An Innovative Energy Management System for Microgrids with Multiple Grid-Forming Inverters

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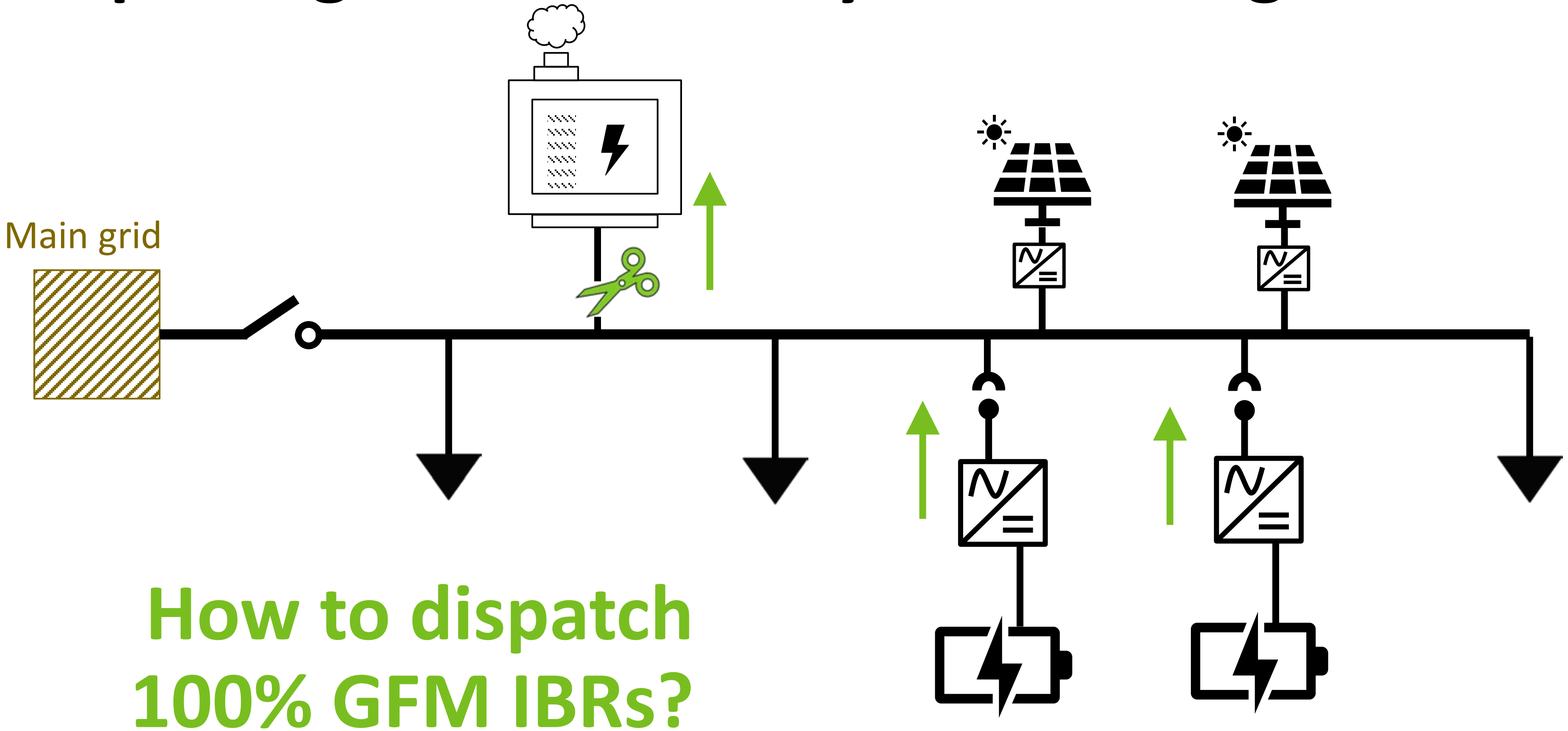
Microgrid GFM IBR Evolution

Grid-Forming (GFM) Inverter-Based Resources (IBRs) are replacing fossil-fueled synchronous generators

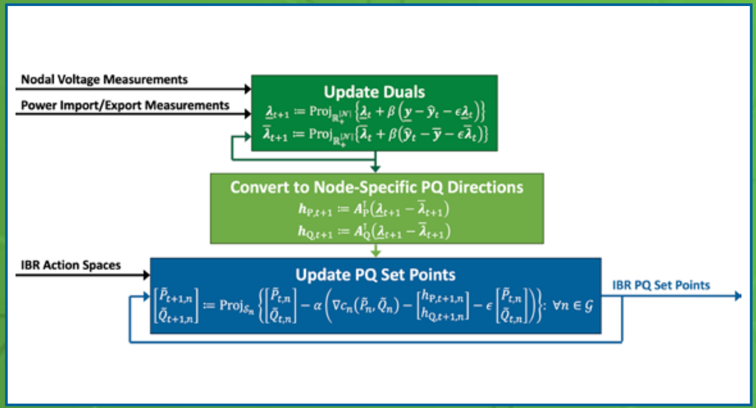


How to dispatch 100% GFM IBRs?

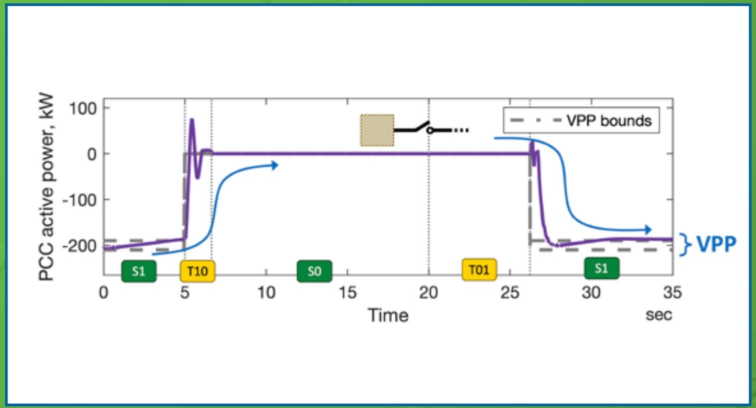
Problem: There are no microgrid energy management systems (EMSs) dispatching **multiple** GFM IBRs.

Approach: Design a generic microgrid EMS to dispatch multiple GFM IBRs **under different operation states**.

Optimal Control Algorithms

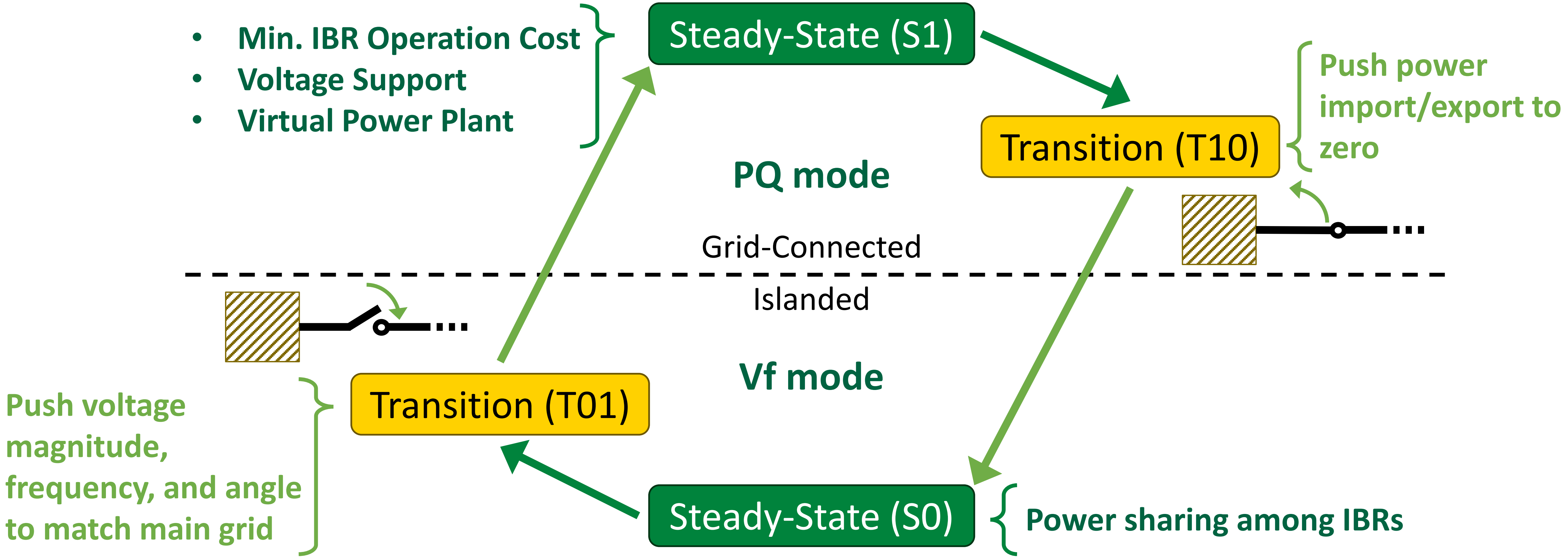


Numerical Demonstration



Microgrid Operation States

State-Dependent Objectives for GFM IBRs



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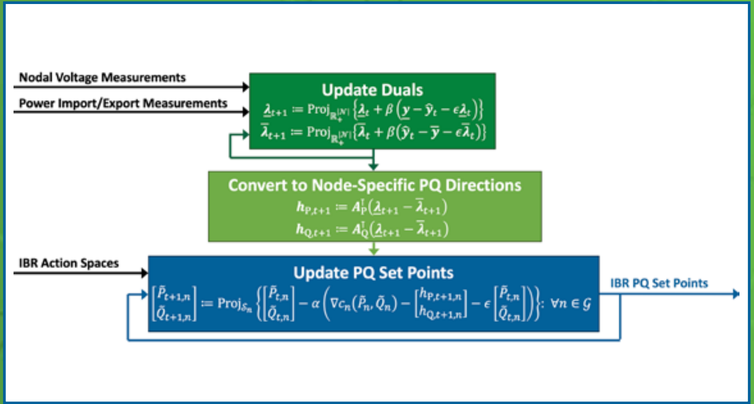

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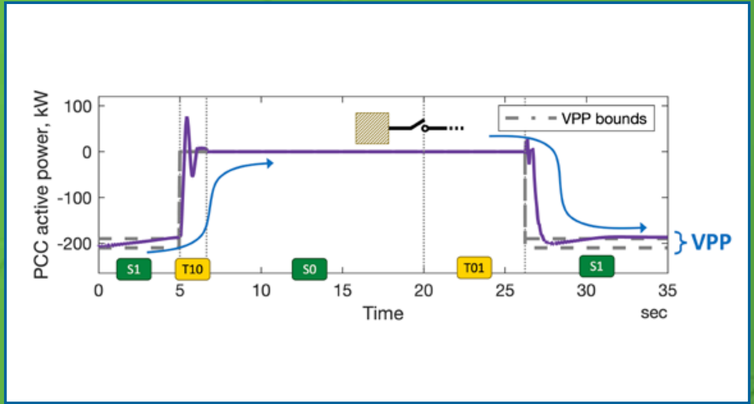


Grid-Connected Operation

Microgrid supports the main grid as a VPP

Optimal Dispatch Problem

$$\min_{\tilde{\boldsymbol{P}}, \tilde{\boldsymbol{Q}}} \sum_{n \in \mathcal{G}} c_n(\tilde{P}_n, \tilde{Q}_n) \quad \leftarrow \text{IBR Operational Cost}$$

s.t.

$$\underline{P}_0 \leq P_0(\boldsymbol{p}, \boldsymbol{q}) \leq \overline{P}_0$$
$$\underline{Q}_0 \leq Q_0(\boldsymbol{p}, \boldsymbol{q}) \leq \overline{Q}_0$$
$\leftarrow$ Virtual Power Plant

$$\underline{V}_n \leq V_n(\boldsymbol{p}, \boldsymbol{q}) \leq \overline{V}_n:\ \forall n \in \mathcal{N} \quad \leftarrow \text{Voltage Support}$$

$$(\tilde{P}_n, \tilde{Q}_n) \in \mathcal{S}_n:\ \forall n \in \mathcal{G} \quad \leftarrow \text{IBR Action Space}$$

	Steady-State (S1)	Transition (T10)
IBR Operational Cost	True cost	Reduced cost to transition faster
Virtual Power Plant	Bounds set by main grid operator	Bounds set to zero

Grid-Connected Operation

Primal-Dual Feedback Control of IBRs

Nodal Voltage Measurements →

Power Import/Export Measurements →

Update Duals

$$\underline{\boldsymbol{\lambda}}_{t+1} := \mathrm{Proj}_{\mathbb{R}_+^{|\mathcal{N}|}}\left\{\underline{\boldsymbol{\lambda}}_t + \beta\left(\underline{\boldsymbol{y}} - \hat{\boldsymbol{y}}_t - \epsilon\underline{\boldsymbol{\lambda}}_t\right)\right\}$$

$$\overline{\boldsymbol{\lambda}}_{t+1} := \mathrm{Proj}_{\mathbb{R}_+^{|\mathcal{N}|}}\left\{\overline{\boldsymbol{\lambda}}_t + \beta\left(\hat{\boldsymbol{y}}_t - \overline{\boldsymbol{y}} - \epsilon\overline{\boldsymbol{\lambda}}_t\right)\right\}$$

↓

Convert to Node-Specific PQ Directions

$$\boldsymbol{h}_{\mathrm{P},t+1} := \boldsymbol{A}_{\mathrm{P}}^{\top}\left(\underline{\boldsymbol{\lambda}}_{t+1} - \overline{\boldsymbol{\lambda}}_{t+1}\right)$$

$$\boldsymbol{h}_{\mathrm{Q},t+1} := \boldsymbol{A}_{\mathrm{Q}}^{\top}\left(\underline{\boldsymbol{\lambda}}_{t+1} - \overline{\boldsymbol{\lambda}}_{t+1}\right)$$

↓

IBR Action Spaces →

Update PQ Set Points

$$\begin{bmatrix}\tilde{P}_{t+1,n}\\ \tilde{Q}_{t+1,n}\end{bmatrix} := \mathrm{Proj}_{\mathcal{S}_n}\left\{\begin{bmatrix}\tilde{P}_{t,n}\\ \tilde{Q}_{t,n}\end{bmatrix} - \alpha\left(\nabla c_n(\tilde{P}_n, \tilde{Q}_n) - \begin{bmatrix}h_{\mathrm{P},t+1,n}\\ h_{\mathrm{Q},t+1,n}\end{bmatrix} - \epsilon\begin{bmatrix}\tilde{P}_{t,n}\\ \tilde{Q}_{t,n}\end{bmatrix}\right)\right\}: \ \forall n \in \mathcal{G}$$

→ IBR PQ Set Points

Islanded Operation – Steady-State

IBR power sharing by balancing collective effort

Effort = Reference – Nodal Value

Discounted Active Power Effort: $b_{\mathrm{f},n}(\tilde{f}_n - f_n(\boldsymbol{p},\boldsymbol{q}))$

Discounted Reactive Power Effort: $b_{\mathrm{V},n}(\tilde{V}_n - V_n(\boldsymbol{p},\boldsymbol{q}))$

Average Discounted Effort

$$\frac{1}{|\mathcal{G}|}\sum_{n\in\mathcal{G}} b_{\mathrm{f},n}\left(\tilde{f}_n - f_n(\boldsymbol{p},\boldsymbol{q})\right) =: e_{\mathrm{f}}(\tilde{\boldsymbol{f}},\boldsymbol{p},\boldsymbol{q})$$

$$\frac{1}{|\mathcal{G}|}\sum_{n\in\mathcal{G}} b_{\mathrm{V},n}\left(\tilde{V}_n - V_n(\boldsymbol{p},\boldsymbol{q})\right) =: e_{\mathrm{V}}(\tilde{\boldsymbol{V}},\boldsymbol{p},\boldsymbol{q})$$

Optimal Dispatch Problem: Equalize effort differences from the average

$$\min_{\tilde{\boldsymbol{V}},\tilde{\boldsymbol{f}}} \frac{1}{2}\sum_{n\in\mathcal{G}}\left(b_{\mathrm{f},n}\left(\tilde{f}_n - f_n(\boldsymbol{p},\boldsymbol{q})\right) - e_{\mathrm{f}}(\tilde{\boldsymbol{f}},\boldsymbol{p},\boldsymbol{q})\right)^2 + \frac{1}{2}a\sum_{n\in\mathcal{G}}\left(b_{\mathrm{V},n}\left(\tilde{V}_n - V_n(\boldsymbol{p},\boldsymbol{q})\right) - e_{\mathrm{V}}(\tilde{\boldsymbol{V}},\boldsymbol{p},\boldsymbol{q})\right)^2$$

$$\text{s.t.} \quad \underline{V}_n \le \tilde{V}_n \le \overline{V}_n,\ \underline{f}_n \le \tilde{f}_n \le \overline{f}_n:\ \forall n \in \mathcal{G}$$

Islanded Operation – Steady-State

Gradient-Descent Feedback Control of IBRs

IBR Voltage Magnitude and Frequency Measurements

Calculate Average Efforts

$$\tilde{e}_{\mathrm{f},t} := \frac{1}{|\mathcal{G}|}\sum_{n\in\mathcal{G}} b_{\mathrm{f},n}\left(\tilde{f}_n - \hat{f}_n\right)$$

$$\tilde{e}_{\mathrm{V},t} := \frac{1}{|\mathcal{G}|}\sum_{n\in\mathcal{G}} b_{\mathrm{V},n}\left(\tilde{V}_n - \hat{V}_n\right)$$

Update Vf Reference Points

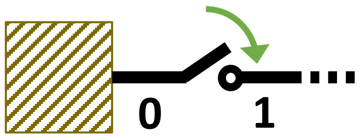
$$\tilde{f}_{t+1,n} := \mathrm{Proj}_{[\underline{f}_n,\overline{f}_n]}\left\{\tilde{f}_{t,n} - \eta_{\mathrm{f}}\frac{|\mathcal{G}|-1}{|\mathcal{G}|} b_{\mathrm{f},n}\left(\tilde{f}_{t,n} - \hat{f}_{t,n} - \tilde{e}_{\mathrm{f},t}\right)\right\}:\ \forall n \in \mathcal{G}$$

$$\tilde{V}_{t+1,n} := \mathrm{Proj}_{[\underline{V}_n,\overline{V}_n]}\left\{\tilde{V}_{t,n} - \eta_{\mathrm{V}}\frac{|\mathcal{G}|-1}{|\mathcal{G}|} a b_{\mathrm{V},n}\left(\tilde{V}_{t,n} - \hat{V}_{t,n} - \tilde{e}_{\mathrm{V},t}\right)\right\}:\ \forall n \in \mathcal{G}$$

IBR Vf Reference Points

Islanded Operation – Transition

Push voltage magnitude, frequency, and angle to match the main grid.



Optimal Dispatch Problem

$$\min_{\tilde{\boldsymbol{V}},\tilde{\boldsymbol{f}}} \frac{1}{2}\Big(\big(f_1(\boldsymbol{p},\boldsymbol{q}) - f_0\big) + \zeta\big(\theta_1(\boldsymbol{p},\boldsymbol{q}) - \theta_0\big)\Big)^2 + a\frac{1}{2}\big(V_1(\boldsymbol{p},\boldsymbol{q}) - V_0\big)^2$$

$$\text{s.t.} \quad \underline{V}_n \le \tilde{V}_n \le \overline{V}_n,\ \underline{f}_n \le \tilde{f}_n \le \overline{f}_n:\ \forall n \in \mathcal{G}$$

Gradient-Descent Feedback Control of IBRs

Main gird and microgrid voltage magnitude, frequency, angle measurements

Update Vf Reference Points

$$\tilde{f}_{t+1,n} := \mathrm{Proj}_{[\underline{f}_n,\overline{f}_n]}\Big\{\tilde{f}_{t,n} - \rho_{\mathrm{f}}\Big(\big(\hat{f}_{t,1} - \hat{f}_{t,0}\big) + \zeta\big(\hat{\theta}_{t,1} - \hat{\theta}_{t,0}\big)\Big)\Big\}:\ \forall n \in \mathcal{G}$$

$$\tilde{V}_{t+1,n} := \mathrm{Proj}_{[\underline{V}_n,\overline{V}_n]}\big\{\tilde{V}_{t,n} - \rho_{\mathrm{V}} a\big(\hat{V}_{t,1} - \hat{V}_{t,0}\big)\big\}:\ \forall n \in \mathcal{G}$$

IBR Vf Reference Points

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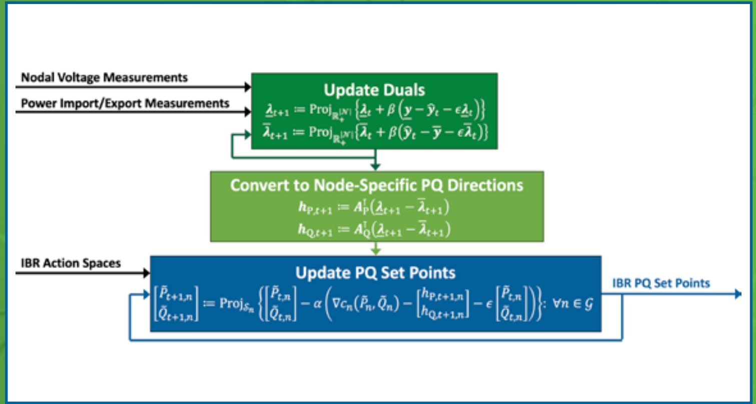
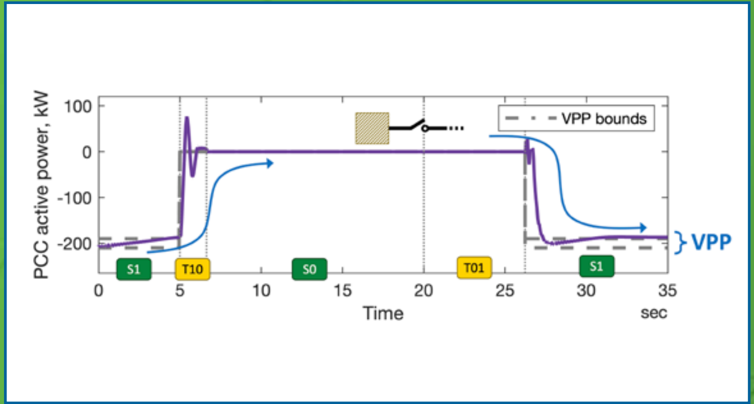
Optimal Control Algorithms



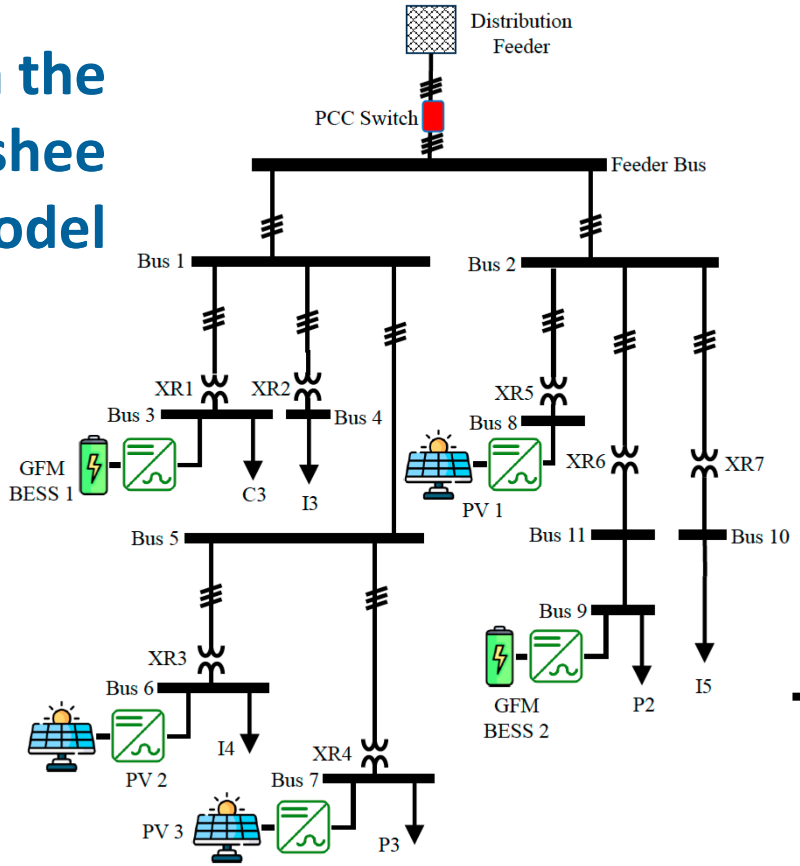
Numerical Demonstration



Numerical Demonstration

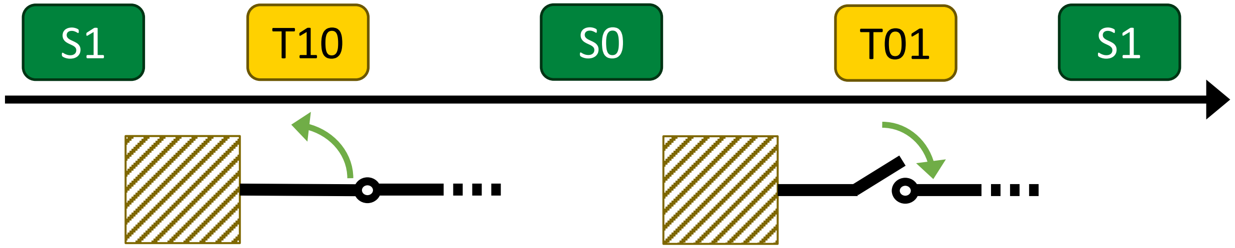
Evaluate the proposed EMS under a cycle of operation states for a 100% renewable microgrid.

Feeder 2 from the benchmark Banshee model



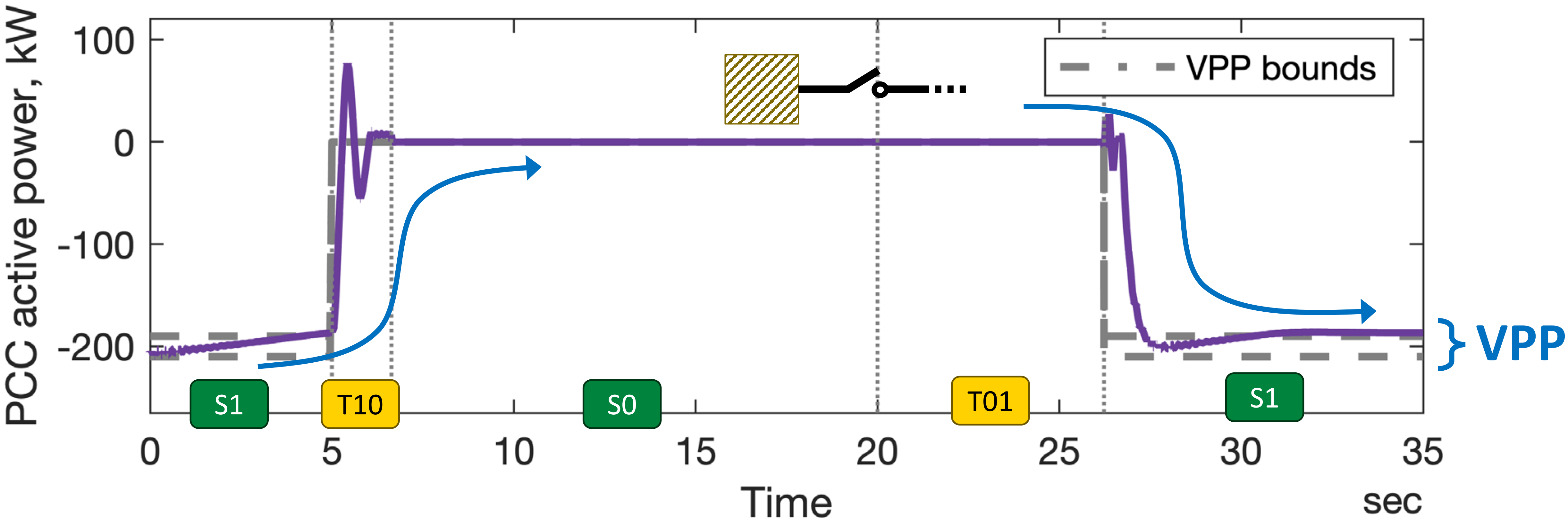
Dynamical simulations in MATLAB Simscape Electrical

- 2 BESS GFM IBRs
- 3 PV GLF IBRs
- Prioritized loads
- 50 µs time resolution



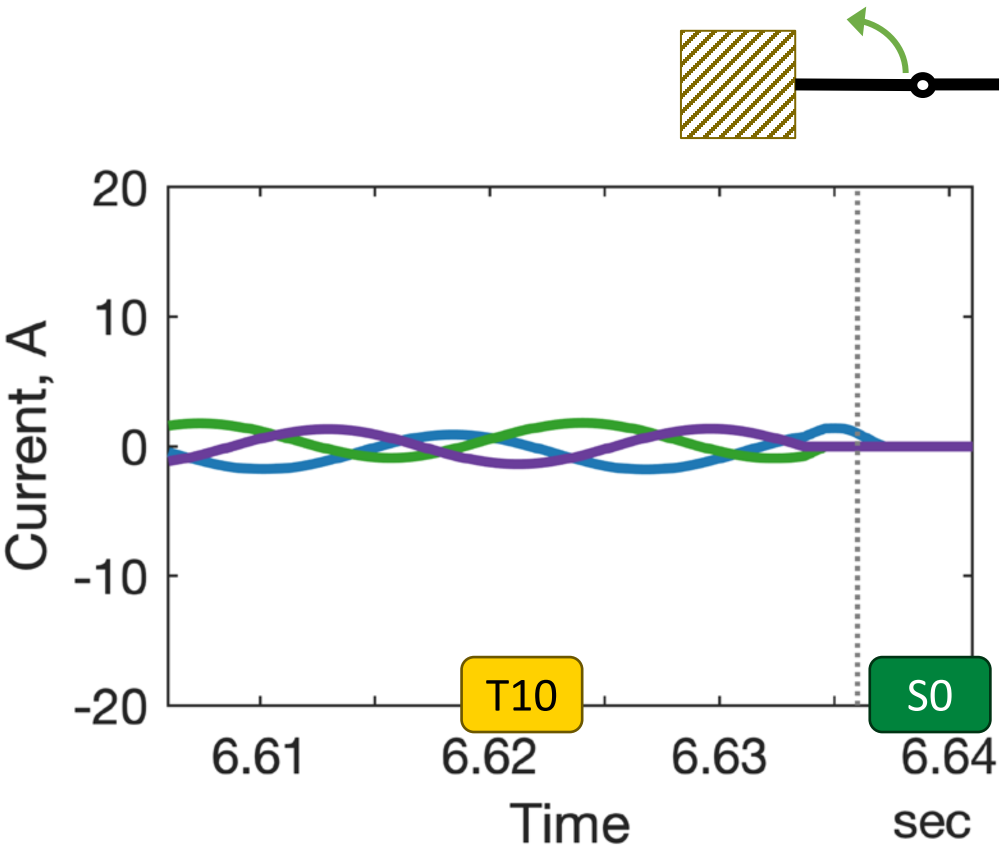
Numerical Demonstration

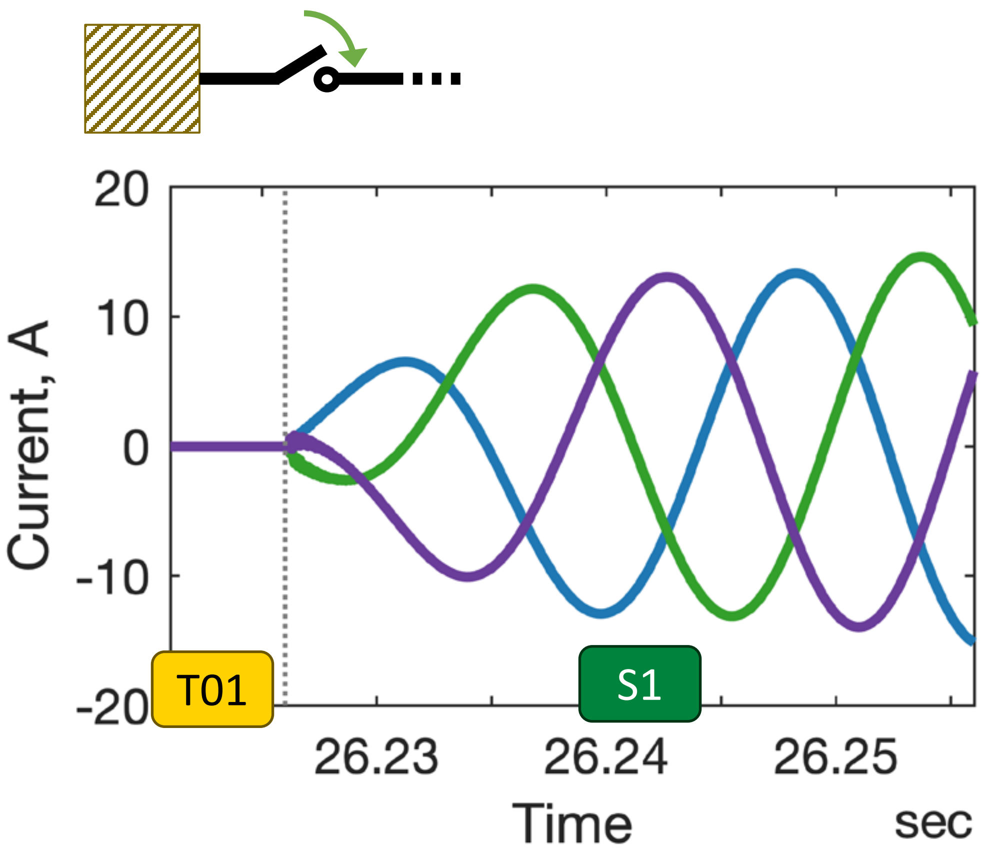
EMS controls microgrid power for islanding and VPP



Numerical Demonstration

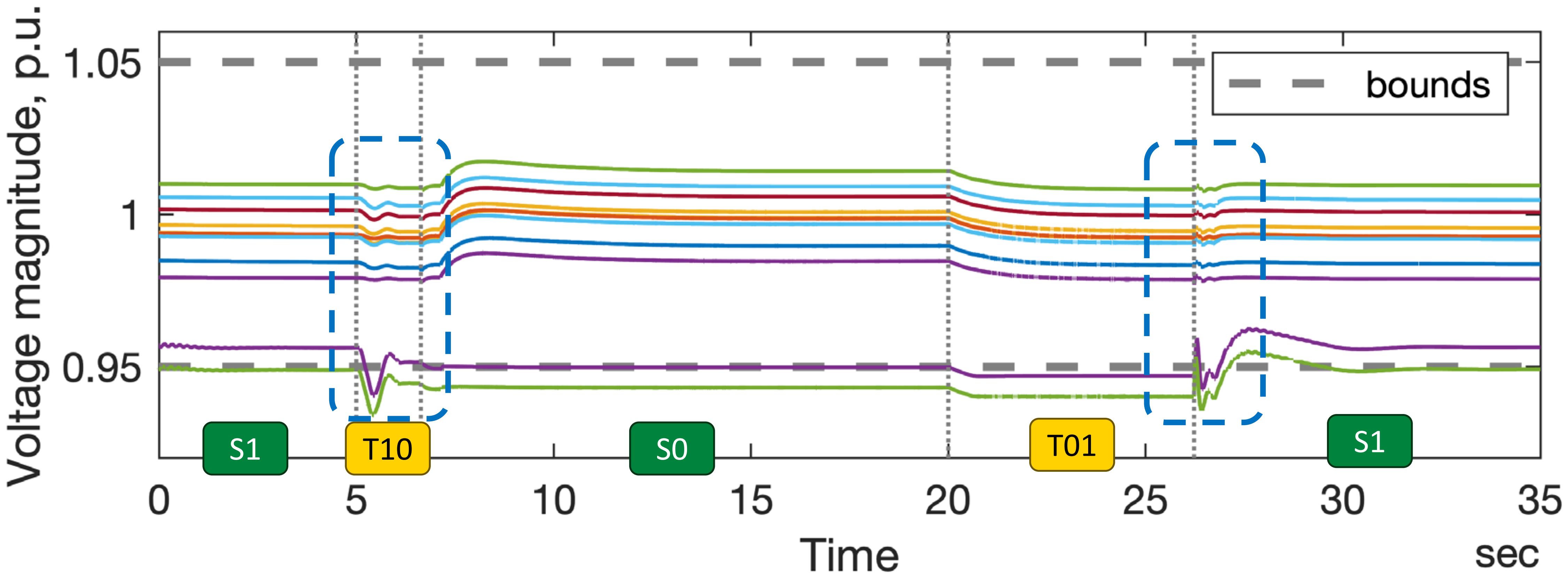
Current through microgrid PCC remains stable





Numerical Demonstration

Nodal voltages are stable, especially during transitions



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Optimal Control Algorithms

Real-time feedback-based control that achieves both microgrid and main grid objectives

Numerical Demonstration

Seamlessly dispatch multiple GFM and GFL IBRs

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Thank you!

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Acknowledgement and Disclaimer

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