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Dynamics-aware Optimal Microgrid Scheduling under Uncertainty

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ZD. Chu, N. Zhang and **F. Teng*** "Frequency-Constrained Resilient Scheduling of Microgrid: A Distributionally Robust Approach", *IEEE Trans. Smart Grid*, 2021

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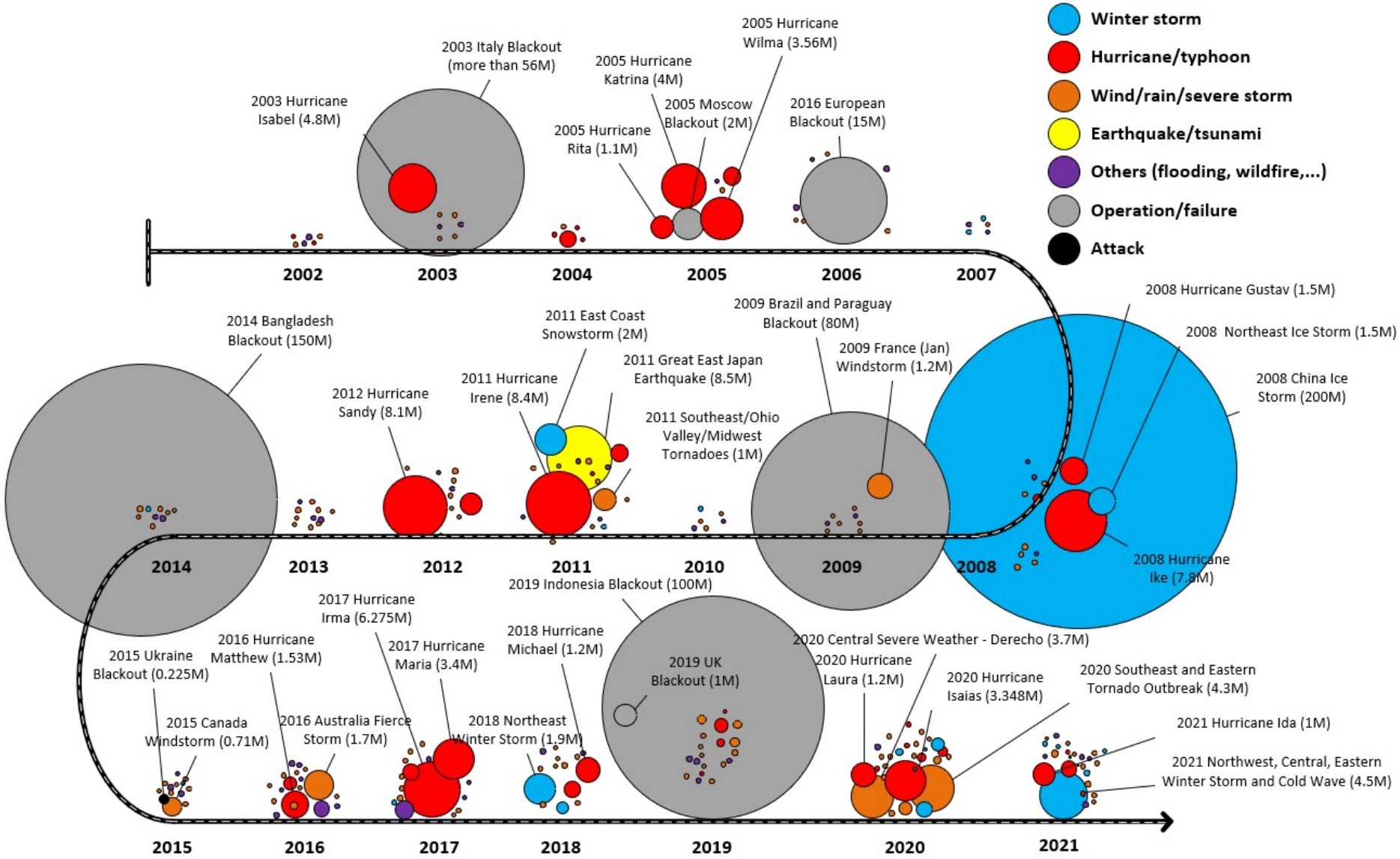
Backgrounds – Call for Resilience



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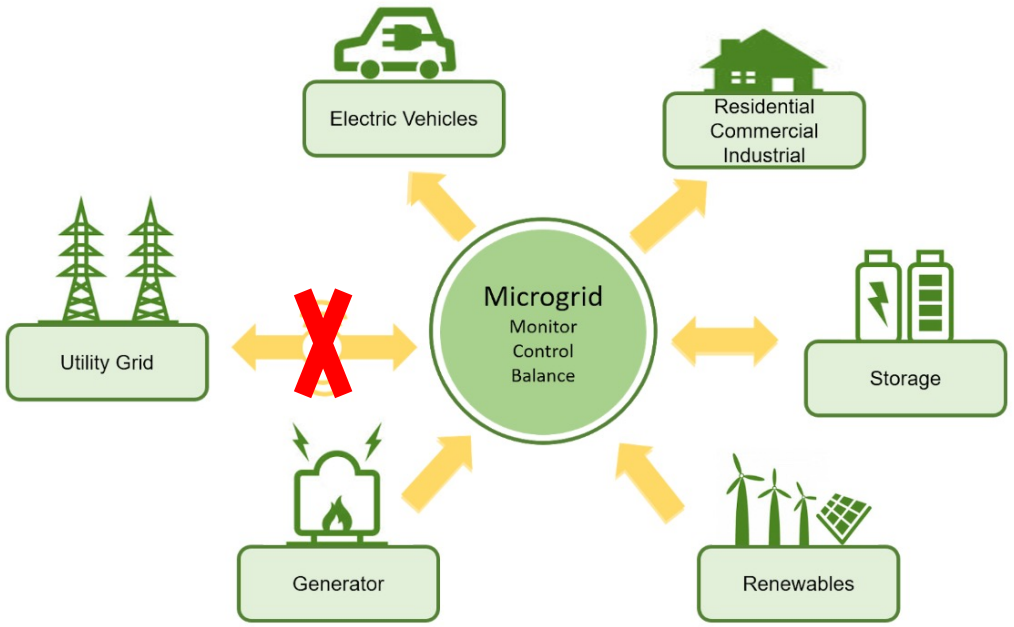
Backgrounds – MGs for Resilience



- Microgrid scheduling with islanding events:

  Grid-connected mode —(External disturbances)→ Islanded mode

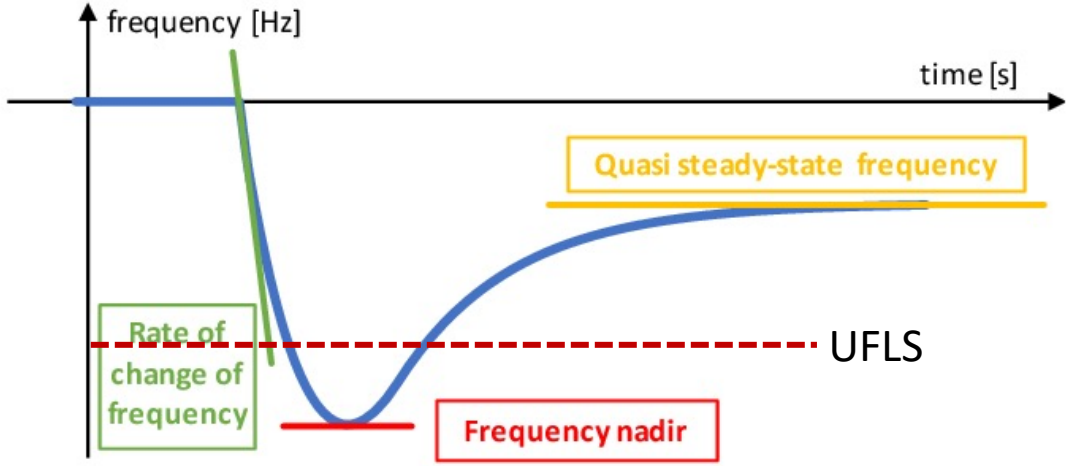
- Existing solutions:

  Energy balance-based MG scheduling

  Dynamics during transition ignored

  - Uncertainty management (renewables, EV and load)
  - Microgrid reconfiguration to enhance resilience
  - Demand response modelling and control
  - Optimal sizing and placement of storage devices

Low Inertia;
Large Disturbance



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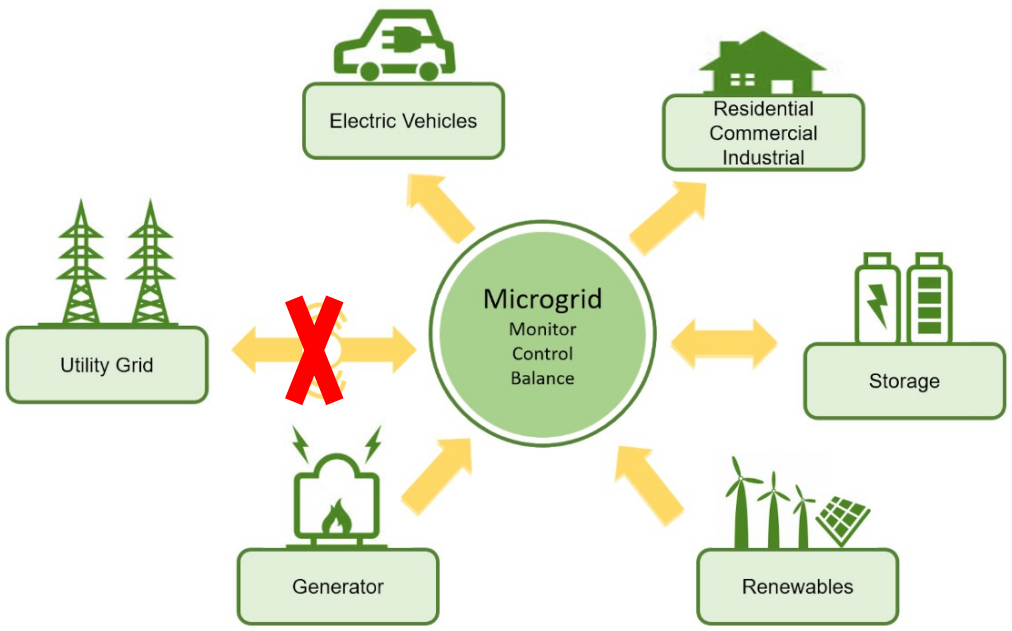
Backgrounds – MGs for Resilience

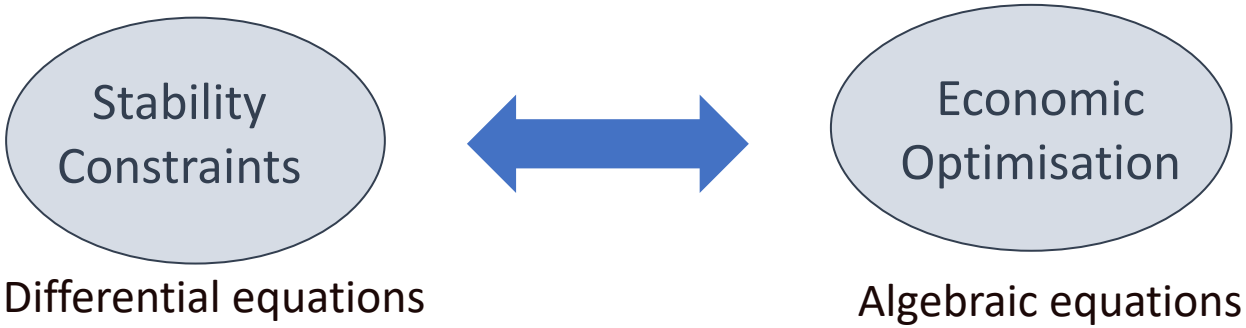


Energy balance-based MG scheduling

Dynamics-aware MG scheduling

RoCoF,
Frequency nadir,
Steady State Frequency.

- Key Concept:



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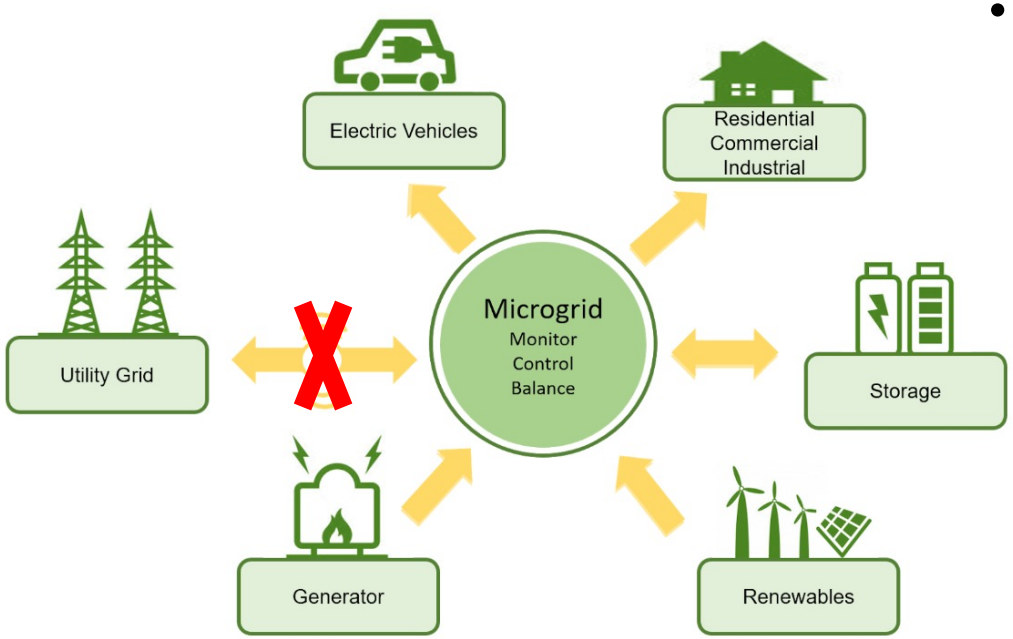
Challenges – PE Modelling

➡ Frequency constrained microgrid scheduling Challenges:



- Modelling of frequency support from IBRs
  - Flexible control
  - Balance between performance and complexity
  - Strict power/current limits of IBRs

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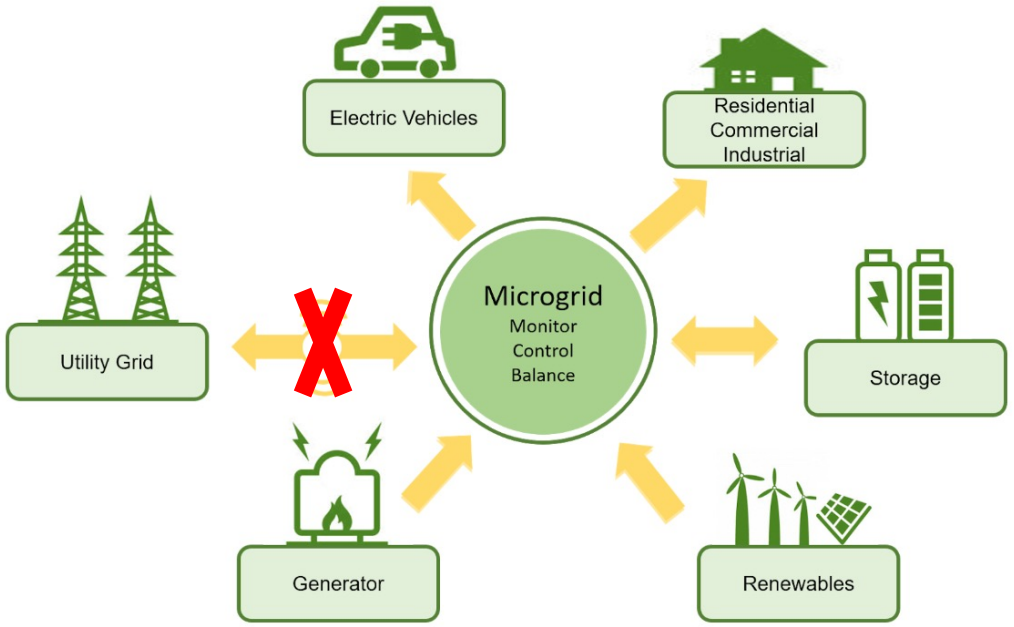
Challenges – Uncertainty

➡ Frequency constrained microgrid scheduling Challenges:



- Uncertainty of noncritical load shedding
  - Estimation of noncritical loads under uncertainty
  - Development of constraints to reflect such uncertainty

↓

Distributionally Robust Optimization, DRO:

Optimize among all the distribution in an ambiguity set

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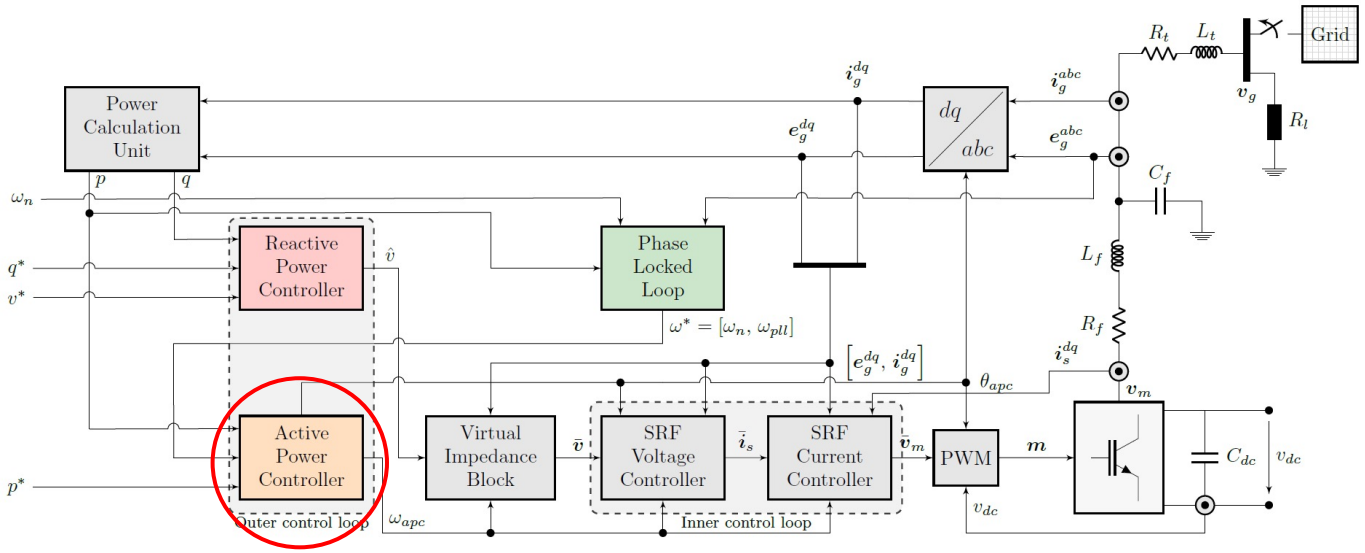
H_{s_b} Synthetic inertia from storage unit b
P_b Normal output power of storage unit b
$\bar{P}_b^{\mathrm{ch}}/\bar{P}_b^{\mathrm{dch}}$ Maximum charging/discharging rate

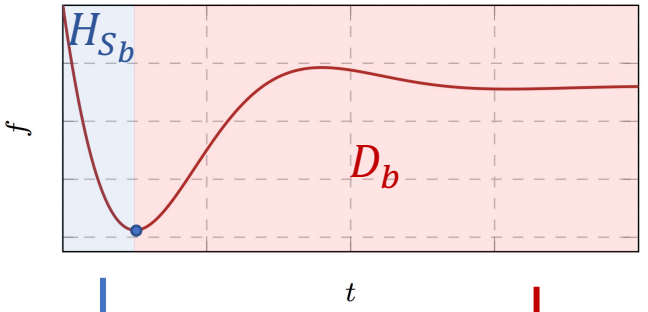
Frequency Support from Storage Units



General configuration of VSC control structure

- Power limits of inertia and damping provision:

$$\bar{P}_b^{\mathrm{ch}} \le P_b - 2H_{s_b}\Delta\dot{f}(t) - D_b\Delta f(t) \le \bar{P}_b^{\mathrm{dch}}, \quad \forall t \in \mathcal{T}_0$$



$$\bar{P}_b^{\mathrm{ch}} \le P_b + 2H_{s_b}\Delta\dot{f}_{\mathrm{lim}} \le \bar{P}_b^{\mathrm{dch}}$$

$$\bar{P}_b^{\mathrm{ch}} \le P_b - D_b\Delta f_{\mathrm{lim}} \le \bar{P}_b^{\mathrm{dch}}$$

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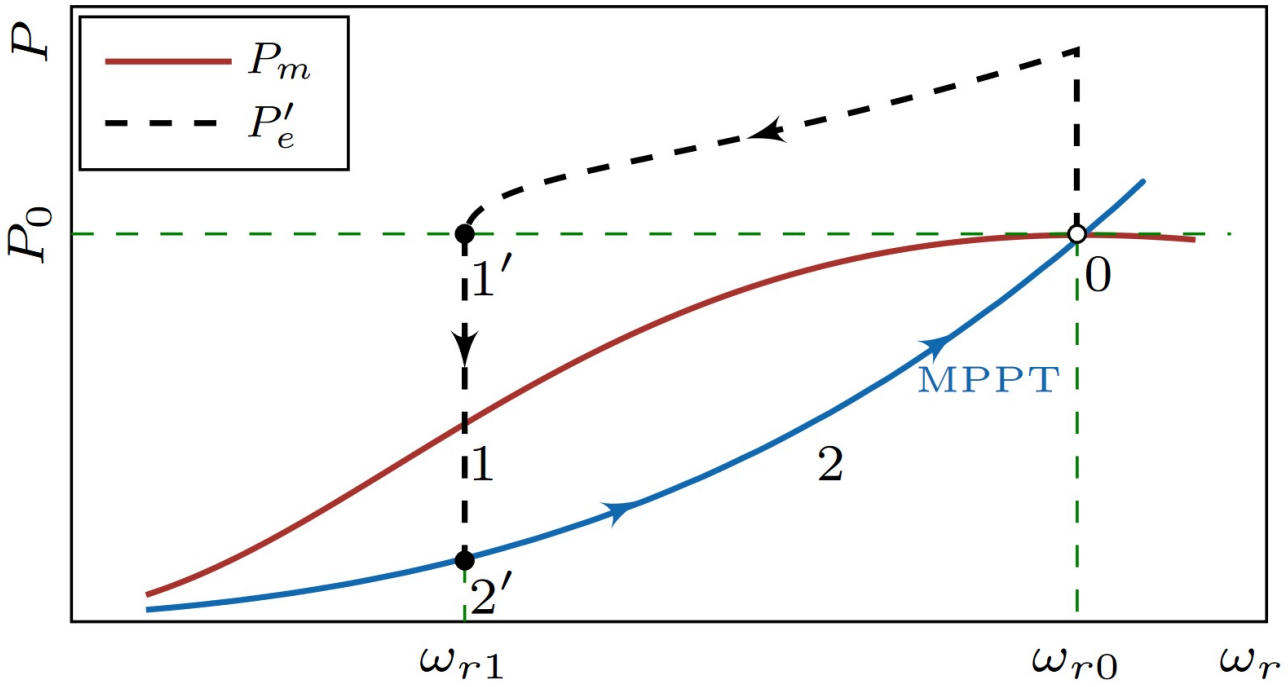
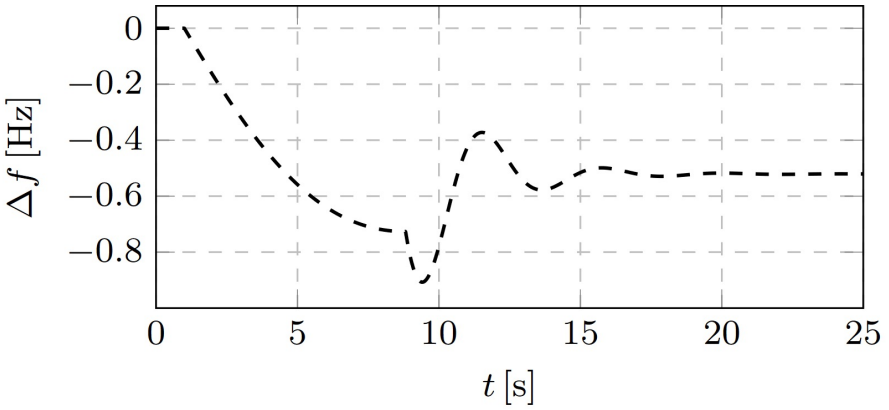
Synthetic Inertia from WTs





Kinetic energy extraction

↓

Rotor deceleration

↓ $(\omega_{r0} \rightarrow \omega_{r1})$

Mechanical power loss

↓ (Termination)

Electric power drop for recovery

↓

Secondary frequency dip

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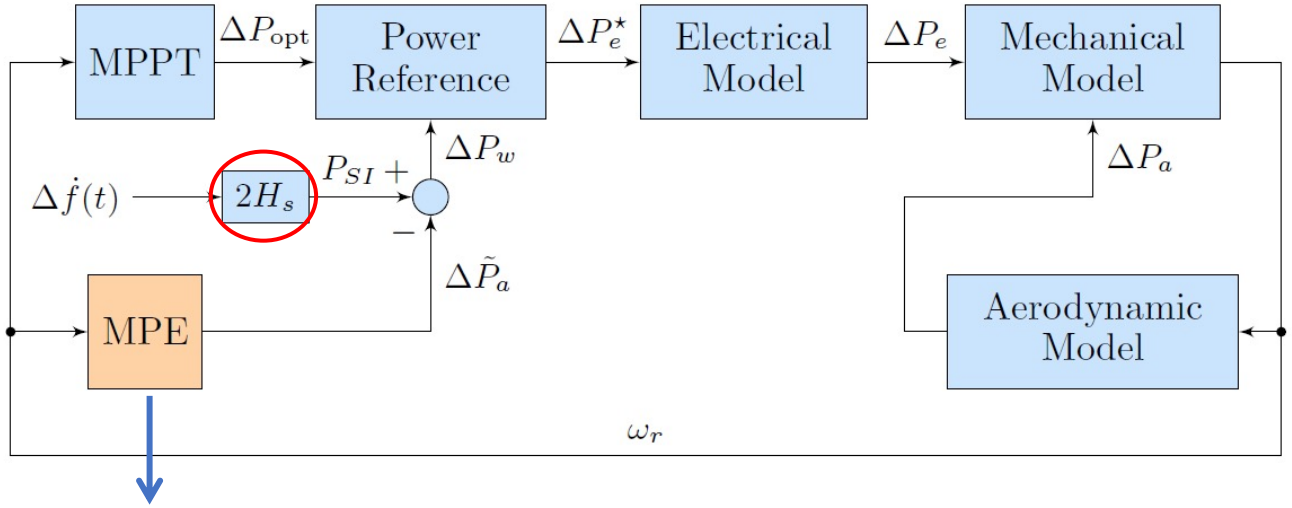
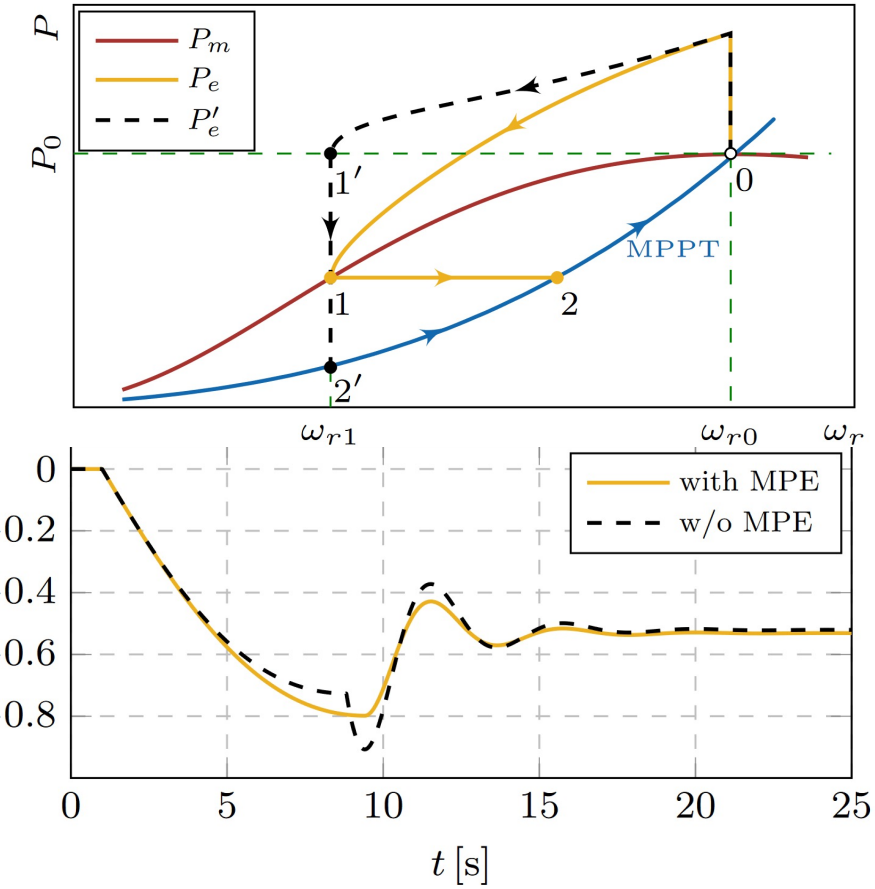
Synthetic Inertia from WTs

WT frequency support scheme



Mechanical Power Estimator



$$\Delta P_w = -2H_s\Delta\dot{f} + \Delta\tilde{P}_a$$

$$\Delta\tilde{P}_a = D_s\Delta f = \gamma H_s^2\Delta f$$

$$H_s \le H_{s,\max}$$

Damping approximation

Z. Chu, U. Markovic, G. Hug and **F. Teng**, "Towards Optimal System Scheduling With Synthetic Inertia Provision From Wind Turbines," in IEEE Transactions on Power Systems, vol. 35, no. 5, pp. 4056-4066, Sept. 2020

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F. Teng, V. Trovato and G. Strbac, "Stochastic Scheduling with Inertia-dependent Fast Frequency Response" *IEEE Trans. Power Syst.*, Vol 31, Issue 2, 2016

Frequency constraints derivation

$$2H\frac{\partial \Delta f(t)}{\partial t} = -D\Delta f(t) + \Delta R(t) - \Delta P_L$$

(Standard form swing equation)

$$\Delta f(t) = \left(\frac{\Delta P_L}{D} + \frac{2HR}{T_d D^2}\right)\left(e^{-\frac{D}{2H}t} - 1\right) + \frac{R}{T_d D}t$$

Nadir constraint: $HR \geq \frac{\Delta P_L^2 T_d}{4\Delta f_{\lim}} - \frac{\Delta P_L T_d D}{4}$

total inertia(H) | total damping(D) | equivalent loss(ΔP_L)

$$2\left(H_c + \sum_b H_{s_b} + \sum_w H_{s_w}\right)\frac{\partial \Delta f(t)}{\partial t} = -(D_0 - \sum_w \gamma_w H_{s_w}^2)\Delta f(t) + \Delta R(t) - (\Delta P_{L_0} - \Delta P_D)$$

Conventional generator | SI from BESS | SI from WTs | Side effect of H_{s_w} | PFR | Infeed power from main Grid | Noncritical load shedding

ΔP_L: decision variable with uncertainty

$$\mathcal{P} = \Big\{\mathbf{D} \in \Phi(\Delta P_L) : \mathbb{E}^{\mathbf{D}}(\Delta P_L) = \Delta P_{L_\mu},\ \mathrm{Var}^{\mathbf{D}}(\Delta P_L) = \sigma^2\Big\}$$

$$HR \geq \frac{\Delta P_L^2 T_d}{4\Delta f_{\lim}} - \frac{\Delta P_L T_d D_0}{4} + \frac{\Delta P_L T_d \sum_{w\in\mathcal{W}} \gamma_w H_{s_w}^2}{4}$$

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Frequency Nadir Constraint

ΔP_L: decision variable with uncertainty

$$\mathcal{P} = \Big\{ \mathbf{D} \in \Phi(\Delta P_L) : \mathbb{E}^{\mathbf{D}}(\Delta P_L) = \Delta P_{L_\mu}, \ \mathrm{Var}^{\mathbf{D}}(\Delta P_L) = \sigma^2 \Big\}$$

$$\min_{\mathbf{D}\in\mathcal{P}} \Pr\left\{ HR \geq \frac{\Delta P_L^2 T_d}{4\Delta f_{\lim}} - \frac{\Delta P_L T_d D_0}{4} + \frac{\Delta P_L T_d \sum_{w\in\mathcal{W}} \gamma_w H_{s_w}^2}{4} \right\} \geq \eta$$

(DRO)

$$HR \geq \frac{T_d}{4}\left[\frac{(\Delta P_{L_\mu} + \xi\sigma)^2}{\Delta f_{\lim}} - D_0(\Delta P_{L_\mu} + \xi\sigma) \right] + \frac{\Delta P_L^{\max} T_d \sum_{w\in\mathcal{W}} \gamma_w H_{s_w}^2}{4}$$

$$HR \geq \frac{T_d}{4} x_1^2 + \frac{\Delta P_L^{\max} T_d \sum_{w\in\mathcal{W}} \gamma_w H_{s_w}^2}{4}$$

(Rotated quadratic cone)

$$YZ \geq \sum x_i^2$$

$$x_1^2 = x_2^2 - dx_2$$

$$x_1^2 = \frac{(\Delta P_{L_\mu} + \xi\sigma)^2}{\Delta f_{\lim}} - D_0(\Delta P_{L_\mu} + \xi\sigma)$$

$$= \underbrace{\frac{\Delta P_{L_\mu} + \xi\sigma}{\sqrt{\Delta f_{\lim}}}}_{x_2} \left(\frac{\Delta P_{L_\mu} + \xi\sigma}{\sqrt{\Delta f_{\lim}}} - \underbrace{\sqrt{\Delta f_{\lim}} D_0}_{d} \right)$$

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Frequency-constrained Microgrid Scheduling

$$\min \sum_{s\in\mathcal{S}}\sum_{t\in T}\pi_s\Big(\sum_{g\in\mathcal{G}} c_g^{SU} z_{t,s,g} + \Delta t\Big(\sum_{g\in\mathcal{G}_1} c_g^{R1} y_{t,s,g} + \sum_{g\in\mathcal{G}_2} c_g^{R2} p_{t,s,g} + \sum_{l\in\mathcal{L}} c^{VOLL}\big(p_{t,s,l}^c + (q_{t,s,l}^c)^2\big)\Big)\Big)$$

Constraints:

- Frequency security constraints
- AC power flow and power balance
- Battery storage system
- …

Multiple services optimization:

H_c H_{bs} H_{ws} R ΔP_{L0} ΔP_D

Decision variables (with uncertainty)

MISOCP

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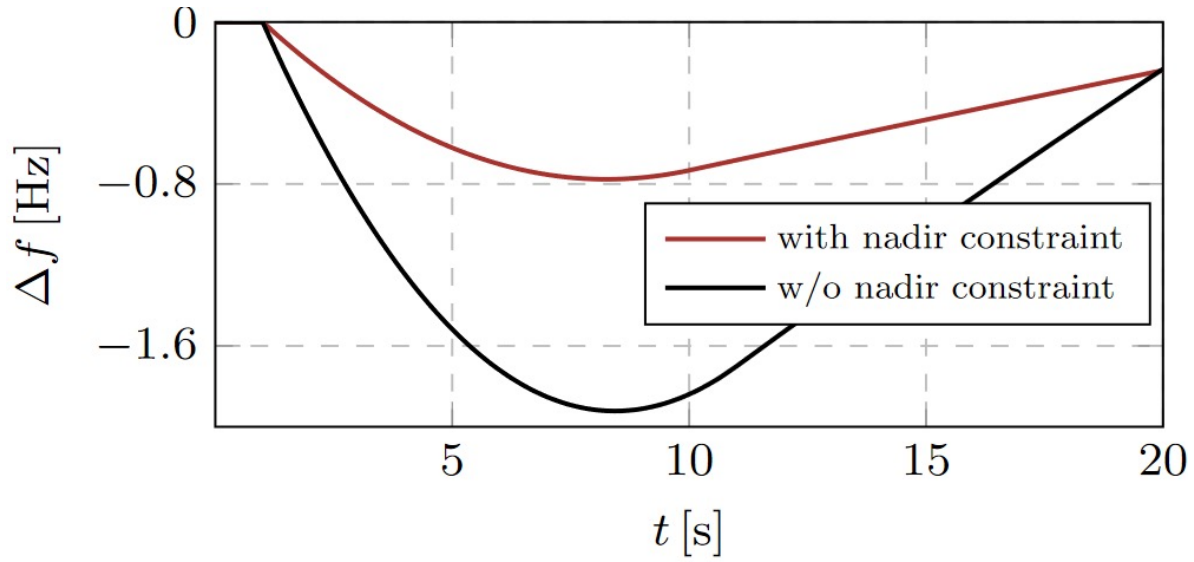
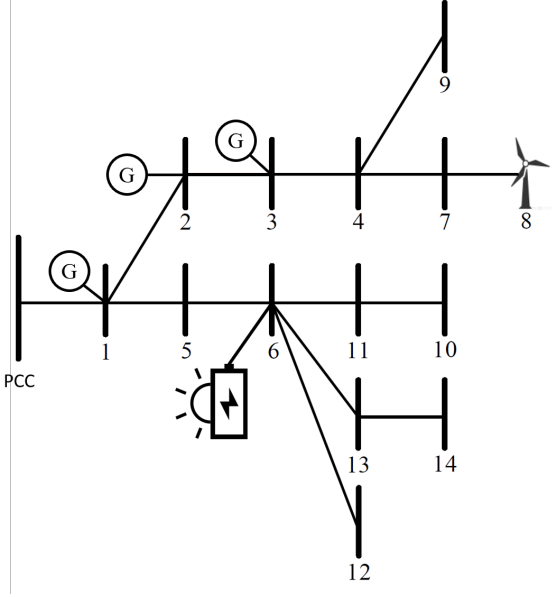
Results

- Frequency nadir validation





	RoCoF	Nadir	Steady-state
Energy-based	✗	✗	●
Dynamics-aware	●	●	●

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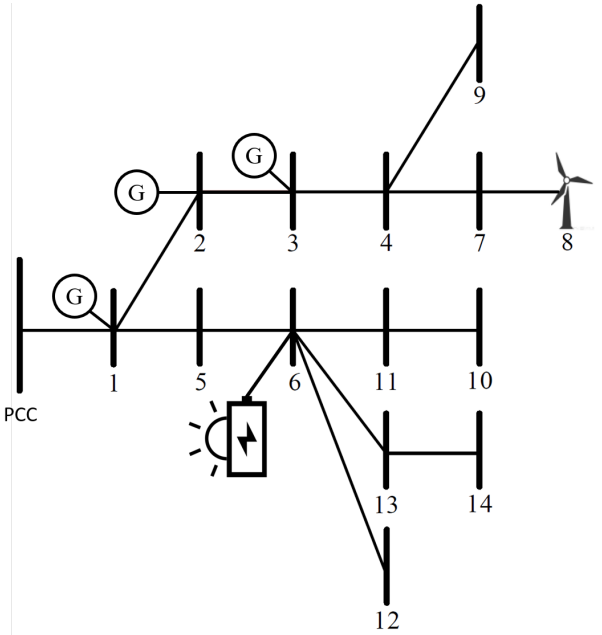
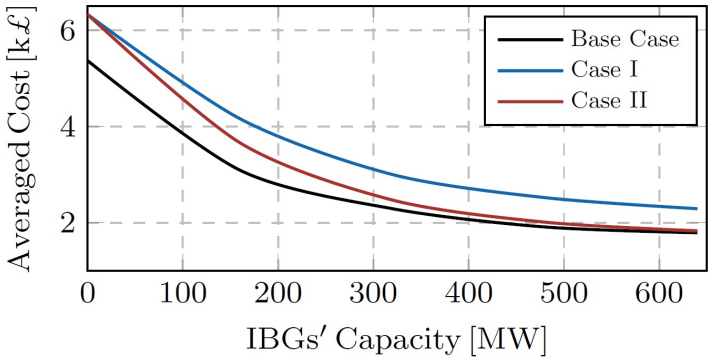
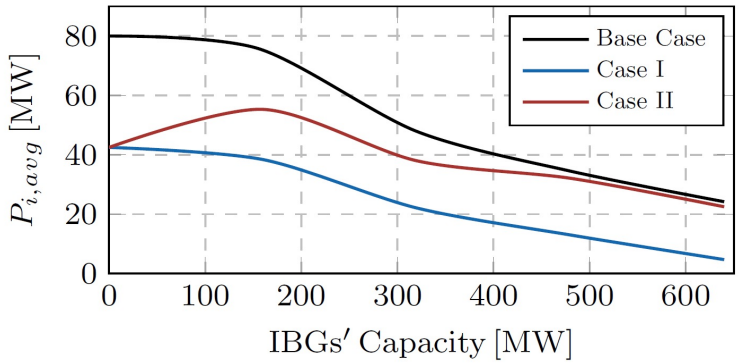
Results

	Dynamic Constraints	SI
Base Case	N	--
Case I	Y	N
Case II	Y	Y

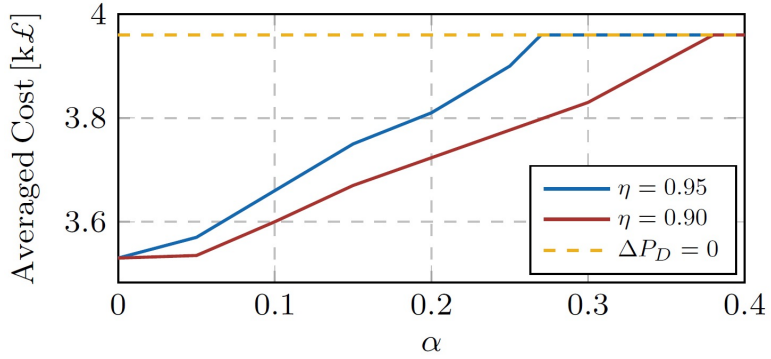


- Impact of dynamic constraints and SI provision





- Impact of uncertainty level of demand shedding



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Conclusion

- A novel dynamics-aware microgrid scheduling model is proposed with optimal microgrid operating conditions, noncritical load shedding as well as the SI from IBGs
- A distributionally robust approach is adopted to account for the uncertainty associated with noncritical load shedding
- The highly nonlinear frequency constraints are further effectively reformulated into SOC leading to overall MISOCP-based optimization problem

Future Work

- Modelling of time delays in noncritical load shedding
- More flexible frequency support strategies from IBGs
- Modelling of multiple uncertainties.

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A Distributionally Robust Approach for Stability-Constrained Microgrid Scheduling

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