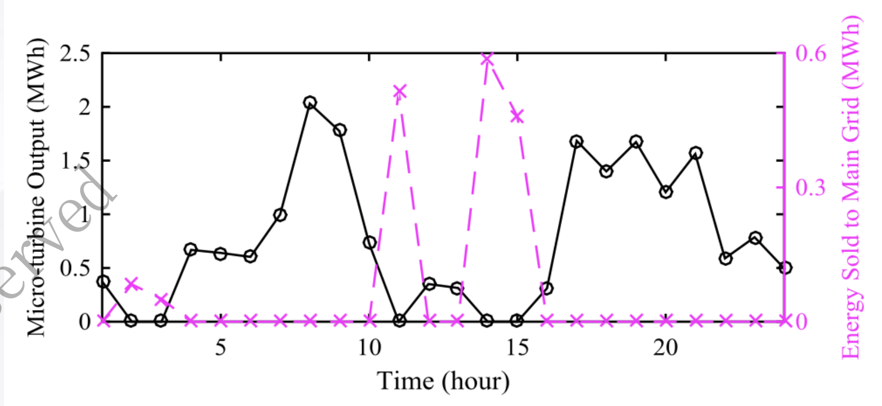
Robustly Coordinated Energy Management

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

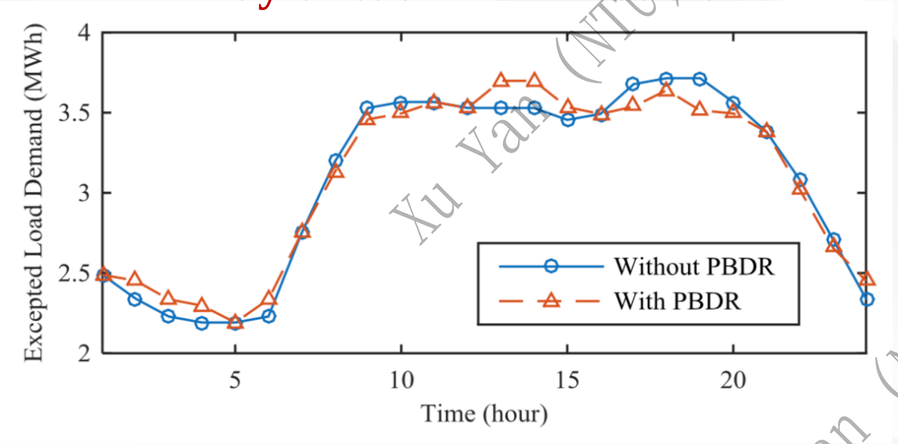
Day-ahead Interval Prediction



Hourly Microturbine Dispatch



Day-ahead PBDR Decision



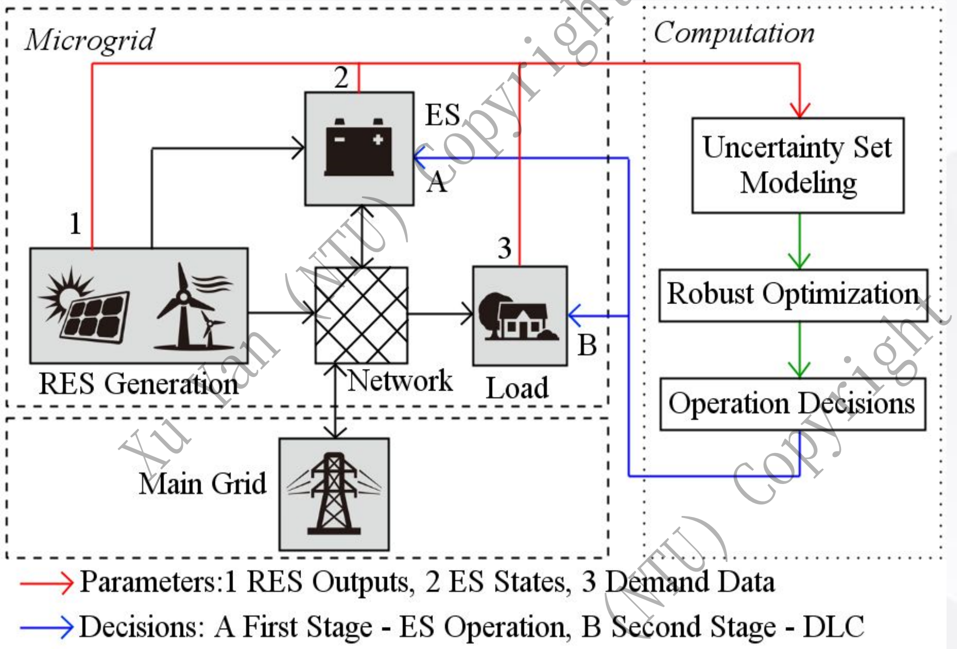
Strategy	Average Profit ($)	Micro-Turbine Generation (MWh)	Energy Bought from Main Grid (MWh)	Energy Sold to Main Grid (MWh)	Average Maximal Voltage Deviation (%)	TSRO beat Single in profit (%)	TSRO beat Single in voltage deviation (%)
Deviation Group 1: $\sigma_{WT} = 5\%M_{WT}; \sigma_{PV} = 5\%M_{PV}; \sigma_D = 1\%M_D$							
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

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

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.**

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Robustly Coordinated Energy Management

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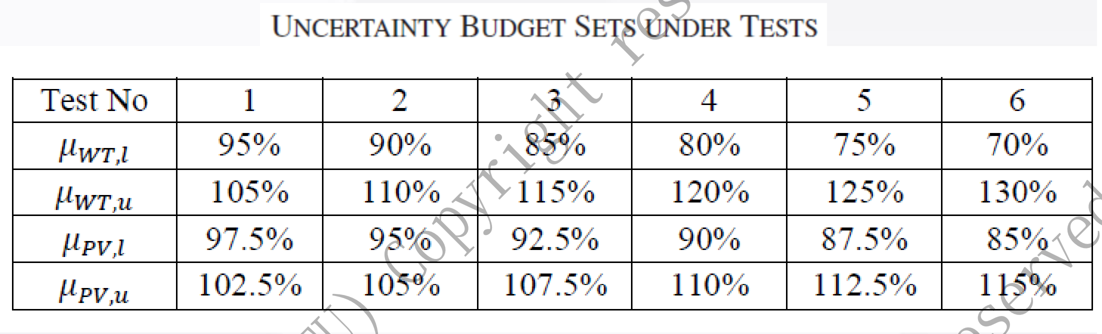
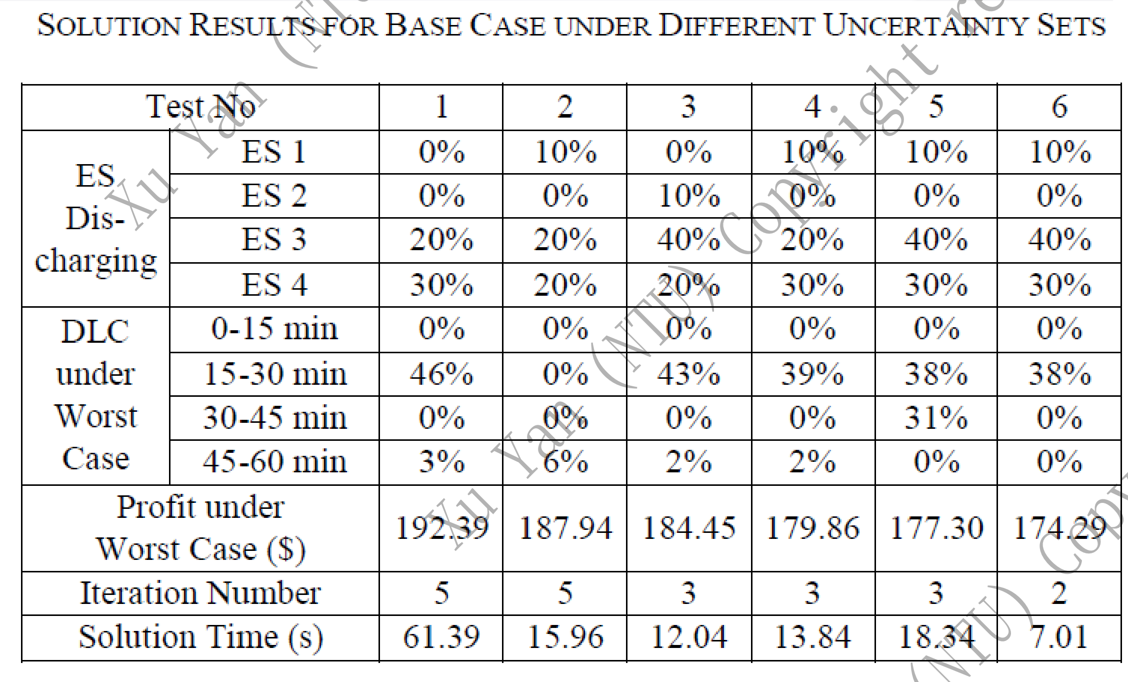


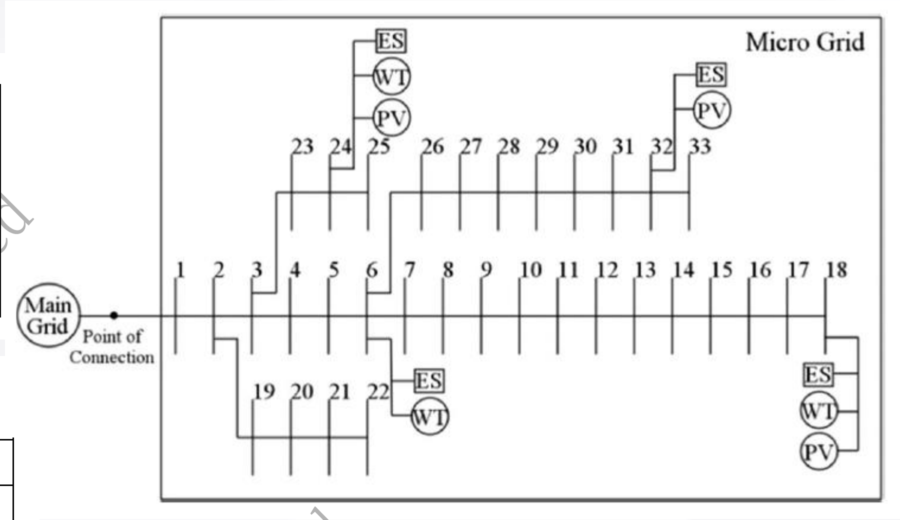
UNCERTAINTY BUDGET SETS UNDER TESTS

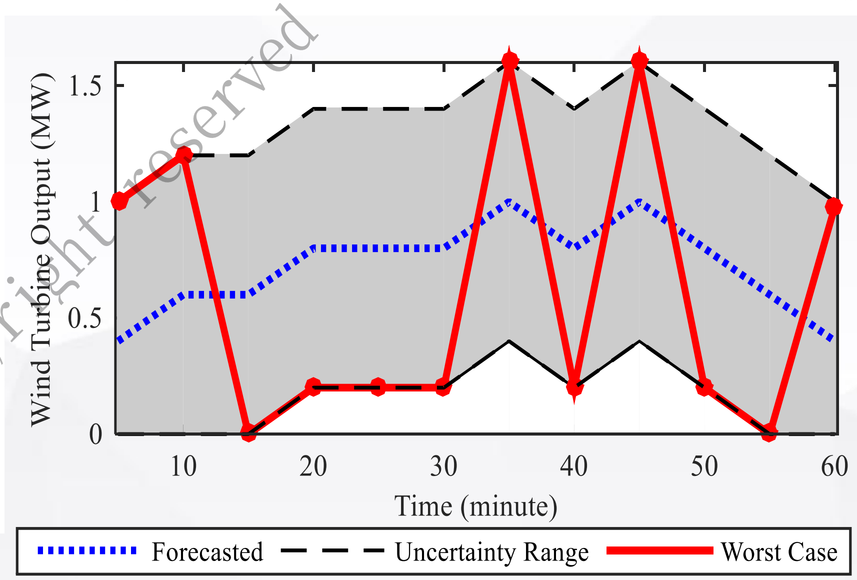
Test No	1	2	3	4	5	6
$\mu_{WT,l}$	95%	90%	85%	80%	75%	70%
$\mu_{WT,u}$	105%	110%	115%	120%	125%	130%
$\mu_{PV,l}$	97.5%	95%	92.5%	90%	87.5%	85%
$\mu_{PV,u}$	102.5%	105%	107.5%	110%	112.5%	115%



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.***

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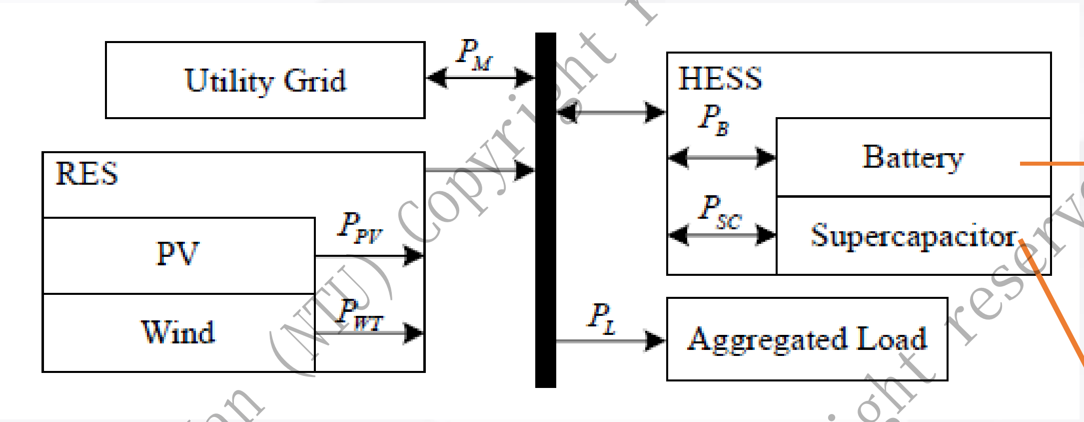
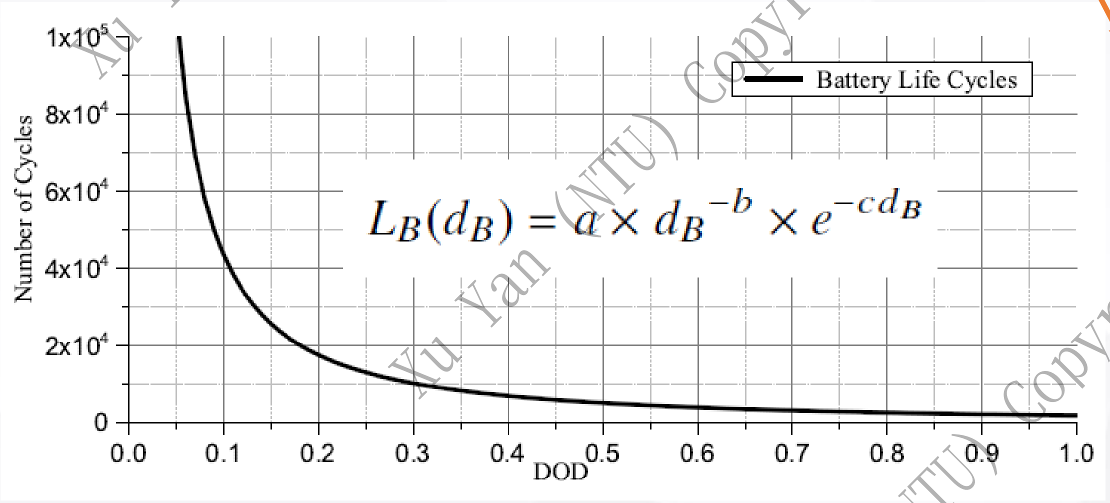
Two-Stage Dispatch of Hybrid Energy Storage considering battery health





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*

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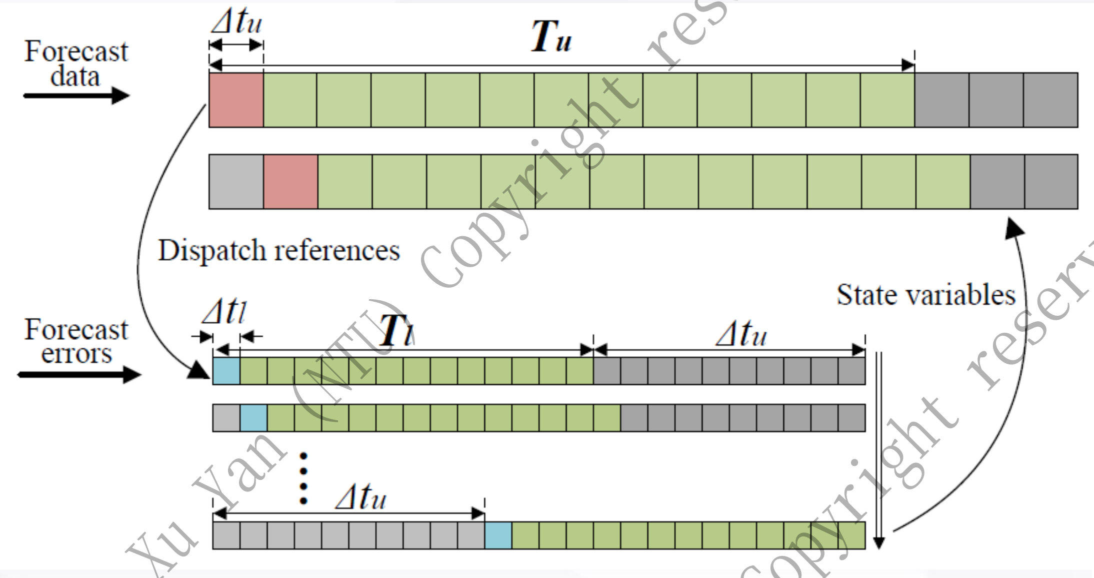
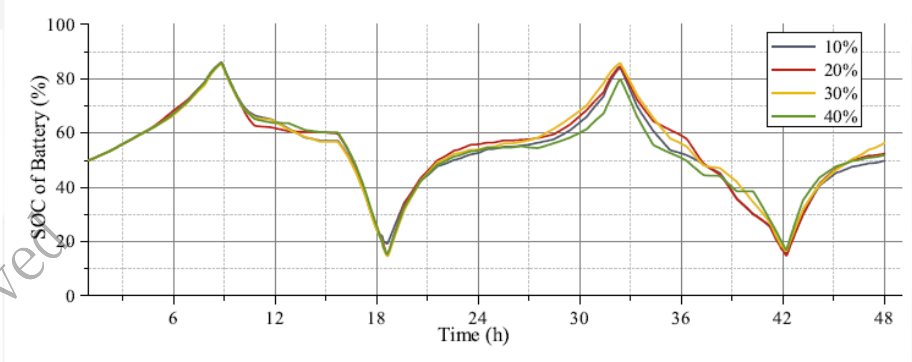
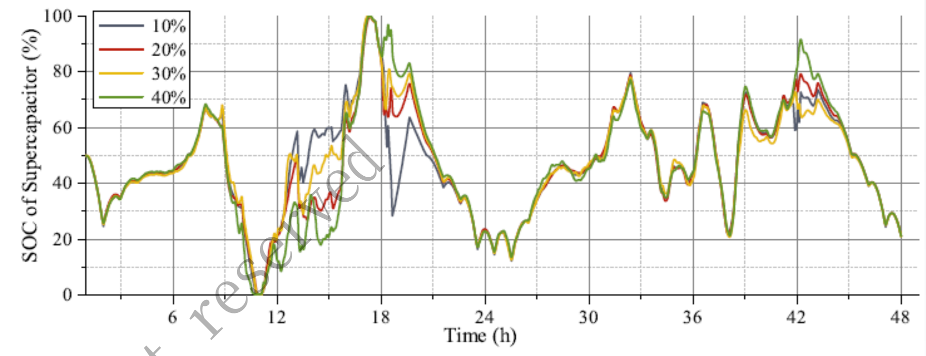


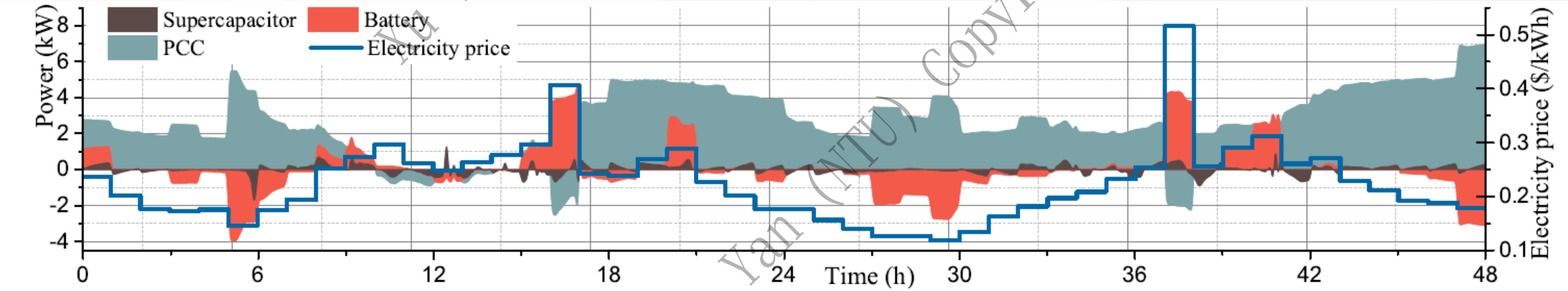


(a) SOC of battery



(b) SOC of supercapacitor

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



(b) Optimal dispatch in real-time pricing

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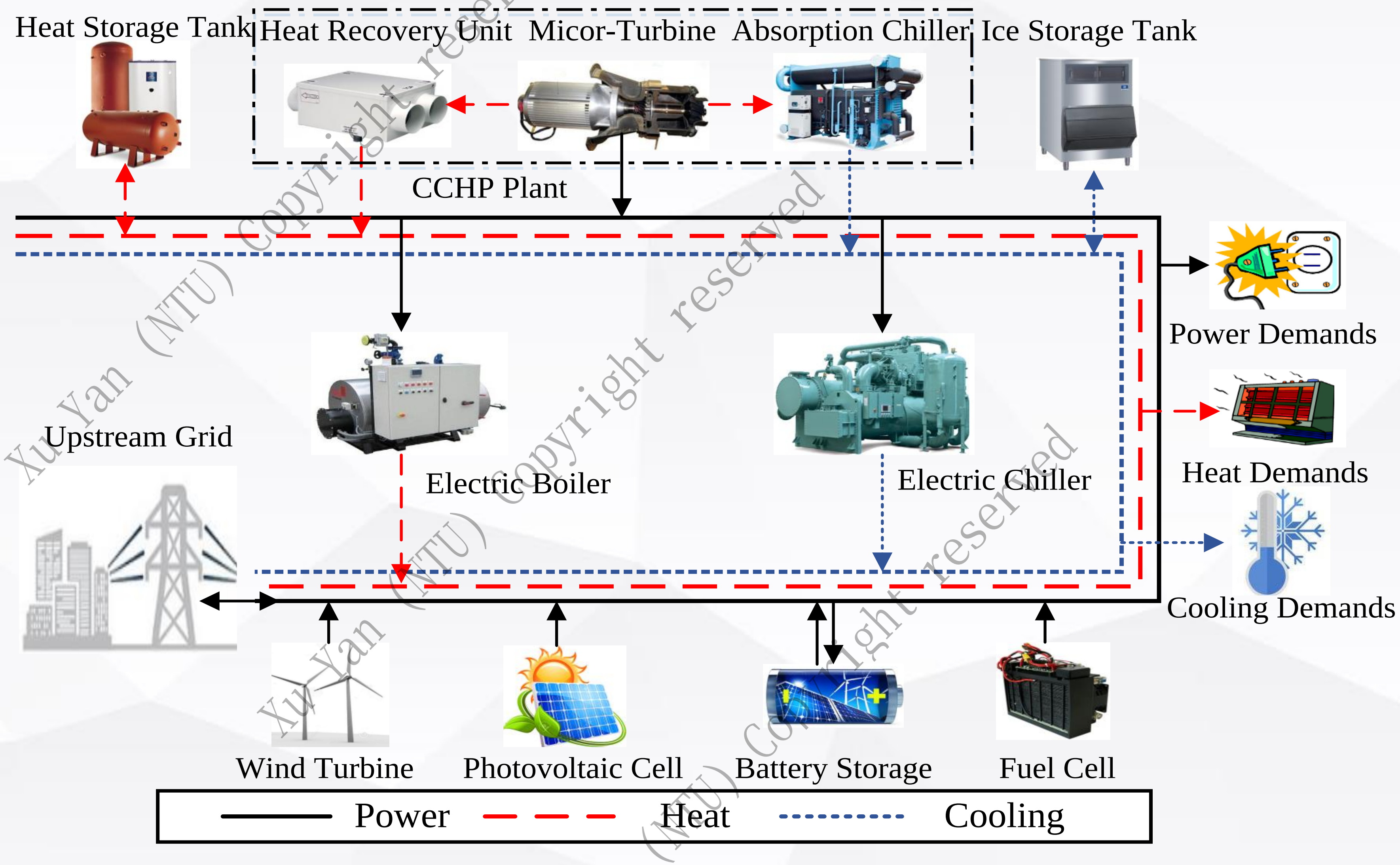
Multi-Energy Microgrid



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**

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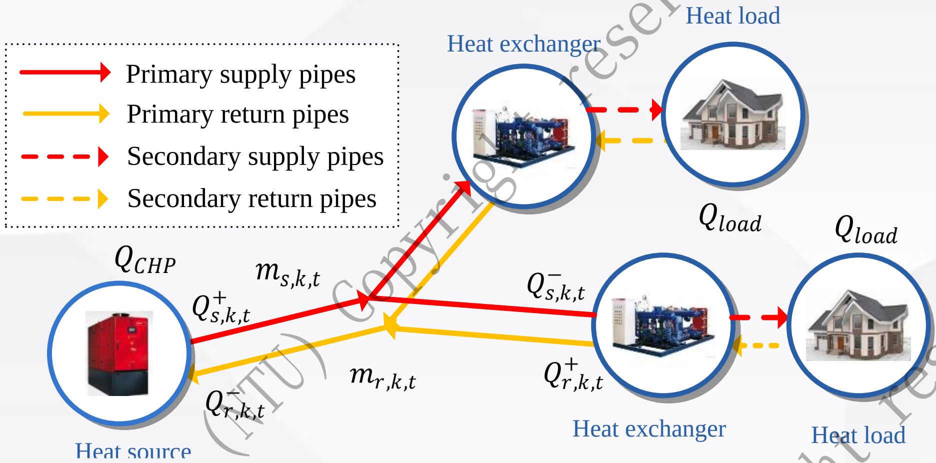
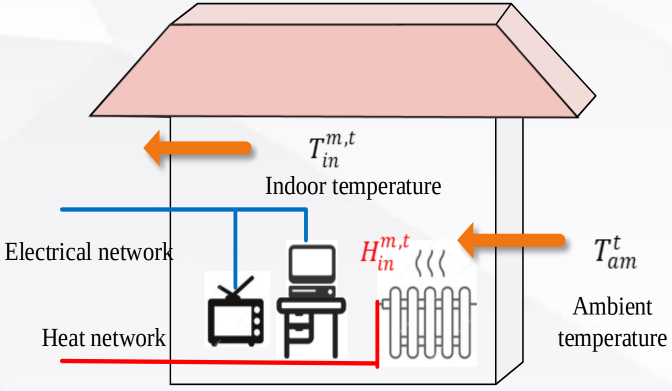
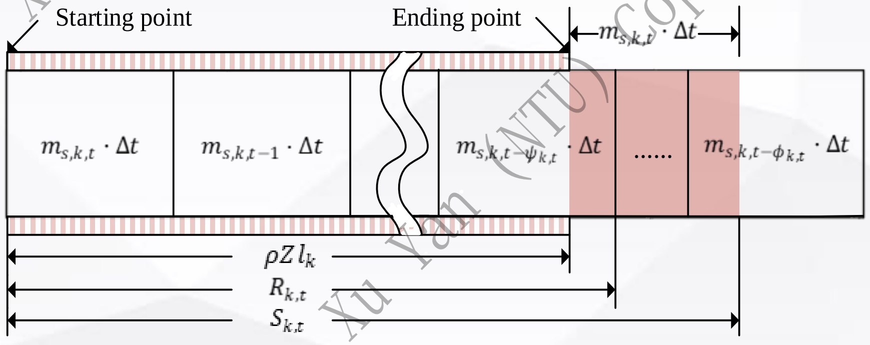
Multi-Energy Microgrid – Modeling of thermal part



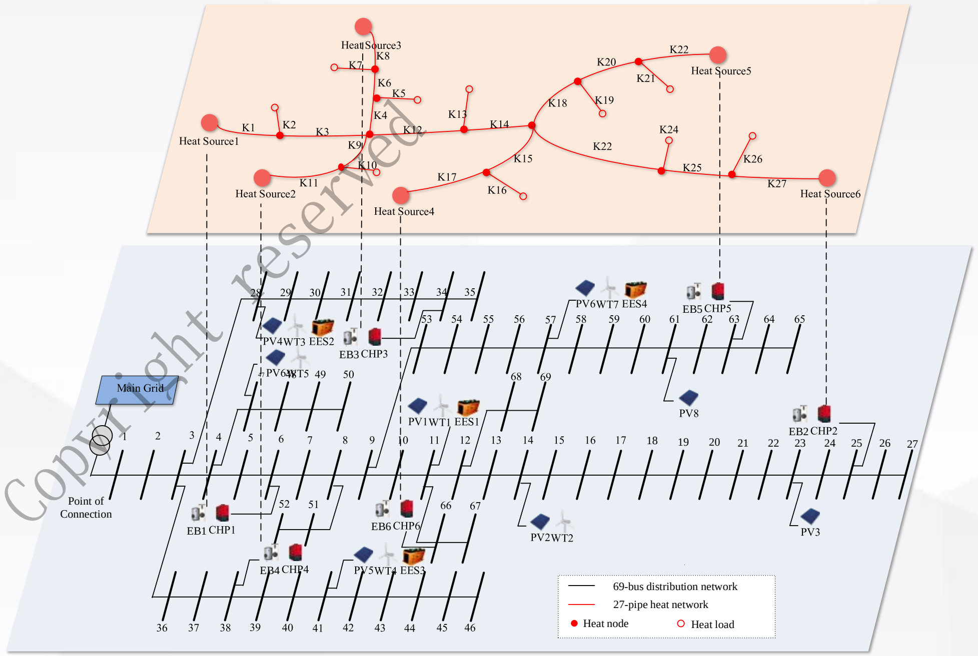
District Heat Network



Thermal conduction of a building



Vertical section of a pipe

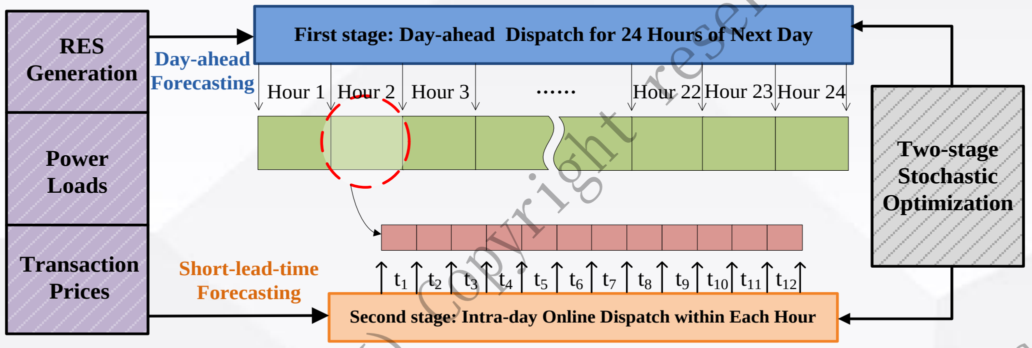


Coupled electric-thermal network

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**

Multi-Energy Dispatch – Two-Stage Coordinated Operation



Temporally-coordinated Stochastic Operation Framework

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

$$\text{s.t.} \quad z\in F_A$$

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

Two-Stage Sstochastic Optimization model

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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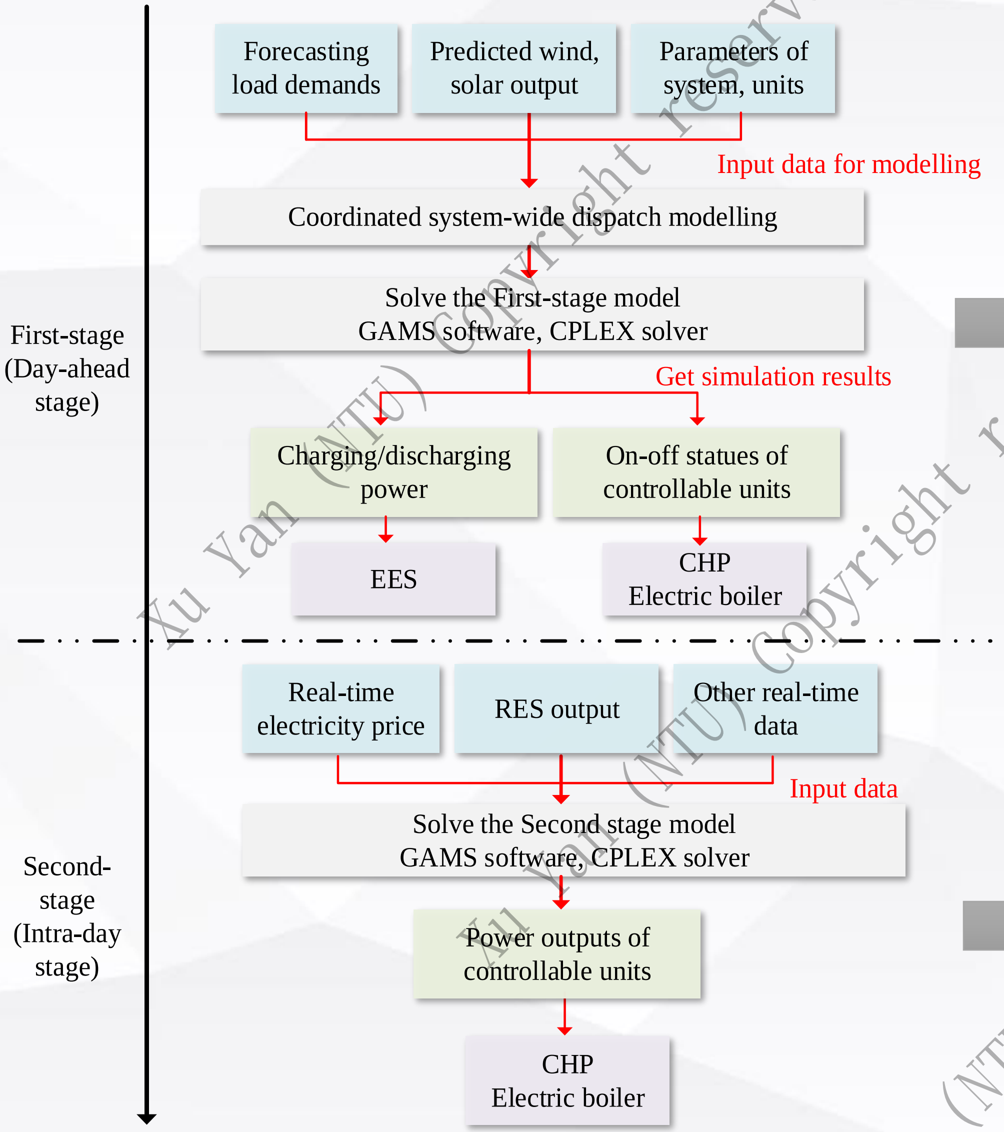
Multi-Energy Dispatch – Two-Stage Coordinated Operation


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

On-off statues of controllable units

EES

CHP
Electric boiler

Second-stage (Intra-day stage)

Real-time electricity price

RES output

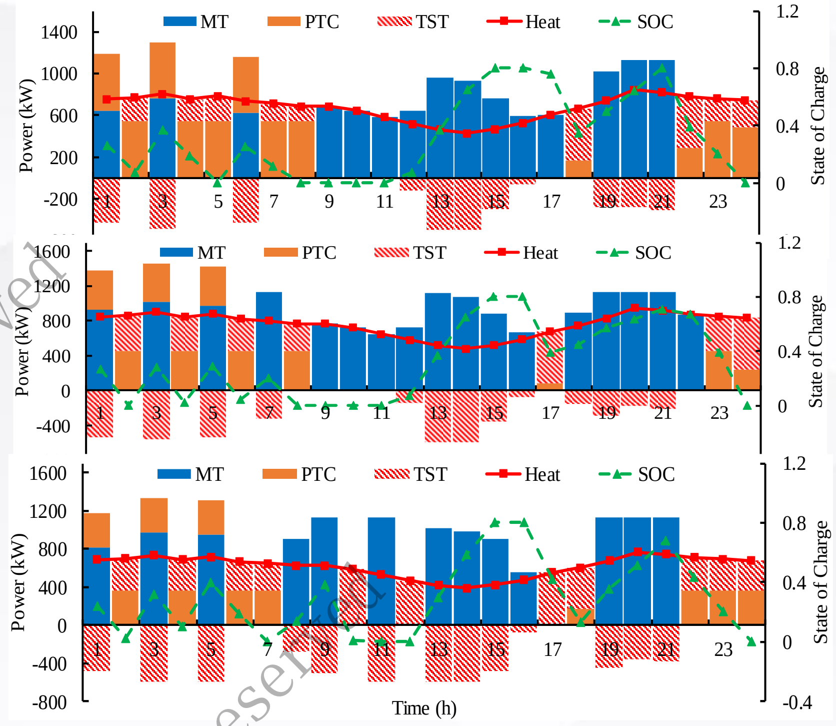
Other real-time data

Input data

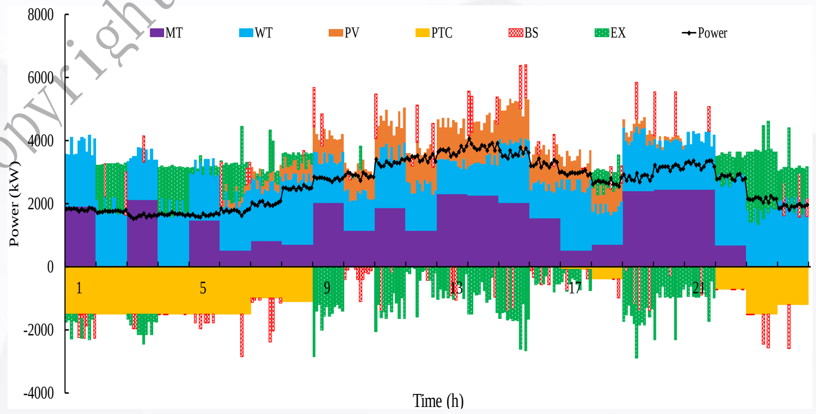
Solve the Second stage model
GAMS software, CPLEX solver

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.**

0. Outline

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

3. Operation
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2) Volt/Var regulation

4. Hierarchy coordination

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

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▪ 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.**

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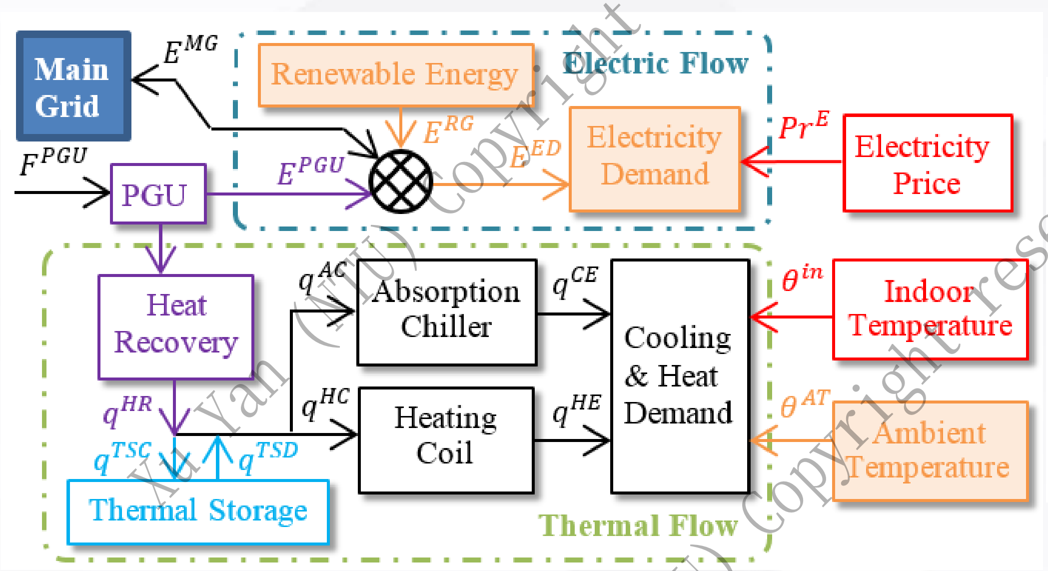
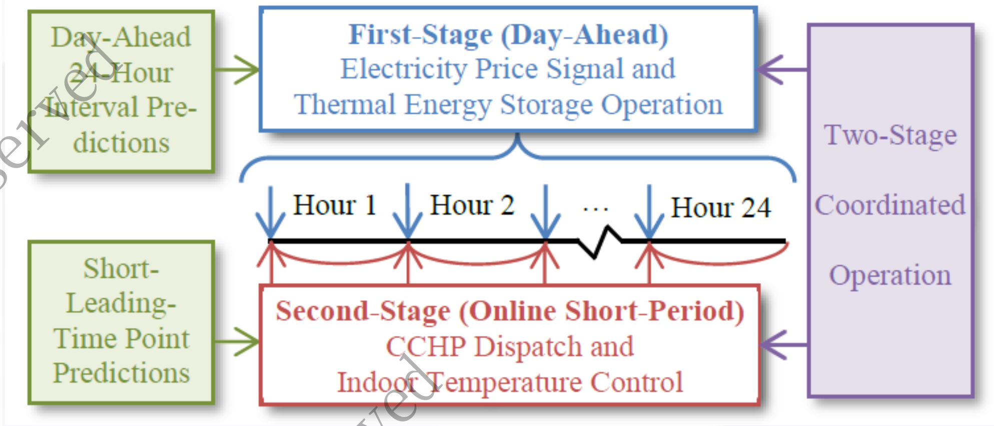
▪ Multi-Energy Demand Response

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

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

s.t. (10)-(47)

Intra-day optimization model

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

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.**

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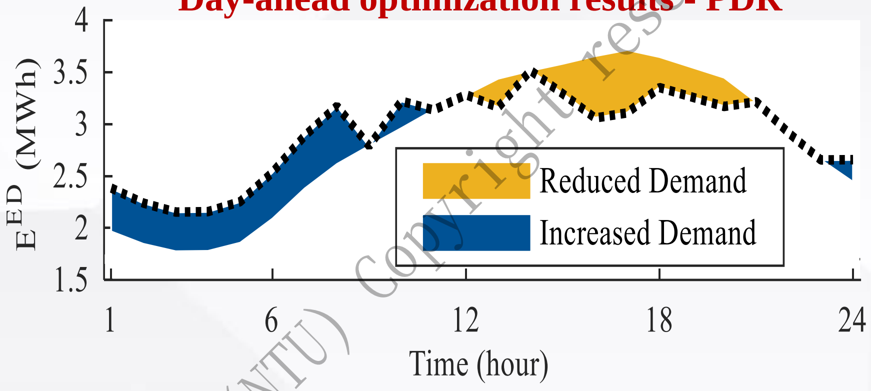
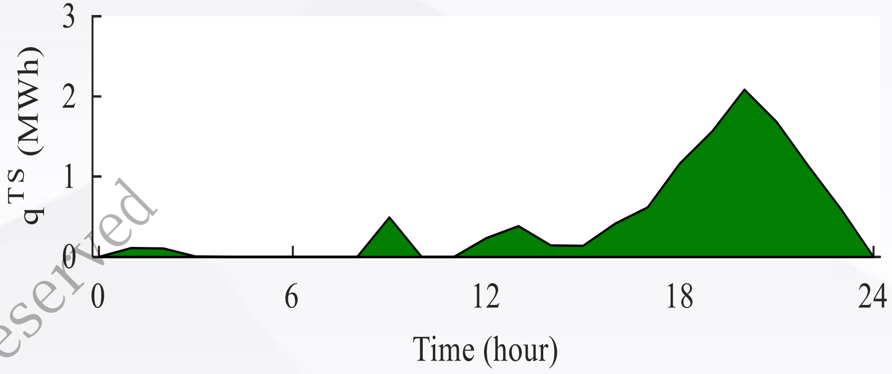
Multi-energy demand response

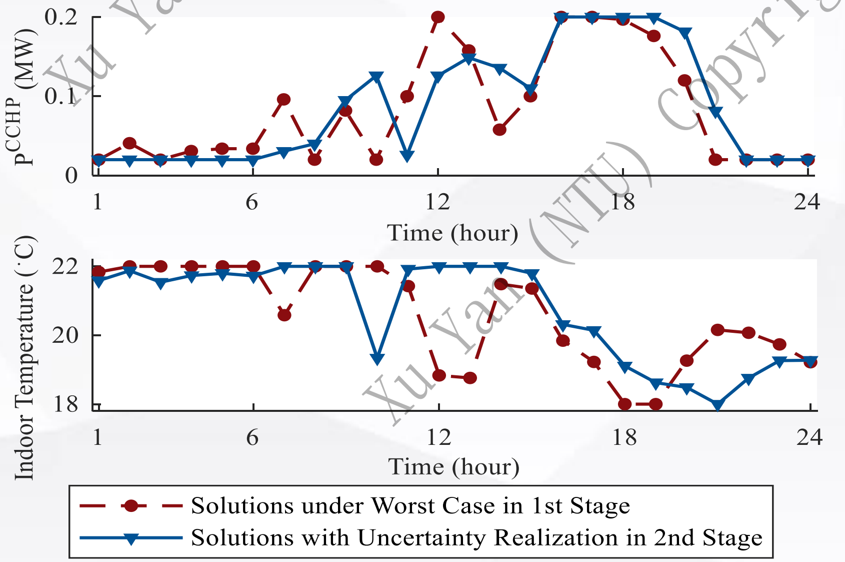
Day-ahead optimization results - PDR



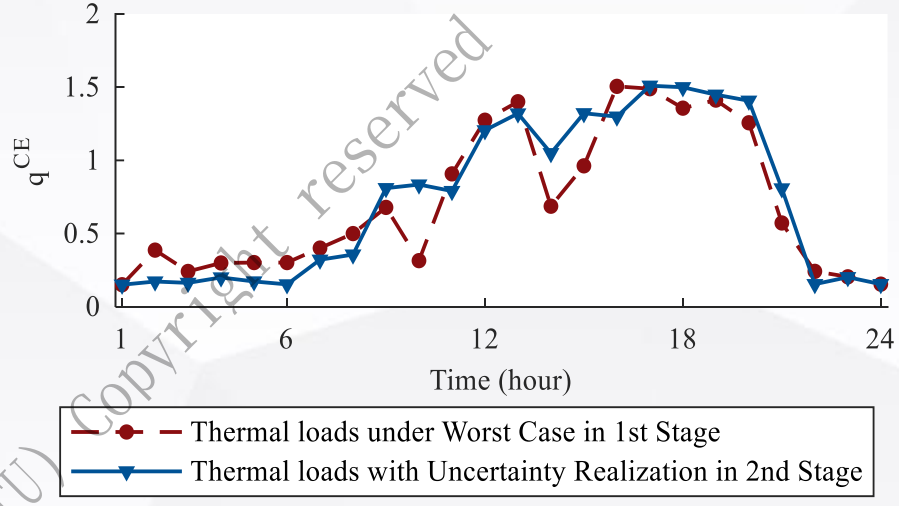
Day-ahead optimization results – thermal ESS



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

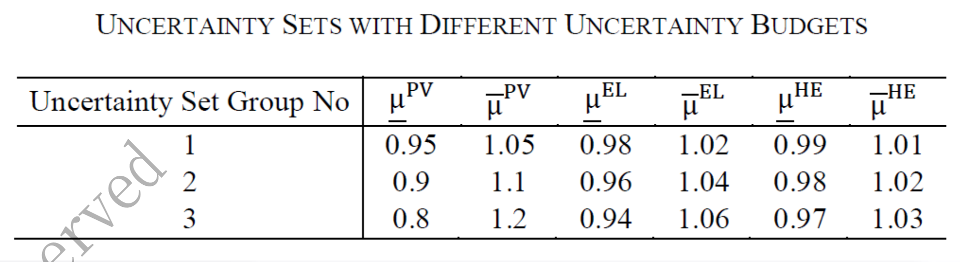
Conservativeness:

Compromise in optimization process when considering uncertainties (Drawback)

Design of Uncertainty Budgets

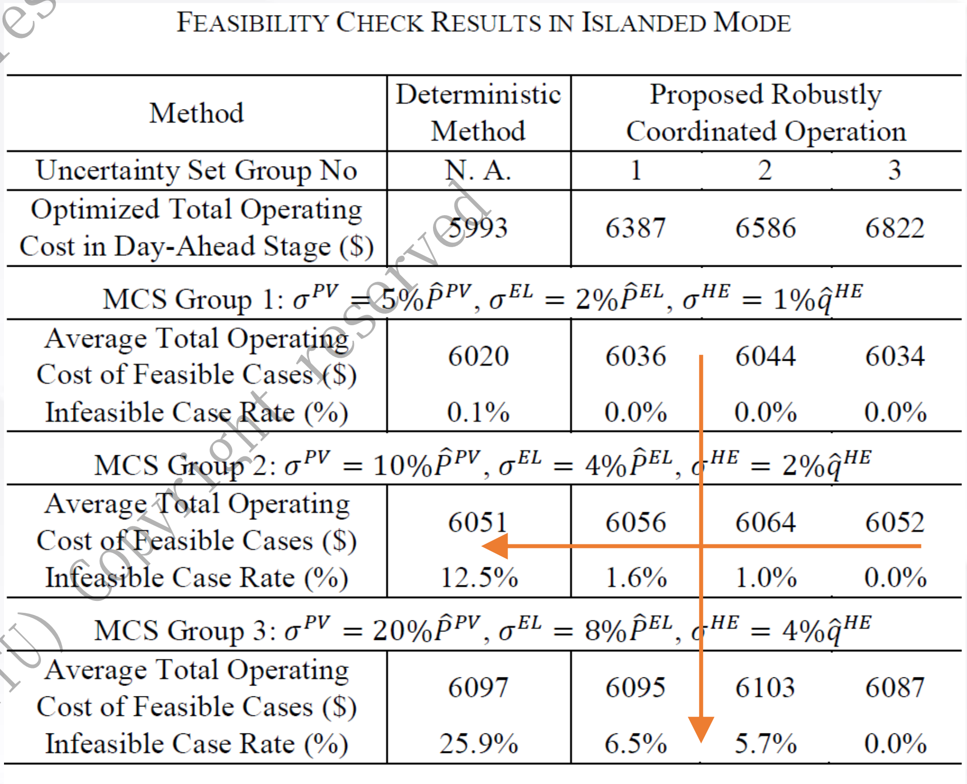
- Larger Budgets
    - -> Higher Robustness
    - -> Higher Conservativeness
- Uncertainty Degree Analysis

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.**

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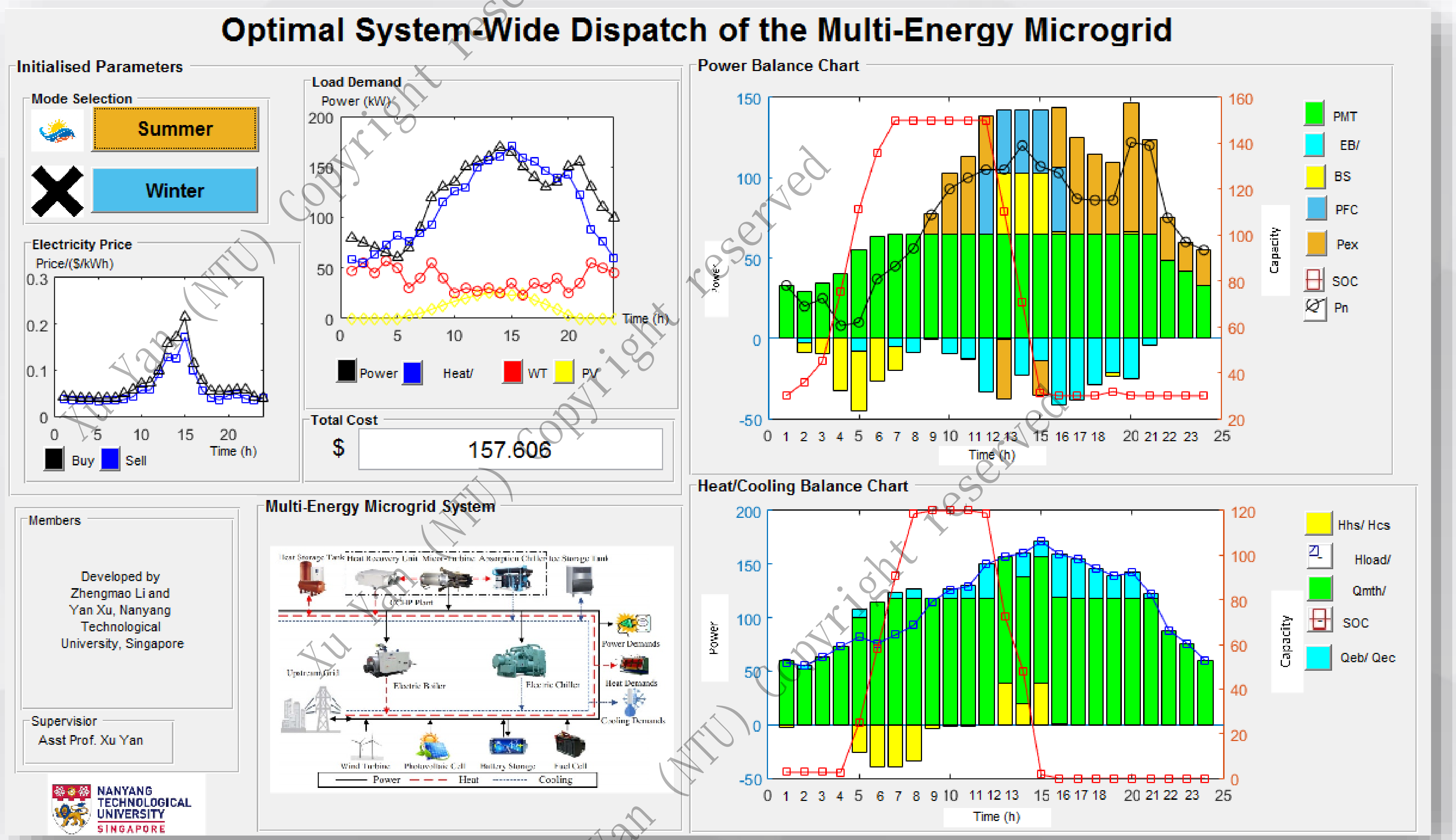
▪ Multi-Energy Dispatch GUI Prototype



Optimal System-Wide Dispatch of the Multi-Energy Microgrid

Initialised Parameters

Mode Selection

Summer

Winter

Total Cost

$ 157.606

Members

Developed by Zhengmao Li and Yan Xu, Nanyang Technological University, Singapore

Supervisor

Asst Prof. Xu Yan

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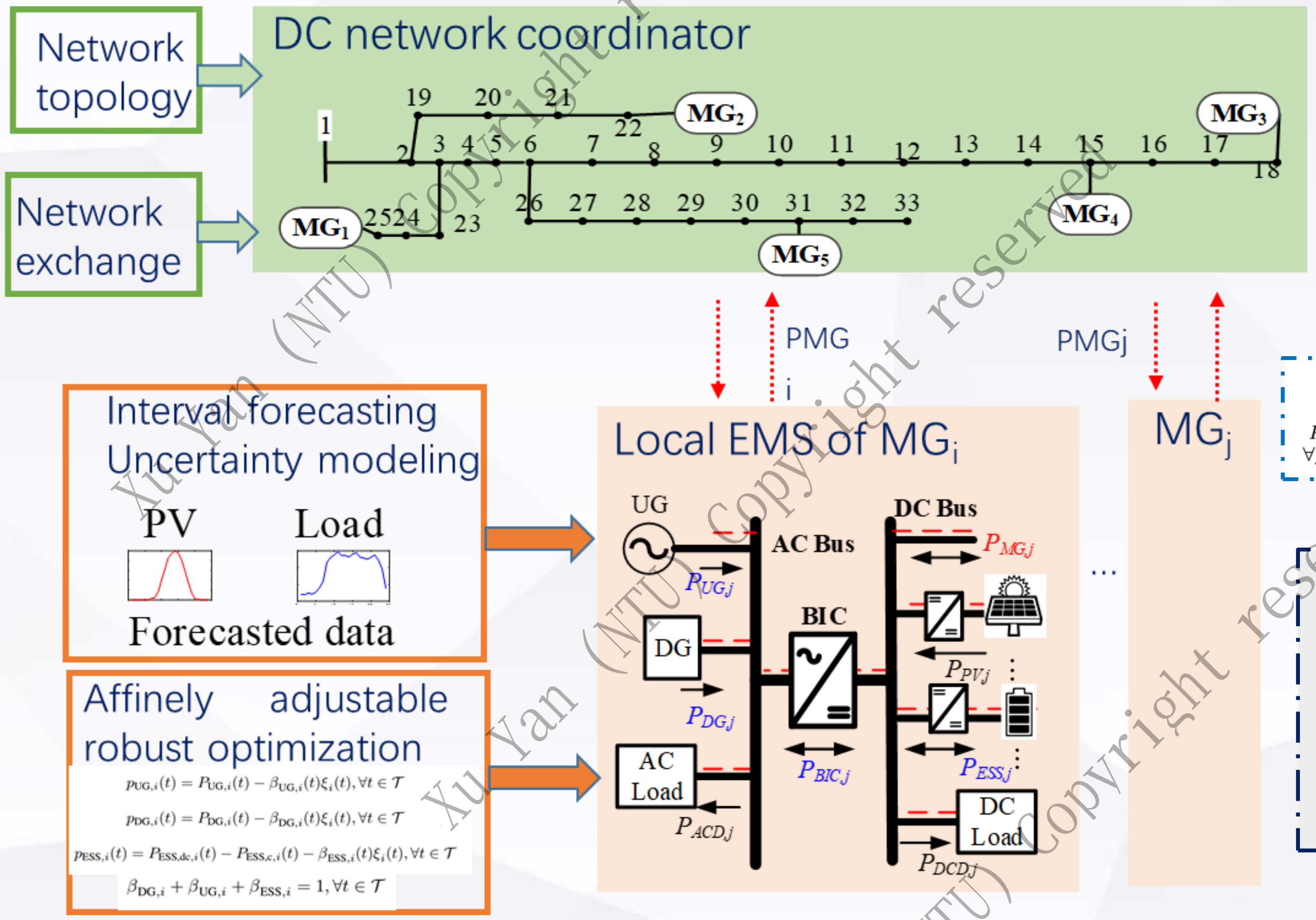
▪ Robustly Coordinated Energy Management

Distributed robust optimization for Networked-Hybrid AC/DC Microgrids



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

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

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

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

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.**

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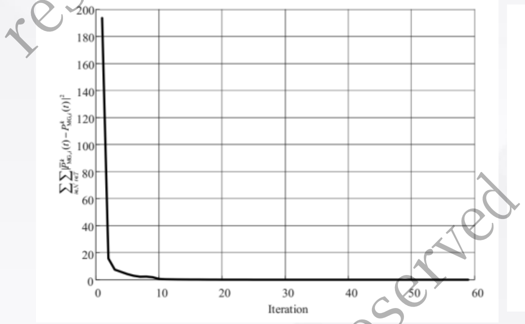
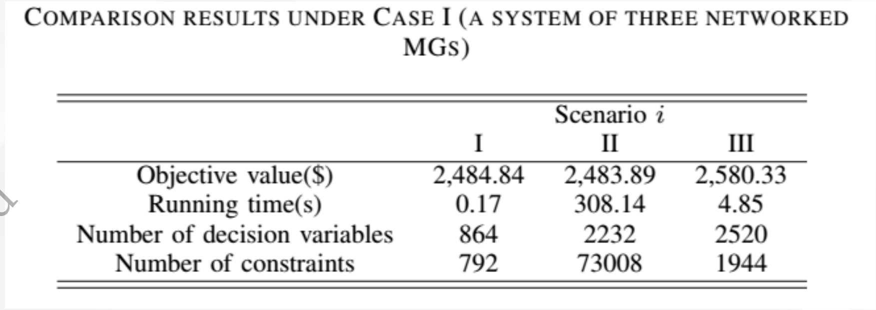
Simulation results

A 3 networked microgrid system in an IEEE 4 bus system

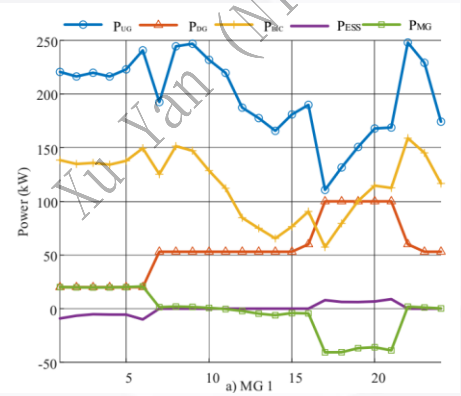
Scenario I: centralized deterministic;
Scenario II: centralized stochastic; (100)
Scenario III: proposed



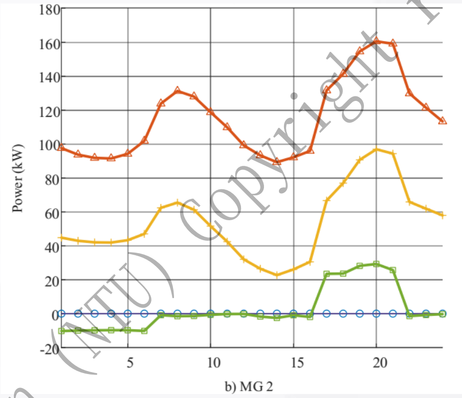


COMPARISON RESULTS UNDER CASE I (A SYSTEM OF THREE NETWORKED MGS)

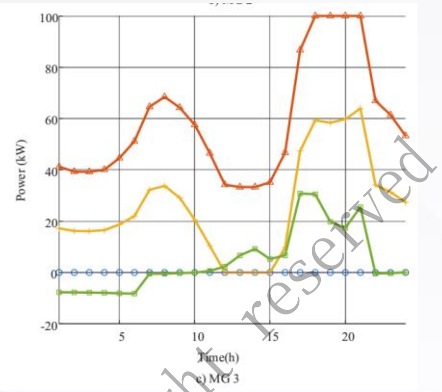
	Scenario i		
	I	II	III
Objective value($)	2,484.84	2,483.89	2,580.33
Running time(s)	0.17	308.14	4.85
Number of decision variables	864	2232	2520
Number of constraints	792	73008	1944



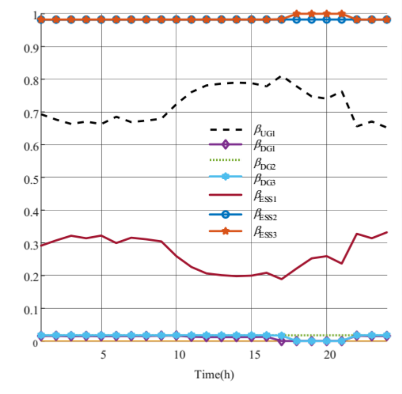
a) MG 1



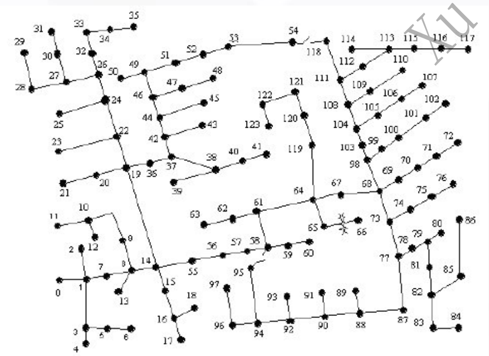
b) MG 2

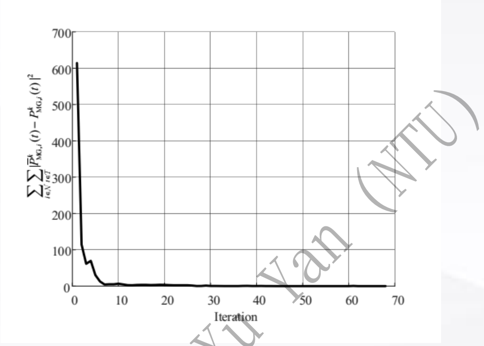


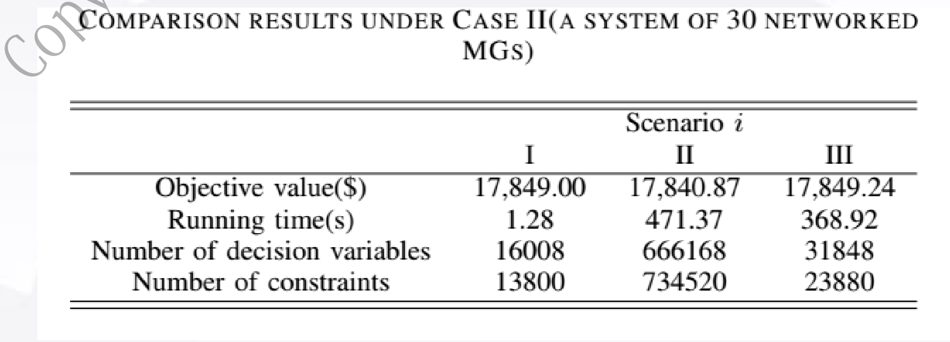
c) MG 3



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

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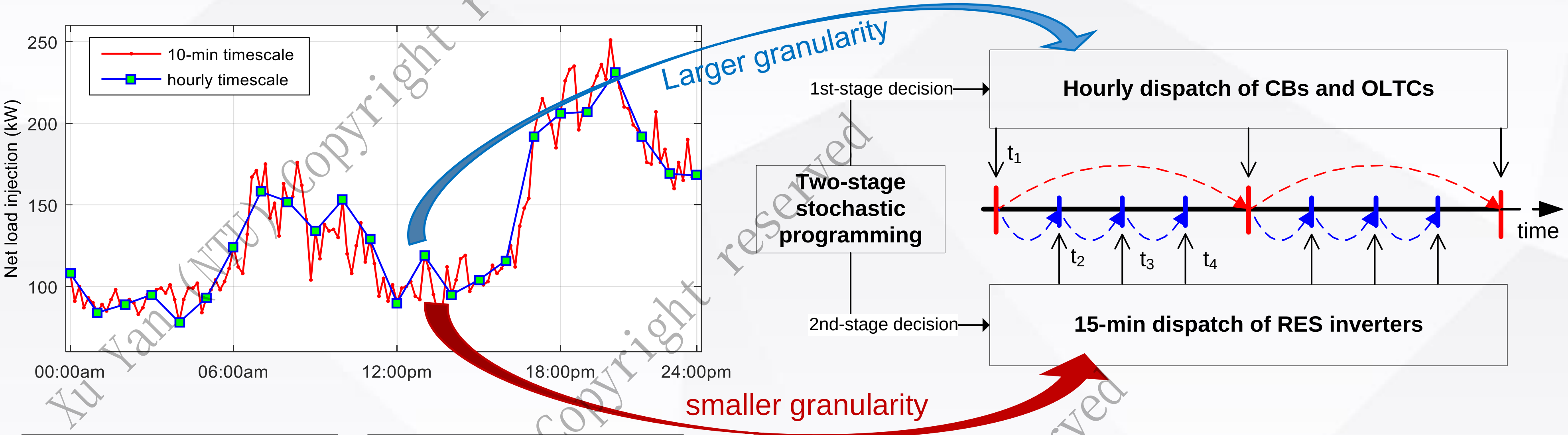
▪ Two-stage Coordinated Volt/Var Regulation under uncertainty

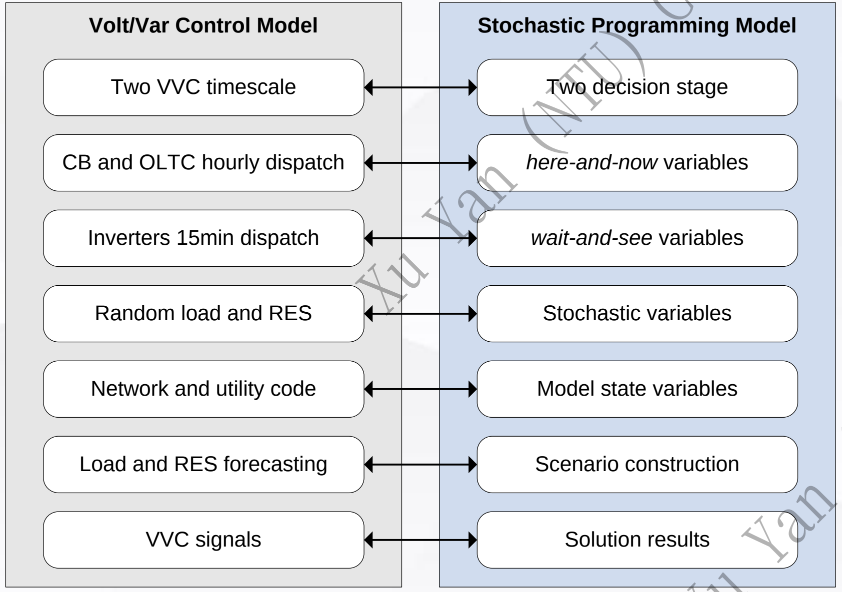
Hourly dispatch of CB and OLTC & 15min dispatch of PV inverters



1st-stage decision → **Hourly dispatch of CBs and OLTCs**

Two-stage stochastic programming

2nd-stage decision → **15-min dispatch of RES inverters**

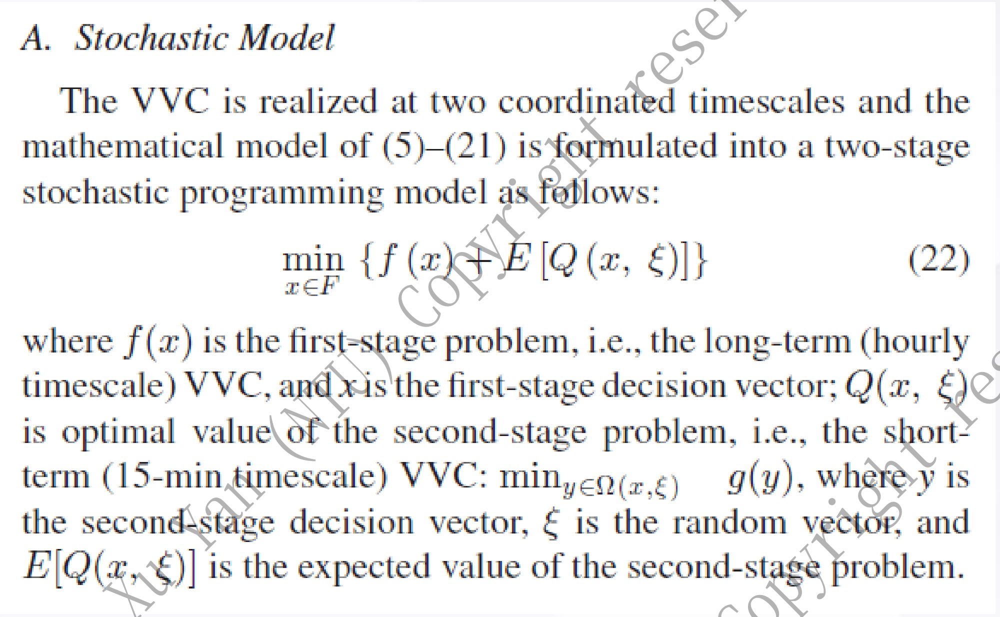


Volt/Var Control Model	**Stochastic Programming Model**
Two VVC timescale	Two decision stage
CB and OLTC hourly dispatch	*here-and-now* variables
Inverters 15min dispatch	*wait-and-see* variables
Random load and RES	Stochastic variables
Network and utility code	Model state variables
Load and RES forecasting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

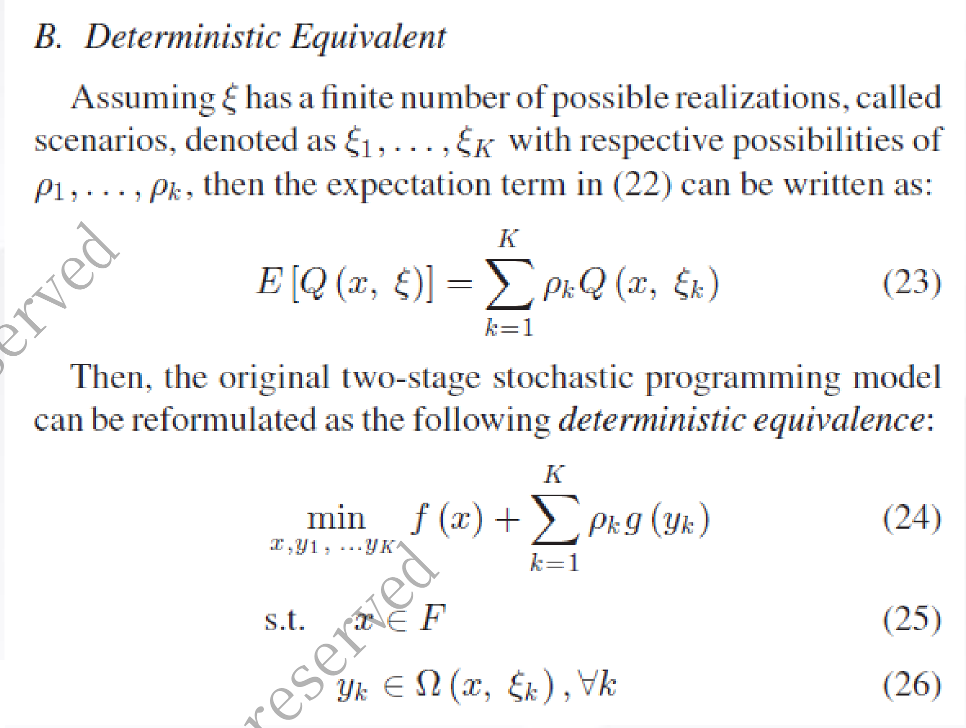


A. *Stochastic Model*

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:

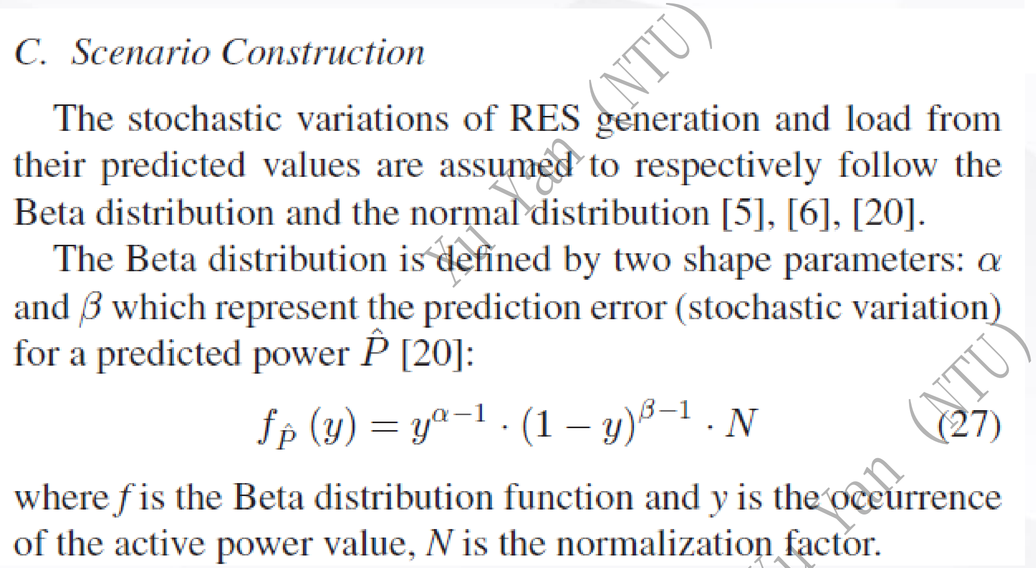
$$E[Q(x,\ \xi)] = \sum_{k=1}^{K}\rho_k Q(x,\ \xi_k) \tag{23}$$

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

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

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

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



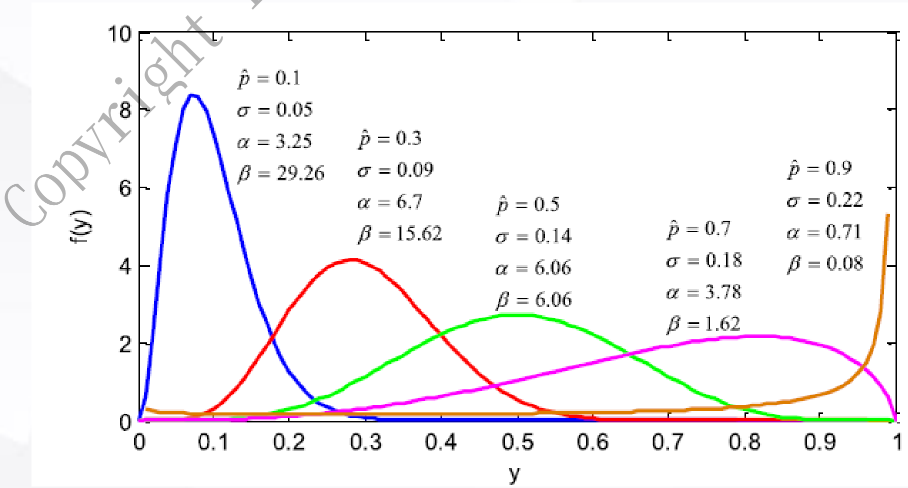
C. *Scenario Construction*

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.



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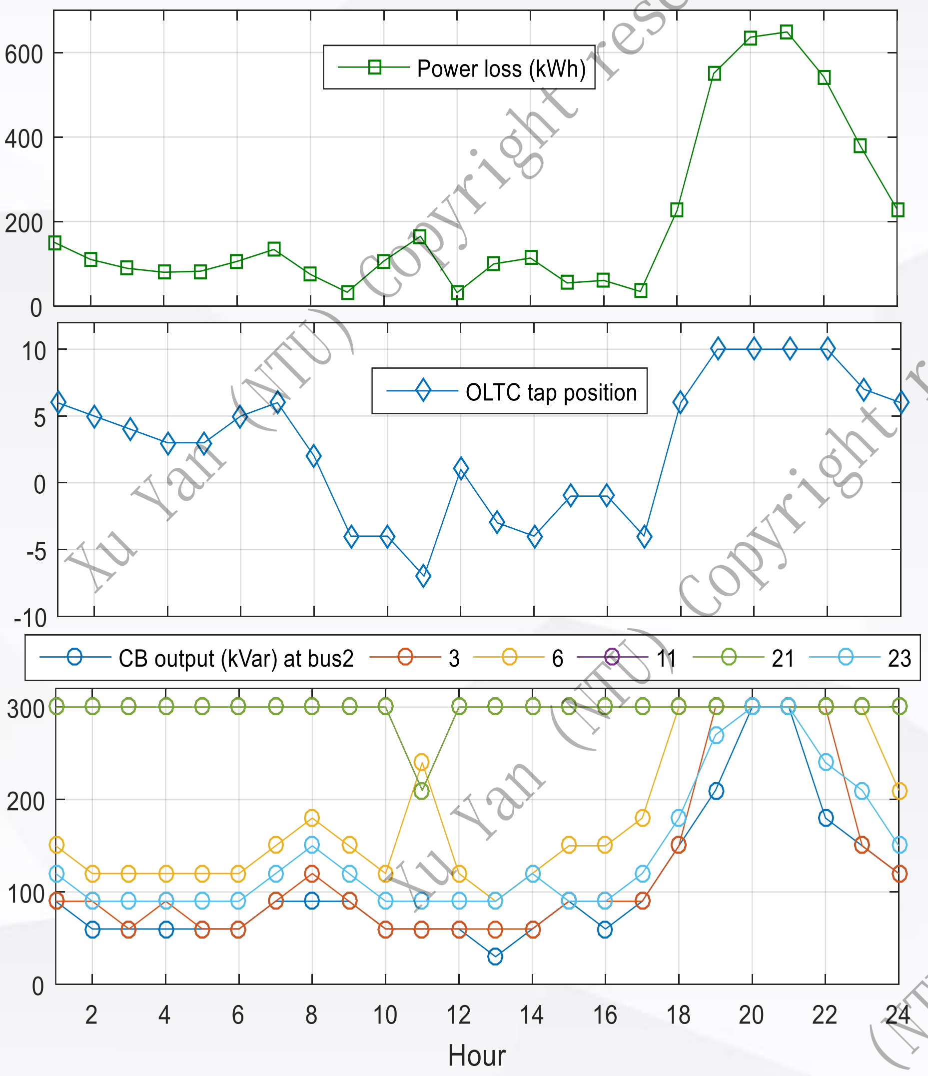
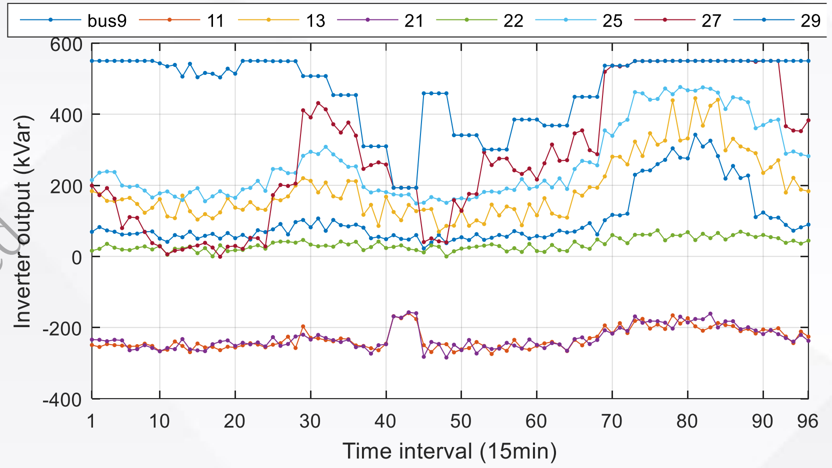
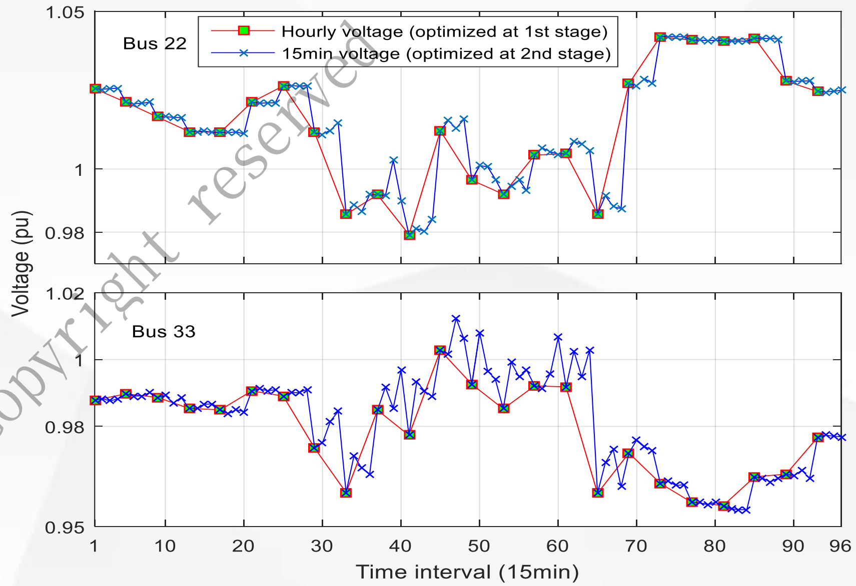
▪ Simulation Results







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

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Multi-Objective Adaptive Robust Voltage/VAR Regulation

- **Minimizing voltage deviation conflicts with minimizing network power loss.**
- **Multi-objective "min-max-min" problem**

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

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

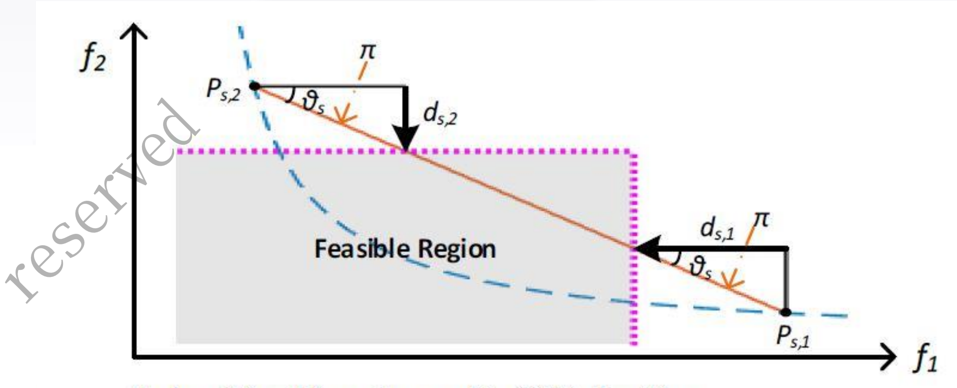
$$\boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{y} \leq \boldsymbol{v}$$

$$\boldsymbol{E}\boldsymbol{x} + \boldsymbol{G}\boldsymbol{y} + \boldsymbol{H}\boldsymbol{u} = \boldsymbol{w}$$

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

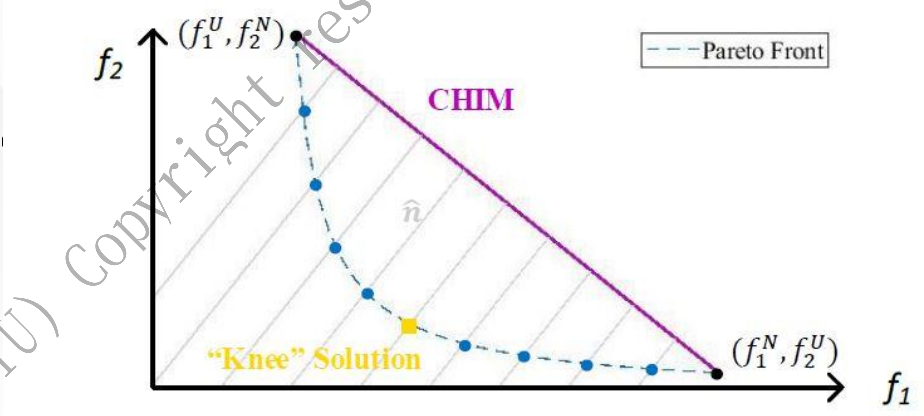
Key point:
1) Voltage deviation index: load-weighted voltage deviation index (LVDI)
2) Which MOP algorithm is more efficient to generat accurate Pareto front and get a fair trade-off?
    a) Classic Weighted-Sum (CWS)
    b) Classic ε-Constrained (CeC)
    c) Adaptive Weighted-Sum (AWS)
    d) Normal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

Adaptive Weighted Sum (AWS)



Reduced feasible region used in AWS algorithm.

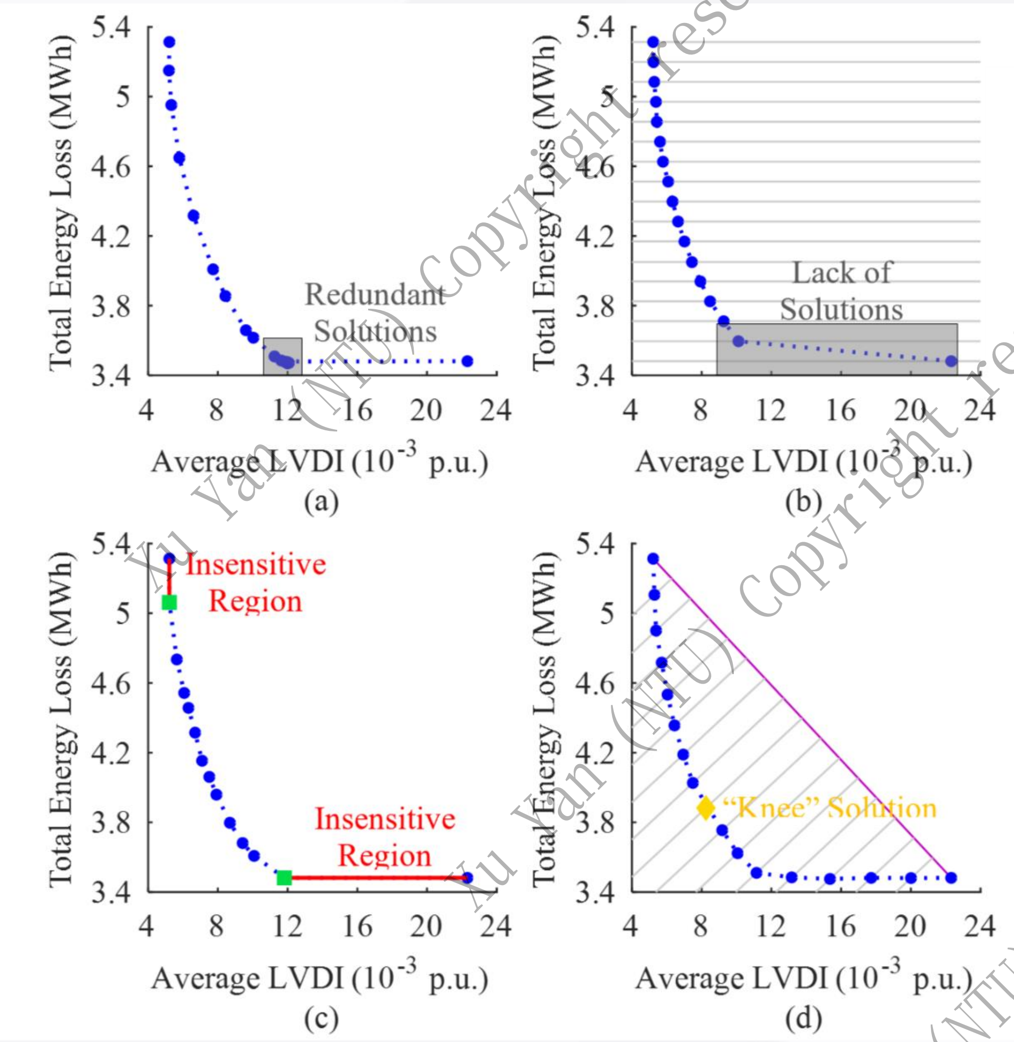
Normal Boundary Intersection (NBI)



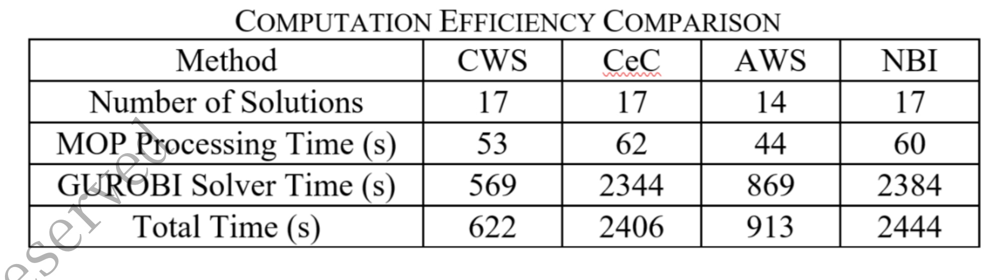
Pareto front generated by NBI algorithm.

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.**

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.**

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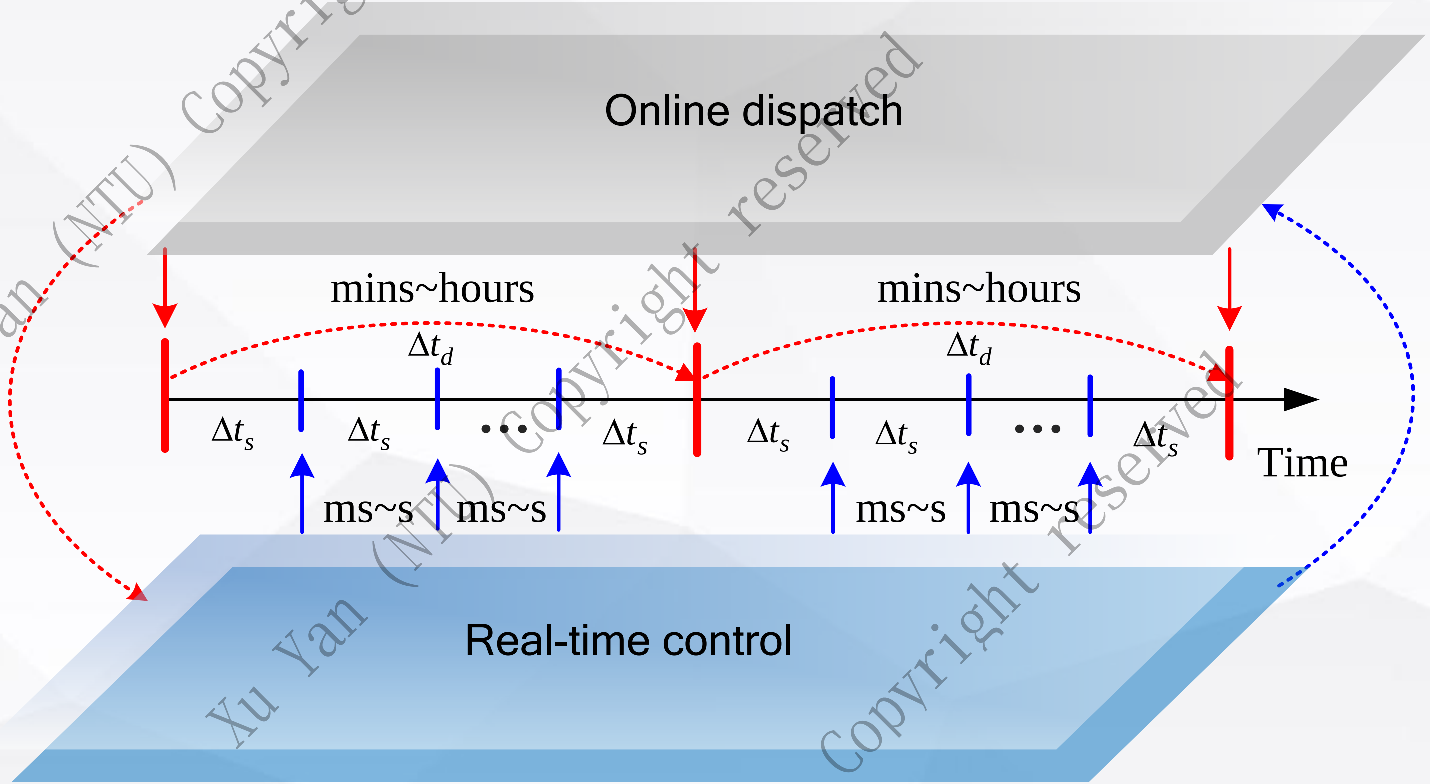
▪ Hierarchically coordinated operation and control of DERs

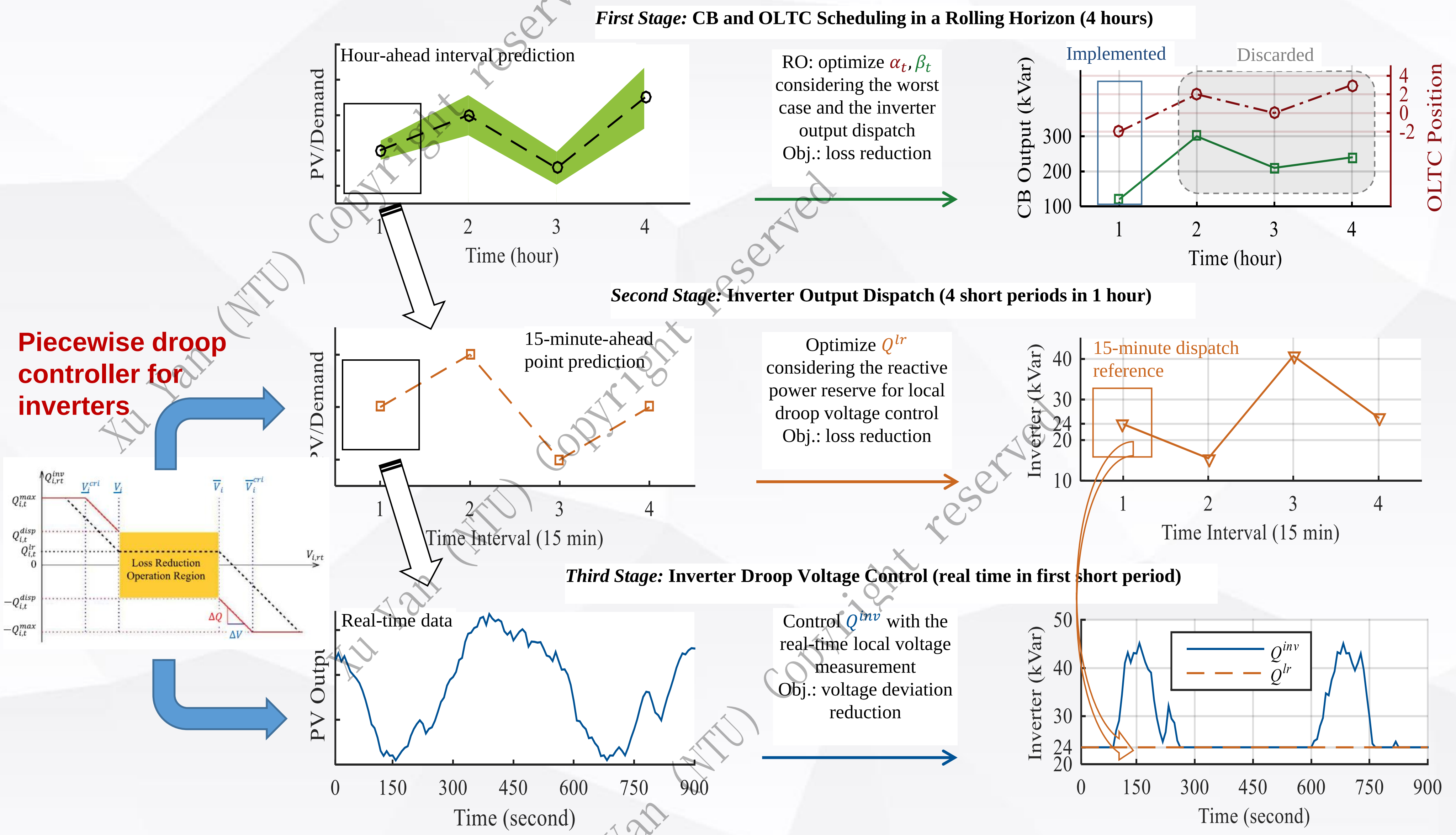
✓ Operational optimization and real-time control are traditionally **decoupled**.

✓ 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)



Piecewise droop controller for inverters

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

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**

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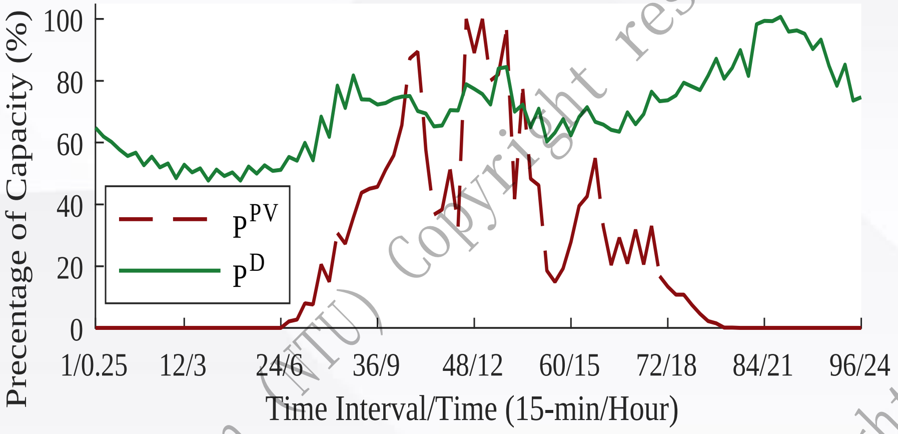
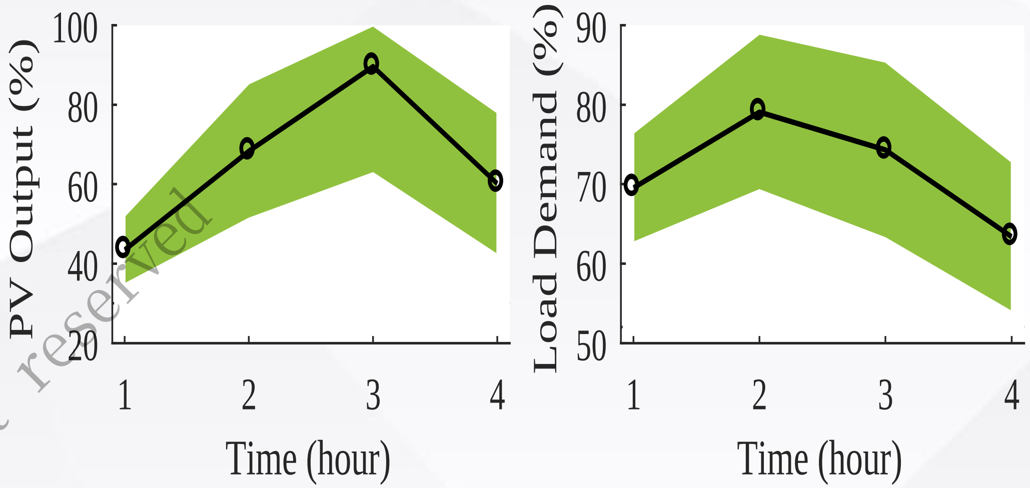
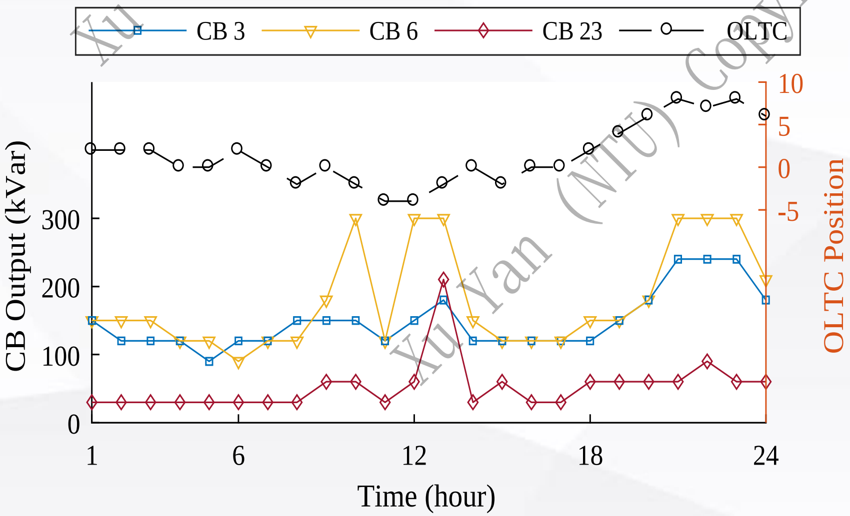
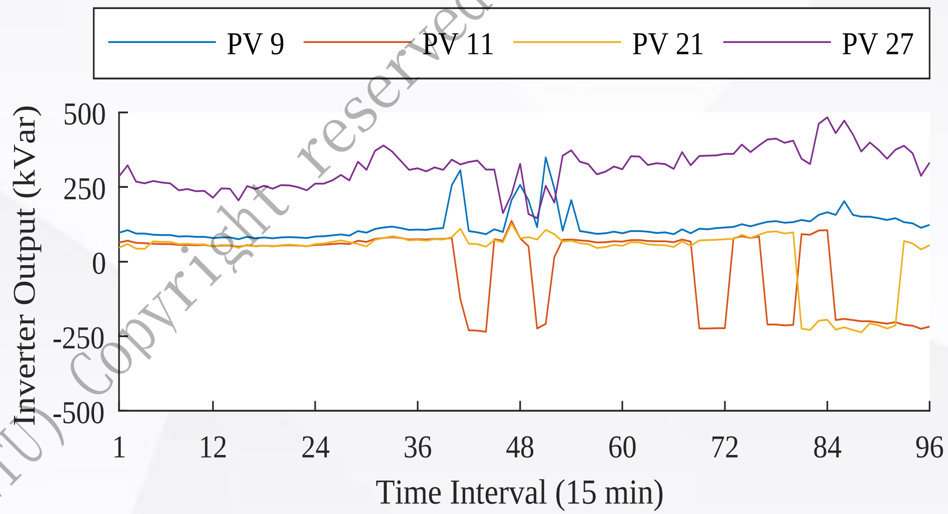
Simulation Results









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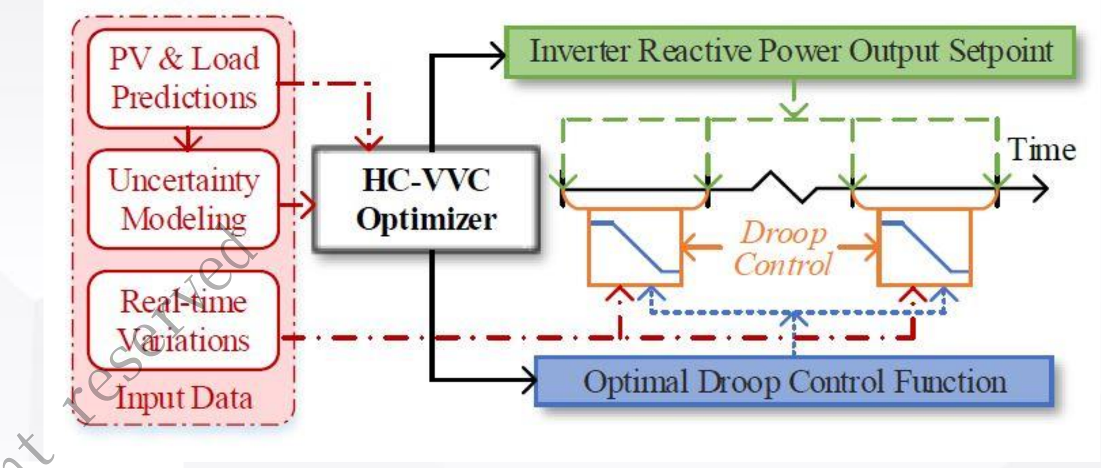
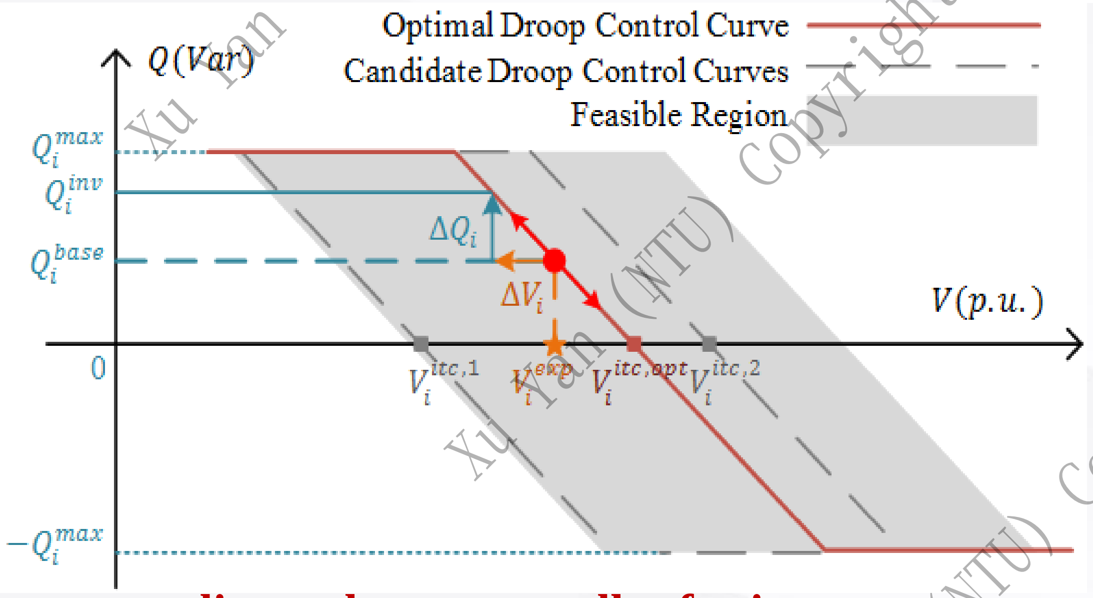
Hierarchically-Coordinated Voltage/VAR Control (HC-VVC)

- ✓ 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*.**

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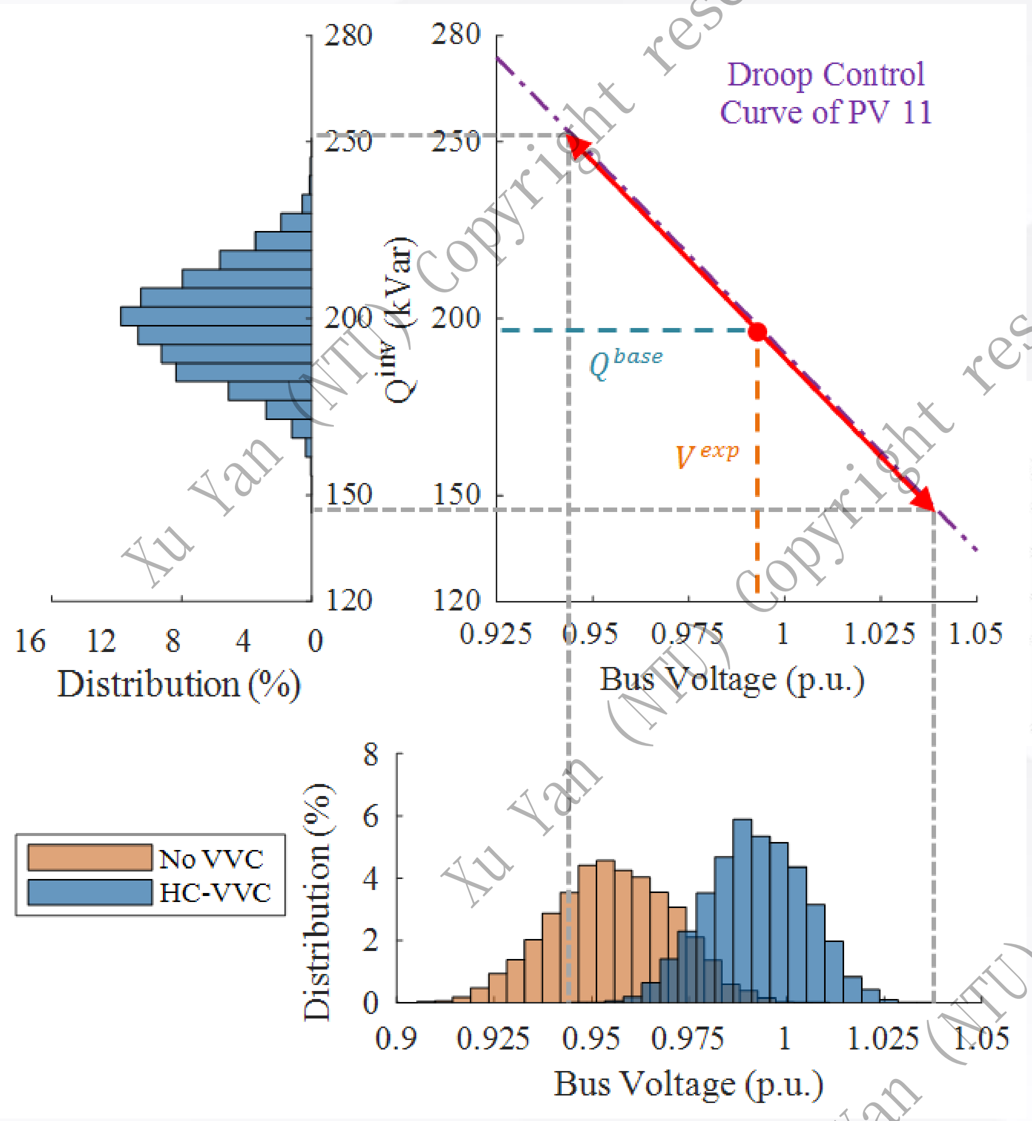
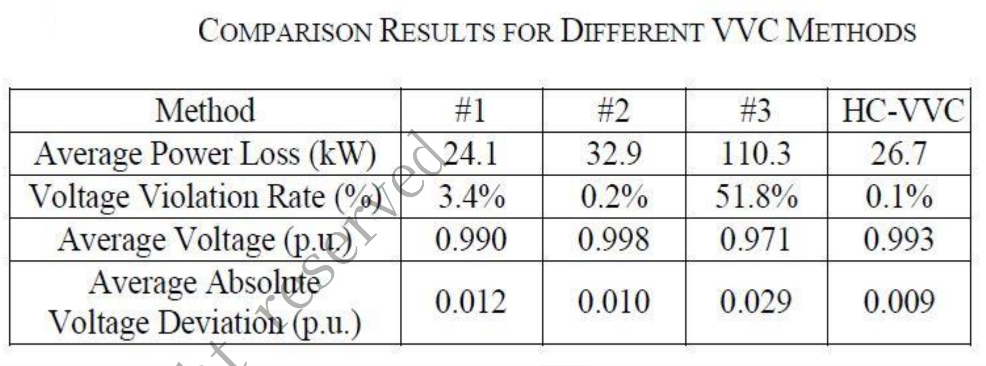
▪ Hierarchically-Coordinated Voltage/VAR Control (HC-VVC)



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, **Y. Xu***, "Hierarchically-Coordinated Voltage/VAR Control of Distribution Networks Using PV Inverters," ***IEEE Trans. Smart Grid*, 2020.**

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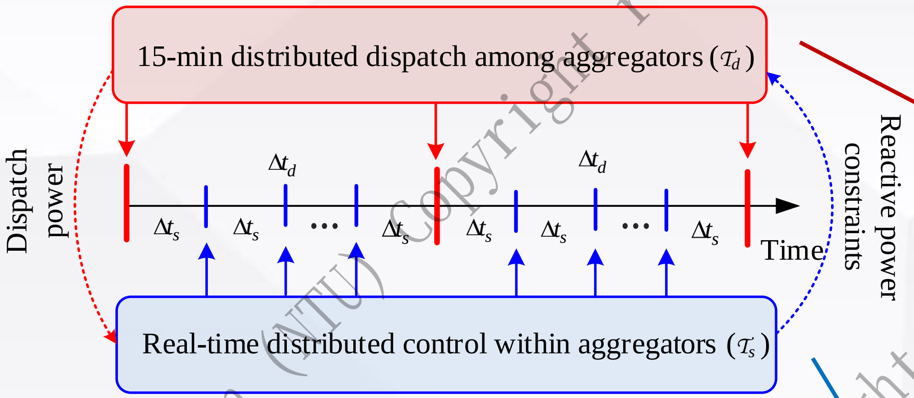
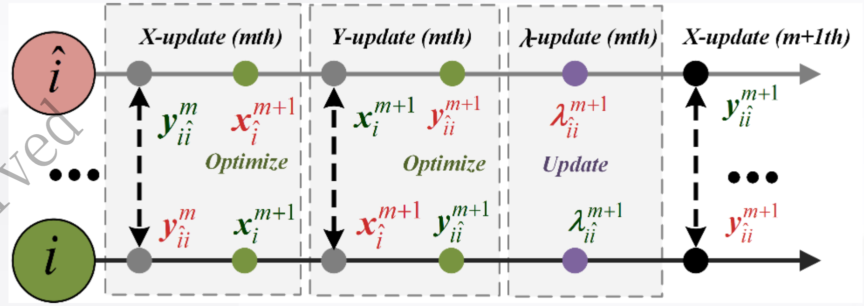
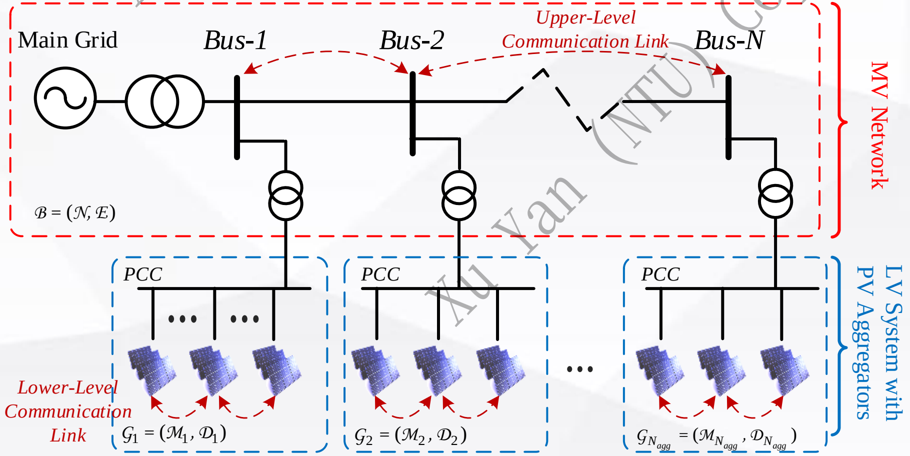
Fully Distributed Two-Level Volt/Var Control

Two-level VVC with time scale coordination

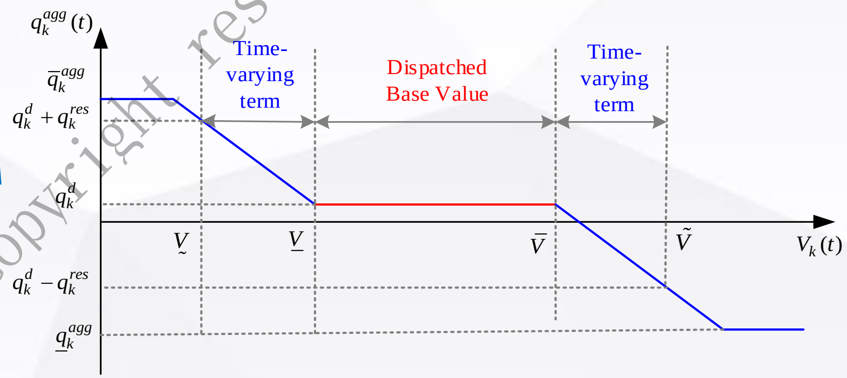


Distributed dispatch by ADMM





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**.

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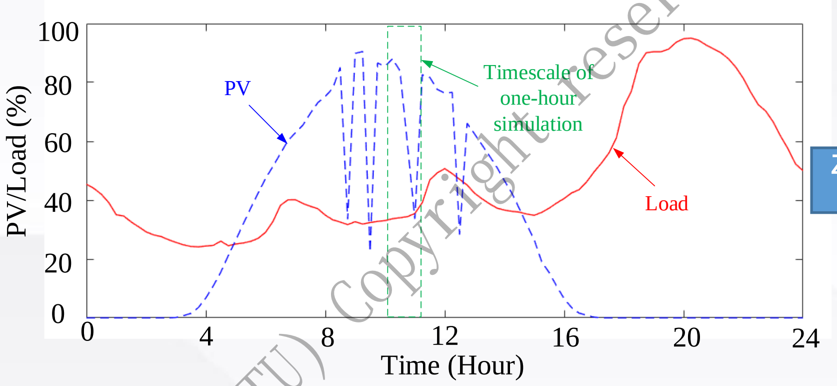
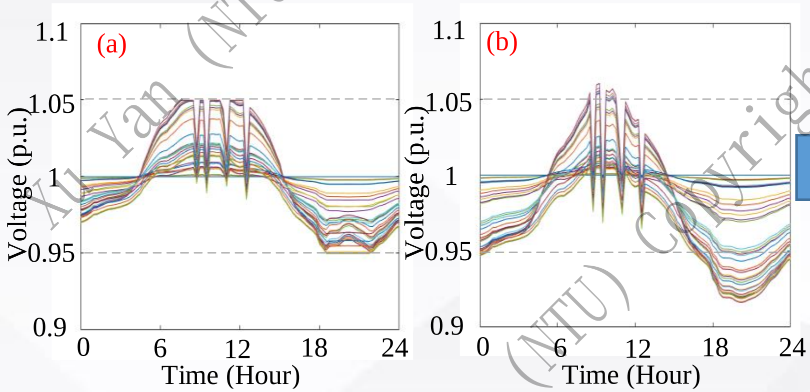
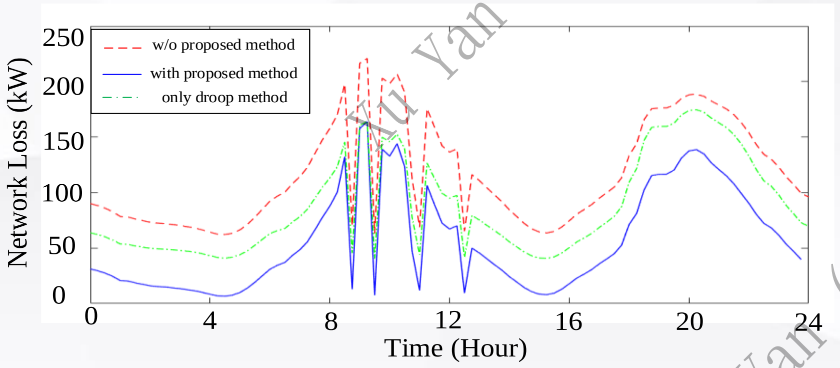
Simulation Results

24-hour simulation with 15 minutes sampling



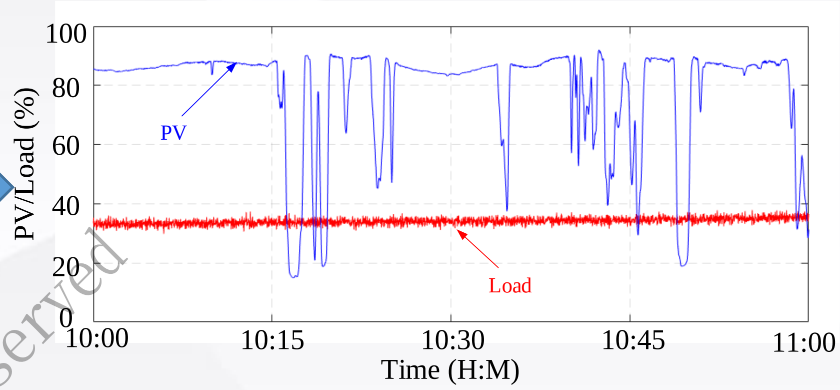


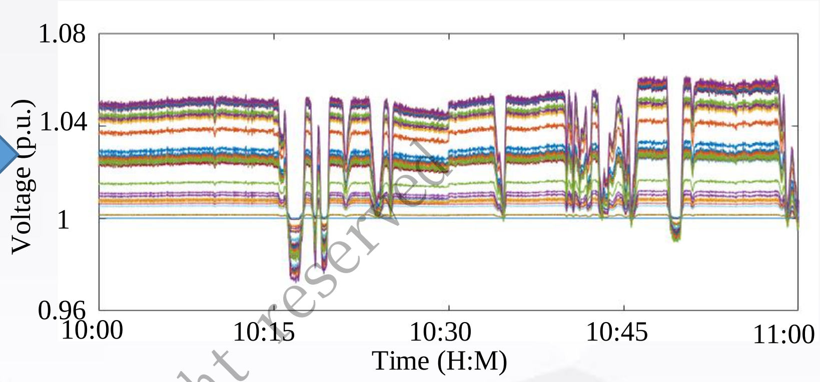


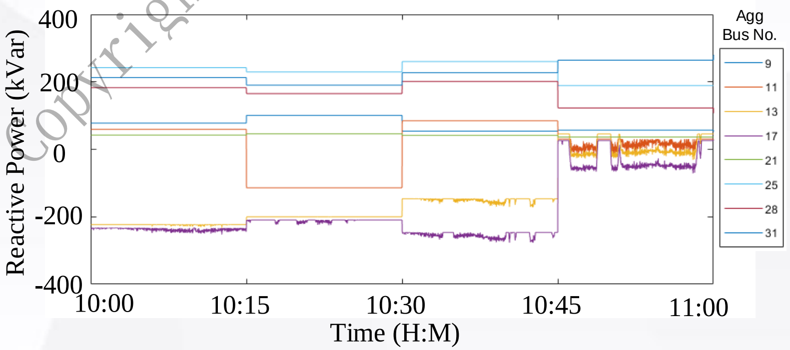
Zoom in

Zoom in

One-hour simulation with 1 second sampling







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**.

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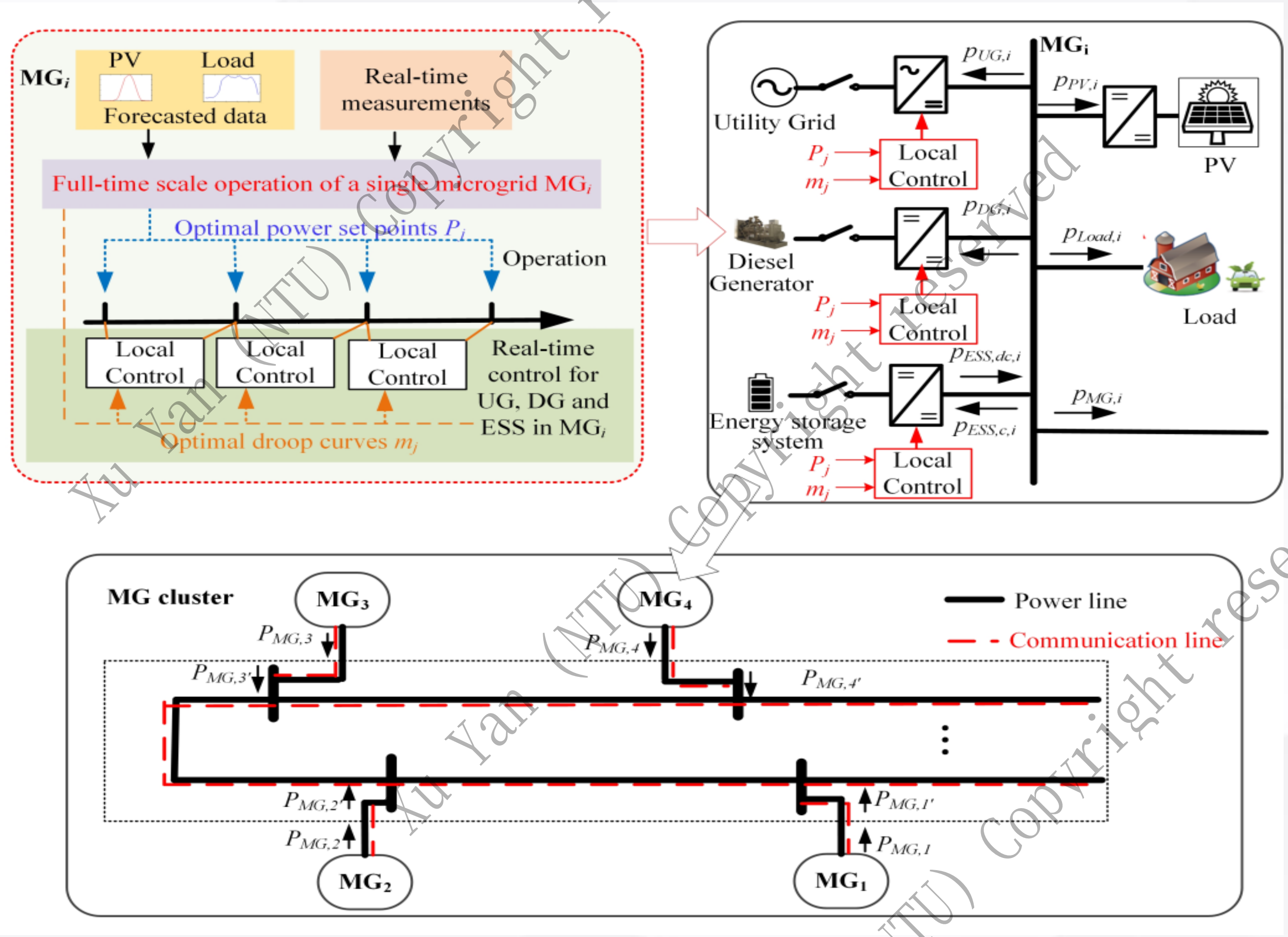
- Hierarchically Coordinated Operation and Control for DC microgrid clusters



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

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

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

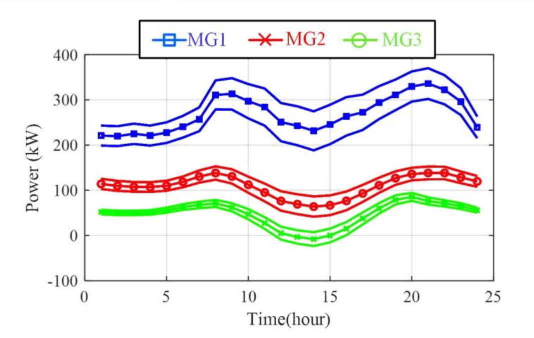
$$p_{\mathrm{ESS},i}-P_{\mathrm{ESS,dc},i}+P_{\mathrm{ESS,c},i}=\beta_{\mathrm{ESS},i}\xi_i$$

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

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

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

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



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.***

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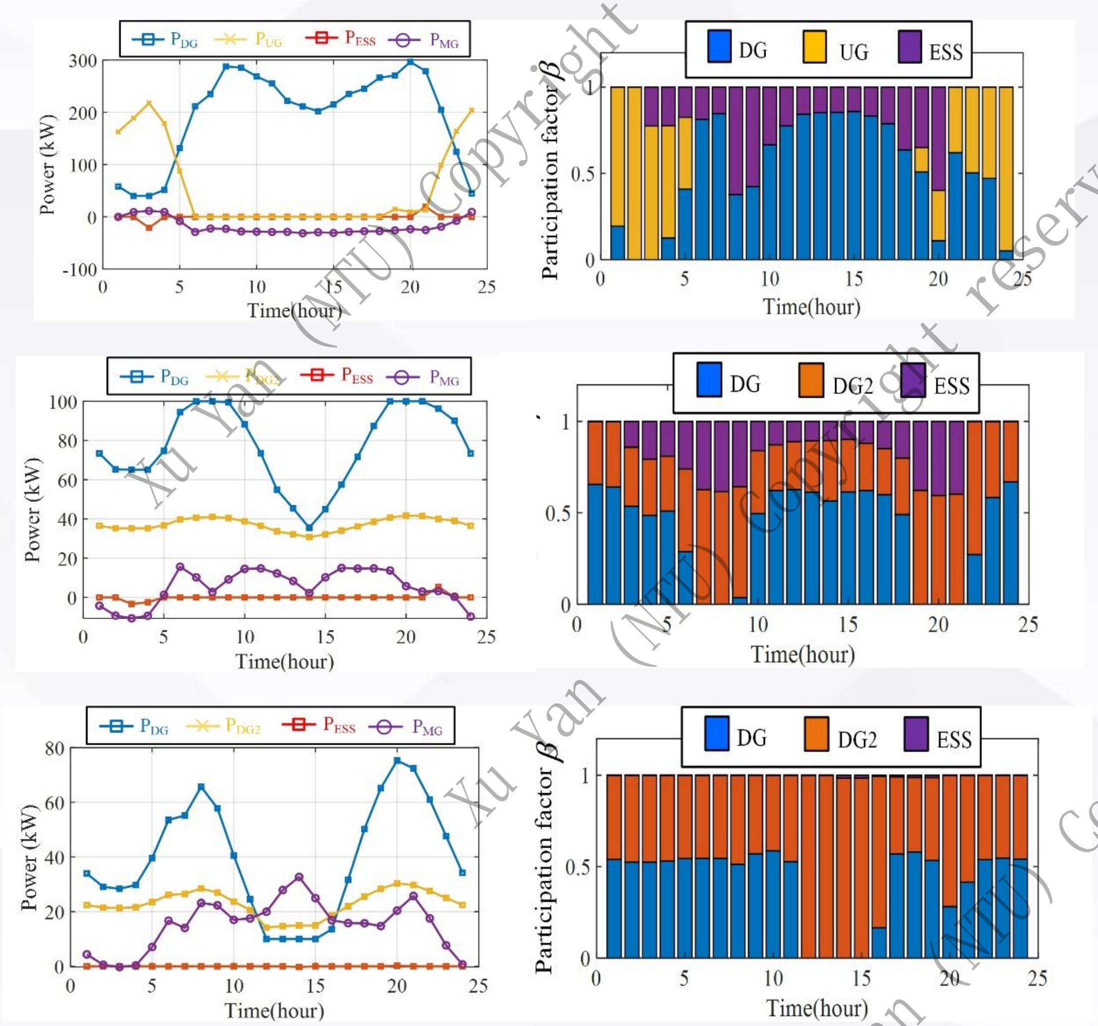
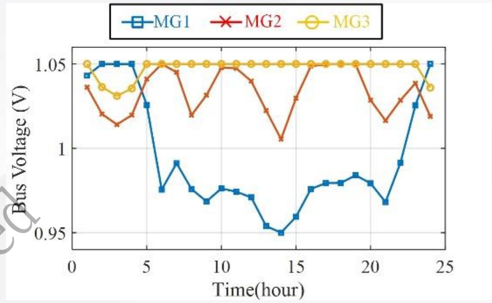
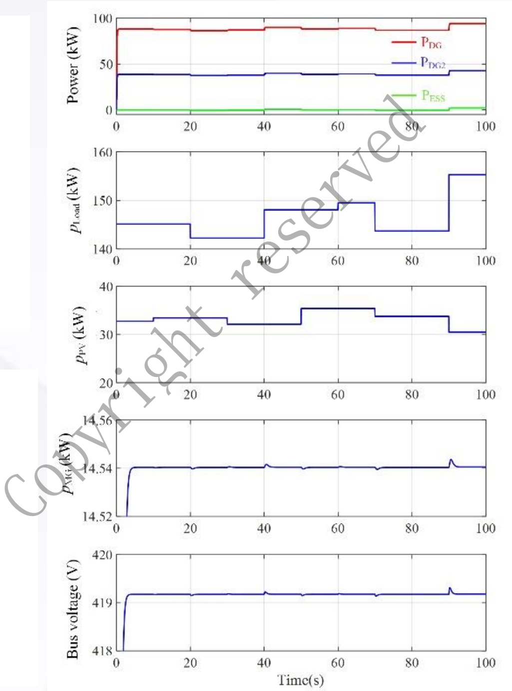
Hierarchically Coordinated Operation and Control for DC microgrid clusters

Dispatch results

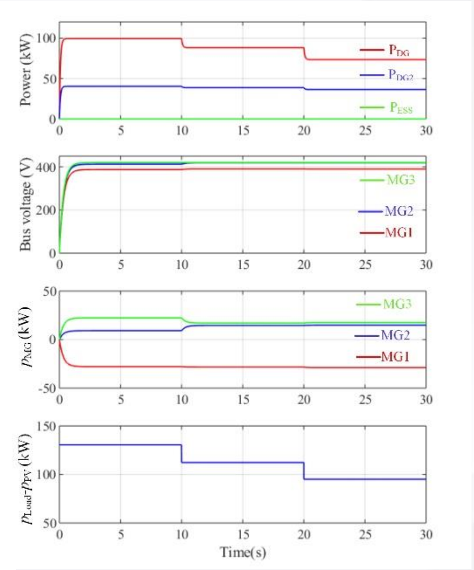




Real-time control results



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.**

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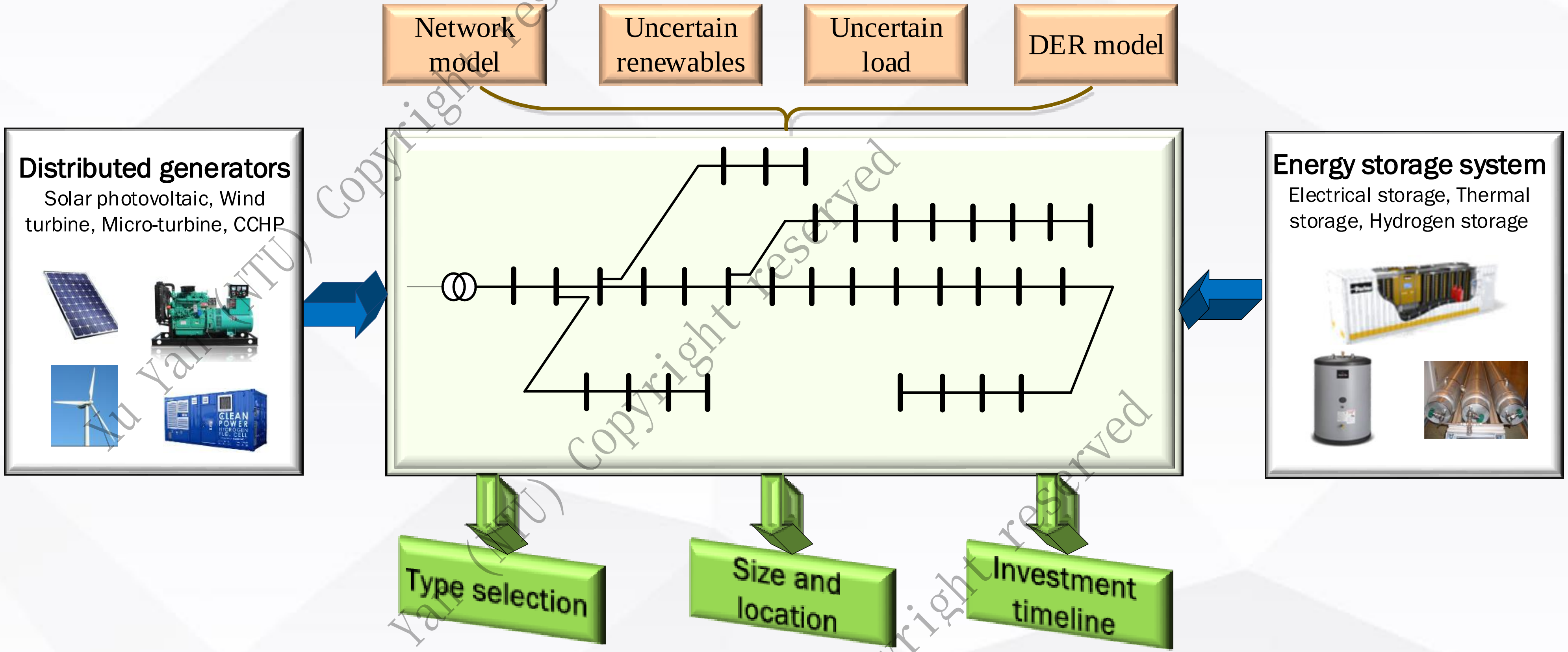
▪ Optimal Planning of DERs in Microgrid



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
...

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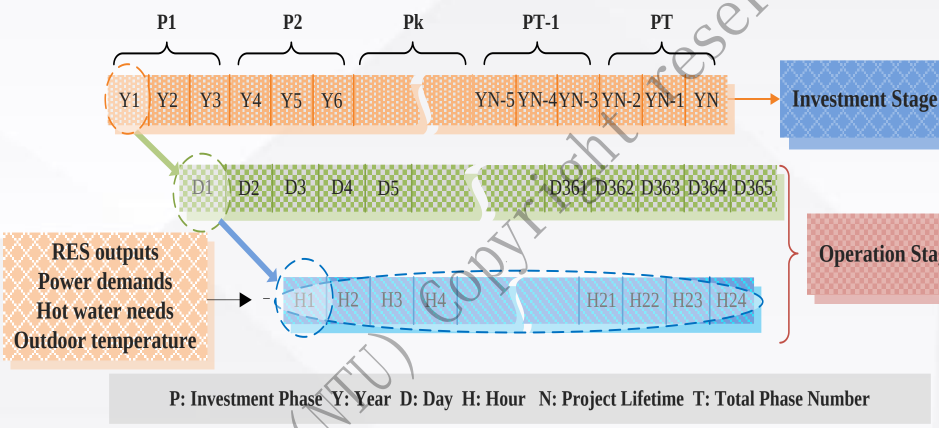
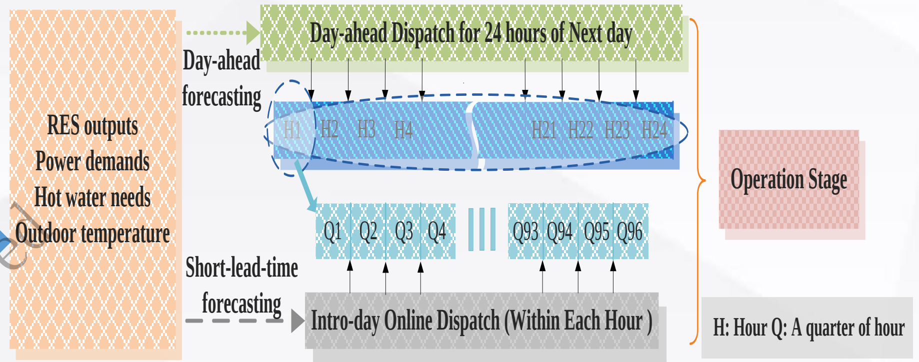
Optimal Placement of Heterogeneous Distributed Generators



Proposed two-stage DG placement method



Sub-stages for system operation

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

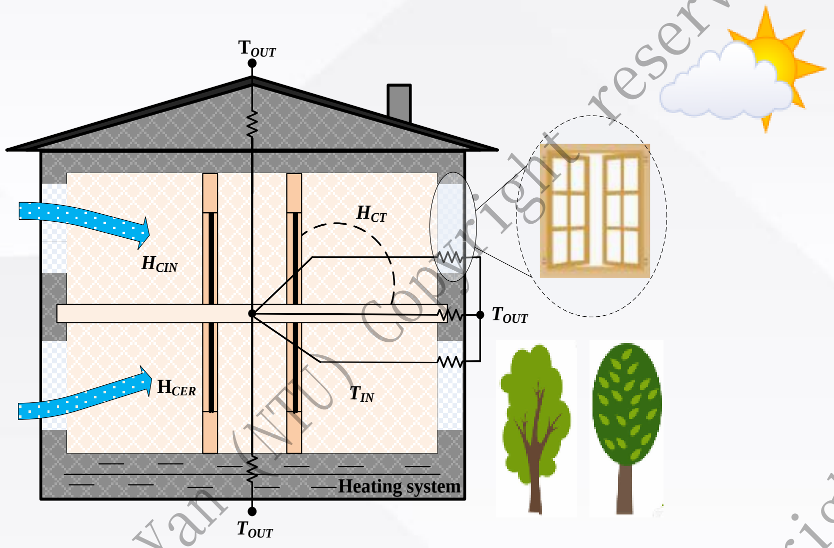
$$\begin{aligned} &\text{Min } G(x|c) = \underset{w}{\text{Min}}\{S(w|c) + E[Q(w|c,\omega)]\} \\ &s.t. \quad w \in CS_w \mid z \\ &\qquad Q(w|c,\omega) = \underset{y}{\text{Min}}\ L(y|c) \\ &\qquad y \in CL(w,\omega) \end{aligned}$$

System multi-stage operation model

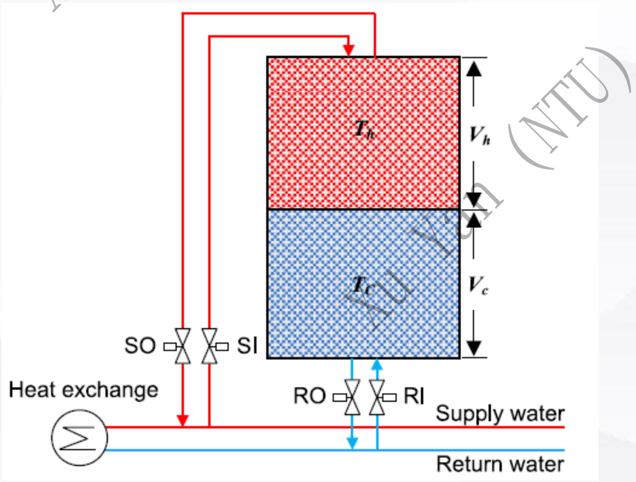
Year/Bus	3	6	9	12	18	22	25	27	30	33
					CCHP unit：Cap-65					
1-4	65	195	65	130	0	0	130	65	0	65
5-8	65	195	65	195	0	65	130	65	65	65
9-12	65	195	65	195	65	65	130	65	65	130
					Electric boiler: A					
1-4	123.2	96	90.7	0	146.8	41.5	167.8	92.9	0	0
5-8	123.2	96	128.1	0	146.8	88.5	214.8	92.9	0	0
9-12	138.5	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.*

Optimal Deployment of Heterogeneous Energy Storage



Typical structure of a room in a residential building



Structure of the thermal storage

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

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

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

Risk-averse objective function

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

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

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

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.

0. Outline

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1) Islanded mode
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5. Planning
1) DG planning
2) ESS planning
3) PRO algorithm

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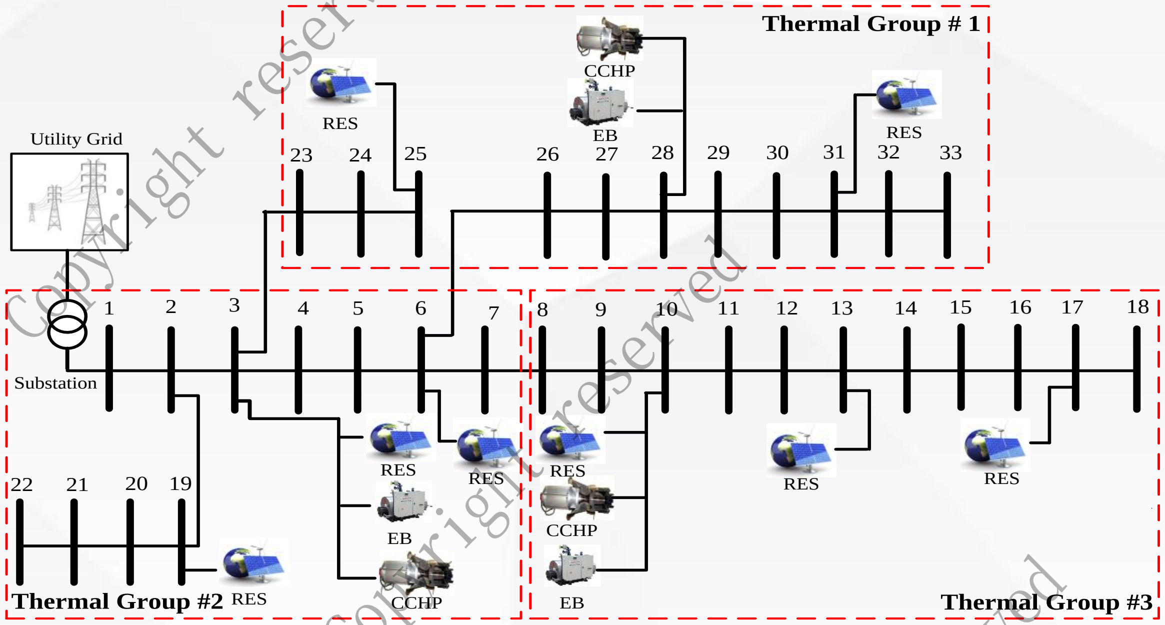
Planning results



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

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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

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

PRO Formulation

$$\min_x a^T x + \sum_{n\in N} \rho_n \left(\max_{u_n \in U_n} \min_{y_n} b^T y_n + c^T u_n \right)$$

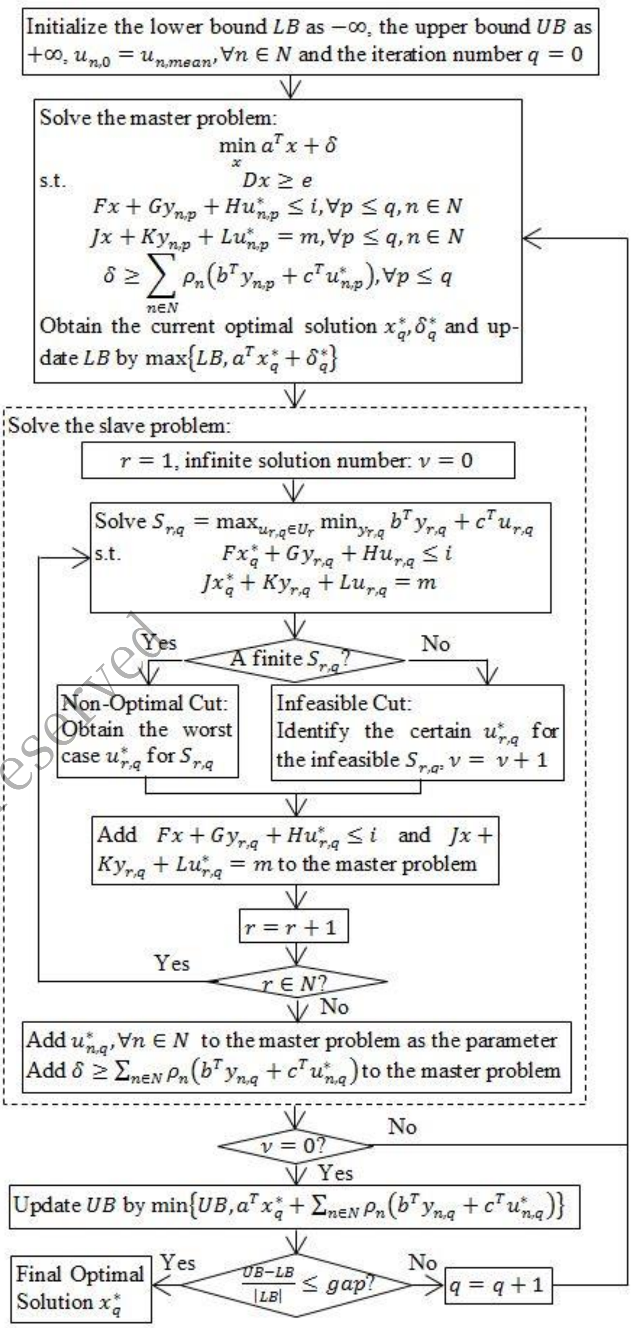
$$\text{s.t.} \quad Dx \geq e$$

$$Fx + Gy_n + Hu_n \leq i, \forall n$$

$$Jx + Ky_n + Lu_n = m, \forall n$$

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:
$$\min_x a^T x + \delta$$
$$\text{s.t.} \quad Dx \geq e$$
$$Fx + Gy_{n,p} + Hu_{n,p}^* \leq i, \forall p \leq q, n \in N$$
$$Jx + Ky_{n,p} + Lu_{n,p}^* = m, \forall p \leq q, n \in N$$
$$\delta \geq \sum_{n\in N} \rho_n \left(b^T y_{n,p} + c^T u_{n,p}^* \right), \forall p \leq q$$
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: $\nu = 0$

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

A finite $S_{r,q}$?

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 $S_{r,q}$, $\nu = \nu + 1$

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

$r = r + 1$

$r \in N$?

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

$\nu = 0$?

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

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

Final Optimal Solution x_q^*

$q = q + 1$

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

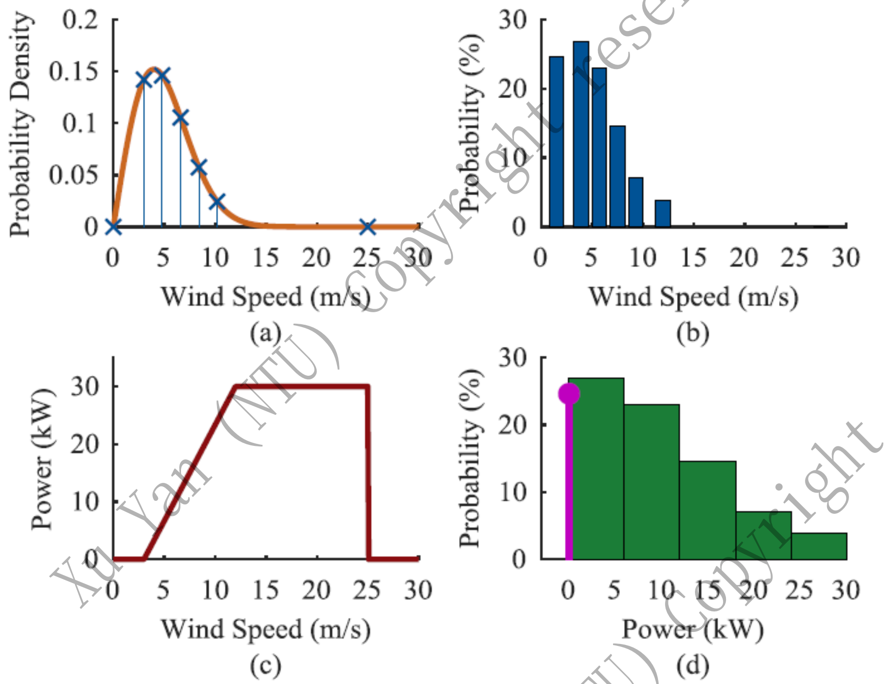
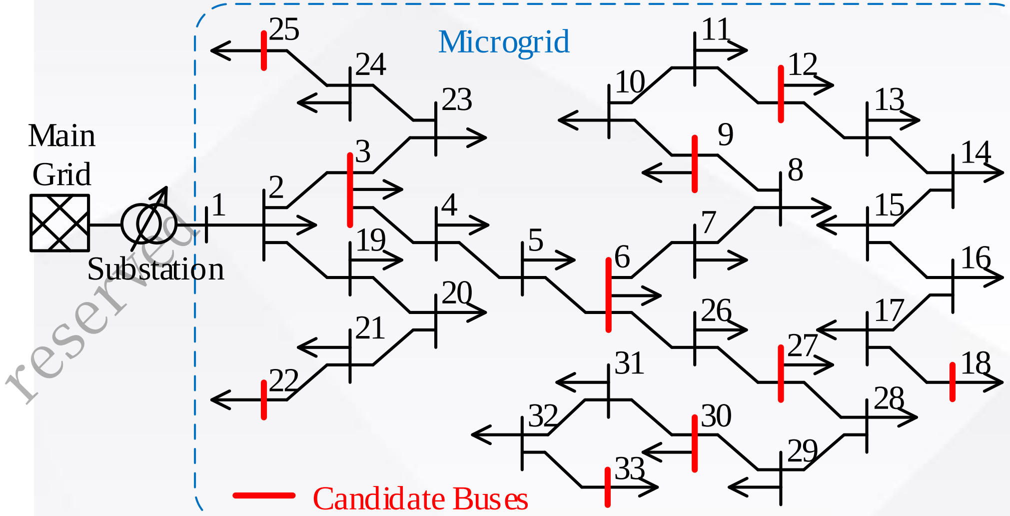


Fig. 3 (a) Wind speed probability density; (b) Wind speed probability; (c) Wind power generation function; (d) Wind power probability.



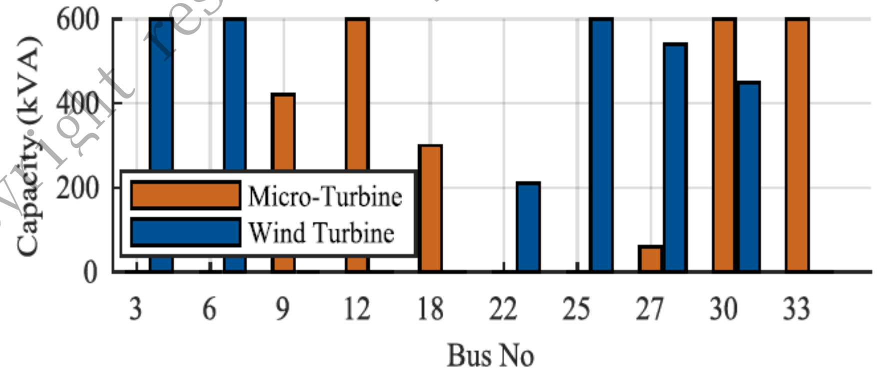


Fig. 4 DG planning decisions.

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

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

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Thank You!