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Constraint-aware Grid-forming control

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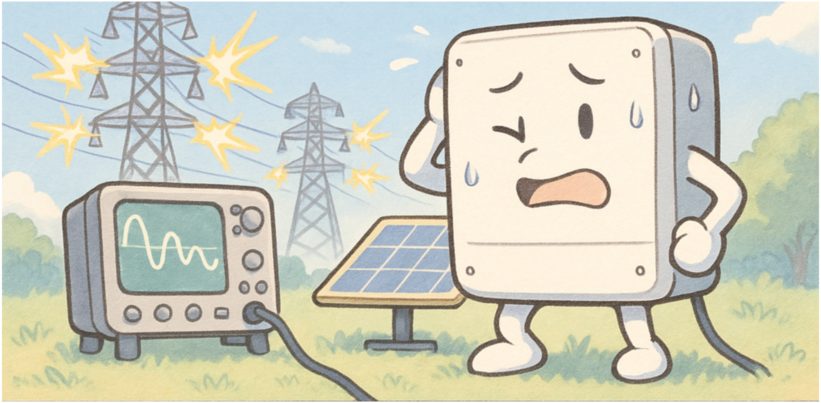
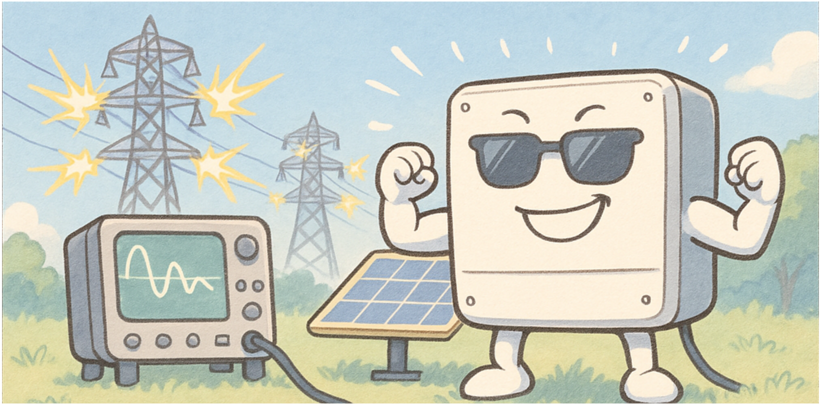
IBRs widely perceived as unreliable



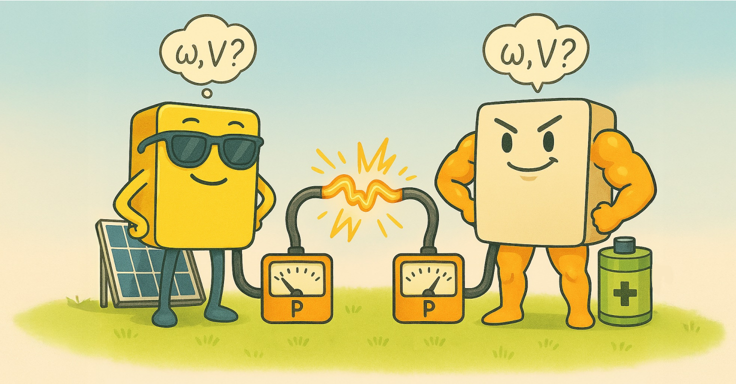
- Long list of incidents blamed on IBRs
  - South Australia blackout, Iberian Peninsula blackout, ...
  - oscillation events in Hawaii, UK, ...
- Grid-following control largely relies on ”strong” and ”stable” grid

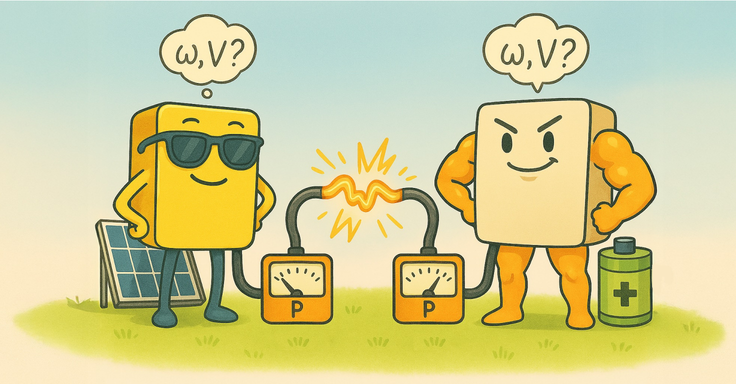
Grid-forming control to the rescue?



- Provides reliable and predictable grid support
  - demonstrated to work for weak grid, strong grid, islanding, ...
  - well understood for battery energy storage systems
- Converter and resource constraints not well understood

GFM converter synchronization through power flows





Power flow

$$P_k \approx \sum_j b_{kj}(\theta_k - \theta_j)$$

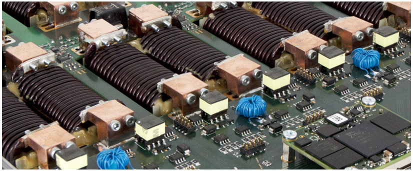
$$Q_k \approx \sum_j b_{kj}(V_k - V_j)$$

Droop control

$$\frac{\mathrm{d}}{\mathrm{d}t}\theta_k = \omega_0 + m_p\left(P_k^\star - P_k\right)$$

$$\tau_v \frac{\mathrm{d}}{\mathrm{d}t} V_k = -V_k + V^\star + m_q\left(Q_k^\star - Q_k\right)$$

Constraints of inverter-based resources and loads



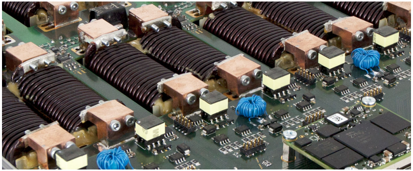
Power Electronics

- semiconductor current
- AC voltage modulation

Resources & loads

- active power and dc voltage
- ramp rate, turbine speed, ...

Constraints of inverter-based resources and loads



Power Electronics

- semiconductor current
- AC voltage modulation

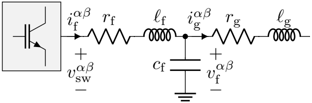
Resources & loads

- active power and dc voltage
- ramp rate, turbine speed, ...

Theory lagging power electronics & power systems practice

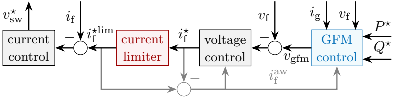
- Voltage ride through in IEEE 2800
  - 12 pages, 6 pages appendix, 2 exceptions, 5 notes, and 26 footnotes
  - focus on steady-state ”current phasor” relative to ”grid voltage phasor”
- Systematic specifications, design, & analysis remain elusive

GFM control architectures with current/power/voltage limiters



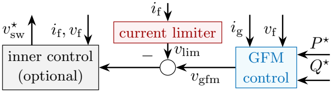
switch-level current limiting

- \+ fast (switching cycle) current limiting
- − severely degrades performance & stability



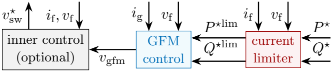
inner current limiter

- \+ fast & straightforward
- − loss of synchronization & GFM features



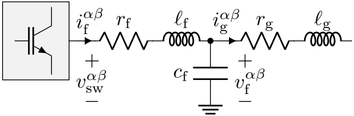
parallel current limiter

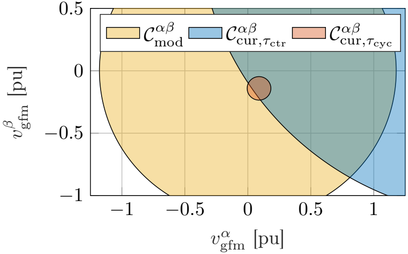
- \+ fast enough & improved transient stability
- − only works well for short-circuit faults



outer current/power/voltage limiter

- \+ least impact on transient stability
- − too slow due to bandwidth limits





- AC voltage modulation limit

$$\mathcal{C}_{\text{mod}}^{\alpha\beta} = \left\{ v_{\text{gfm}}^{\alpha\beta} \in \mathbb{R}^2 \;\middle|\; \|v_{\text{gfm}}^{\alpha\beta}\| \leq V_{\max} \right\}$$

- predicted current assuming sinusoidal voltages with frequency ω

$$i_{\text{f},\tau}^{\alpha\beta}(t) = A_\tau i_{\text{f}}^{\alpha\beta}(t) + B_\tau(v_{\text{gfm}}^{\alpha\beta}(t) - v_{\text{f}}^{\alpha\beta}(t))$$

- current limit at time $t + \tau \in \mathbb{R}$ (M_τ and ρ_τ are functions of r_{f}, ℓ_{f}, τ, ω, ...)

$$\mathcal{C}_{\text{cur},\tau}^{\alpha\beta}(t) = \left\{ v_{\text{gfm}}^{\alpha\beta} \in \mathbb{R}^2 \;\middle|\; \|v_{\text{gfm}}^{\alpha\beta} - v_{\text{f}}^{\alpha\beta}(t) + M_\tau i_{\text{f}}^{\alpha\beta}(t)\| \leq \rho_\tau i_{\max} \right\}$$

- feasible voltages $\mathcal{C}^{\alpha\beta}(t) = \mathcal{C}_{\text{cur},\tau_{\text{ctr}}}^{\alpha\beta}(t) \cup \mathcal{C}_{\text{cur},\tau_{\text{cyc}}}^{\alpha\beta}(t) \cup \mathcal{C}_{\text{mod}}^{\alpha\beta}$ at time $t \in \mathbb{R}$

Feasibility

Proposition 1: Non-empty feasible set

Assume that $\|i_\mathsf{f}^{\alpha\beta}(t_k)\| \leq i_{\max}$ and $v_\mathsf{f}^{\alpha\beta}(t_k) \in \mathcal{C}_{\mathsf{mod}}^{\alpha\beta}(t_k)$. Then, $\mathcal{C}^{\alpha\beta}(t_k)$ is non-empty.

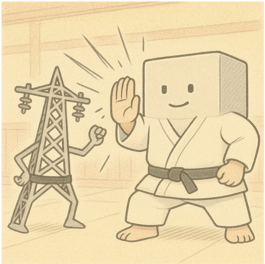
- grid overvoltage can always make the problem infeasible
- feasibility check to formalize when to trip?

GFM droop control

$$\frac{\mathrm{d}}{\mathrm{d}t}\theta = \omega_0 + m_P\,(P^\star - P)$$

$$\tau_v \frac{\mathrm{d}}{\mathrm{d}t} V = -V_k + V^\star + m_Q\,(Q^\star - Q)$$

$$v_{\mathsf{SW}}^{\alpha\beta} = V \begin{bmatrix} \cos(\theta) \\ \sin(\theta) \end{bmatrix}$$



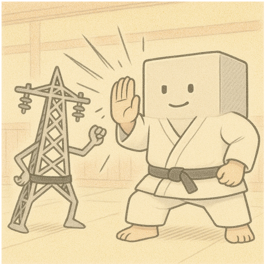
Constraint-aware GFM droop control

GFM droop control

$$\theta_k = f_\theta\left(\theta_{k-1}, P_k^\star, P_k\right)$$

$$V_k = f_V\left(V_{k-1}, Q_k^\star, Q_k\right)$$

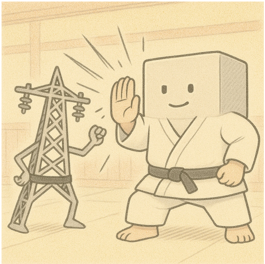
$$v_{\mathsf{sw},k}^{\alpha\beta} = V_k \begin{bmatrix} \cos(\theta_k) \\ \sin(\theta_k) \end{bmatrix}$$



Constraint-aware GFM droop control

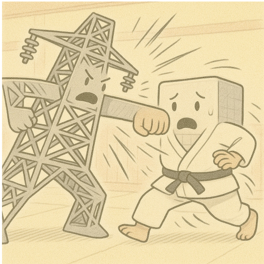
GFM droop control

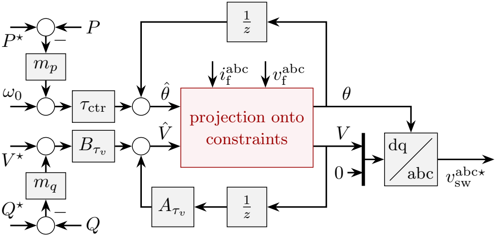
$$\hat{\theta}_k = f_\theta\left(\theta_{k-1}, P_k^\star, P_k\right)$$
$$\hat{V}_k = f_V\left(V_{k-1}, Q_k^\star, Q_k\right)$$

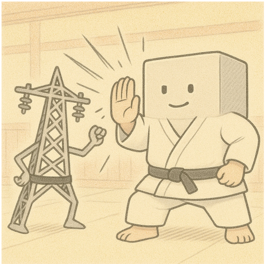


Nearest feasible voltage in constraints $C_k^{\alpha\beta}$

$$(\theta_k, V_k) := \arg\min_{\theta, V} w_\theta(\theta - \hat{\theta}_k)^2 + (V - \hat{V}_k)^2$$
$$\text{s.t.} \quad V \begin{bmatrix} \cos(\theta) \\ \sin(\theta) \end{bmatrix} \in \mathcal{C}_k^{\alpha\beta}$$



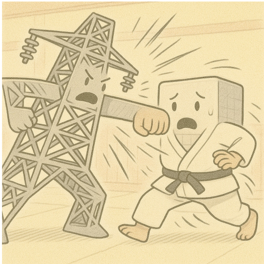




Nearest feasible voltage in constraints $C_k^{\alpha\beta}$

$$(\theta_k,\, V_k) := \operatorname*{arg\,min}_{\theta,\, V}\; w_\theta(\theta - \hat{\theta}_k)^2 + (V - \hat{V}_k)^2$$

$$\text{s.t.} \quad V \begin{bmatrix} \cos(\theta) \\ \sin(\theta) \end{bmatrix} \in \mathcal{C}_k^{\alpha\beta}$$



Projection onto the set of feasible voltages

Polar coordinates

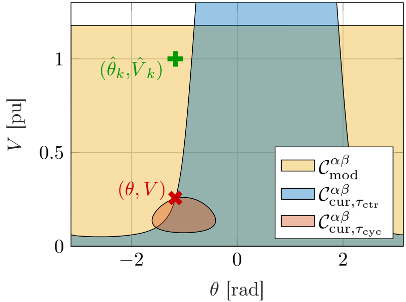
$$\arg\min_{\theta, V} \; w_\theta(\theta - \hat{\theta}_k)^2 + (V - \hat{V}_k)^2$$

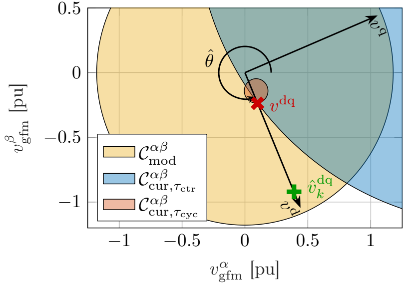
$$\text{s.t.} \quad V \begin{bmatrix} \cos(\theta) \\ \sin(\theta) \end{bmatrix} \in \mathcal{C}_k^{\alpha\beta}$$

dq coordinates

$$\arg\min_{v^{\mathrm{d}}, v^{\mathrm{d}}} \; (v^{\mathrm{d}} - \hat{V}_k)^2 + \frac{w_\theta}{\hat{V}_k}(v^{\mathrm{q}})^2$$

$$\text{s.t.} \quad \begin{bmatrix} \cos(\hat{\theta}_k) & -\sin(\hat{\theta}_k) \\ \sin(\hat{\theta}_k) & \cos(\hat{\theta}_k) \end{bmatrix} \begin{bmatrix} v^{\mathrm{d}} \\ v^{\mathrm{q}} \end{bmatrix} \in \mathcal{C}_k^{\alpha\beta}$$





Efficient computation of the projection in dq frame

Variable splitting results in the QCQP

$$\begin{aligned} \min_{v^{\mathsf{dq}}, z_1, z_2, z_3} \quad & \tfrac{1}{2}(v^{\mathsf{dq}})^{\mathsf{T}} W v^{\mathsf{dq}} + q^{\mathsf{T}} v^{\mathsf{dq}} \\ \text{s.t.} \quad & v^{\mathsf{dq}} = z_n \qquad \forall n \in \{1,2,3\} \\ & z_n \in \mathcal{C}_n^{\mathsf{dq}}(\hat{\theta}) \qquad \forall n \in \{1,2,3\} \end{aligned}$$

ADMM with acceleration

$$v^{\mathrm{dq}}(l+1) = W_\rho^{-1}\left(W\hat{v}^{\mathrm{dq}} + \rho \sum_{n=1}^{3}(z_n(l) - y_n(l))\right)$$

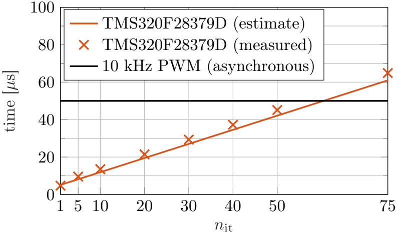
$$\tilde{v}^{\mathrm{dq}}(l+1) = v^{\mathrm{dq}}(l+1) + (\alpha - 1)(v^{\mathrm{dq}}(l+1) - v^{\mathrm{dq}}(l))$$

$$z_n(l+1) = \Pi_{\mathcal{C}_n^{\mathrm{dq}}(\hat{\theta})}\left(\tilde{v}^{\mathrm{dq}}(l+1) + y_n(l)\right)$$

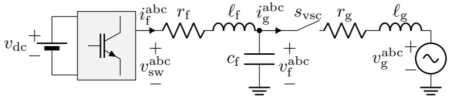
$$y_n(l+1) = y_n(l) + \tilde{v}^{\mathrm{dq}}(l+1) - z_n(l+1)$$

Microcontroller computation time

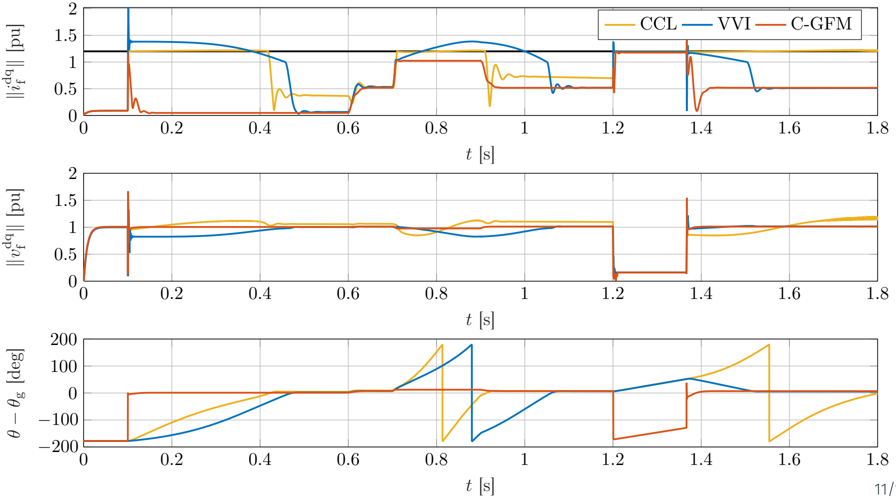
	C-GFM	CCL	CCL+AW	HTVI
comparison	$3n_{\mathrm{it}}$	1	1	4
addition	$36n_{\mathrm{it}}+6$	40	46	52
multiplication	$10n_{\mathrm{it}}+6$	41	64	70
division	$3n_{\mathrm{it}}$	1	1	0
square root	$3n_{\mathrm{it}}+1$	1	1	2
trigonometric	3	2	2	2
total instructions	$55n_{\mathrm{it}}+16$	86	115	130



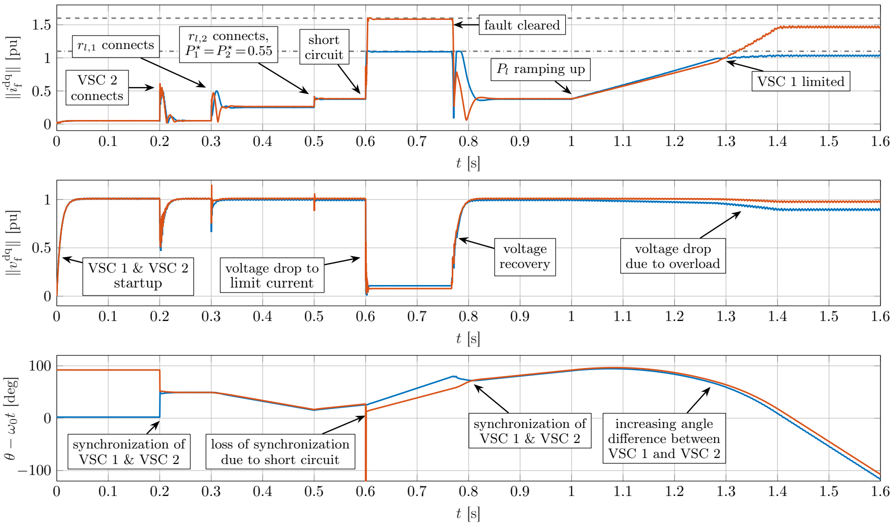
Comparison with variable virtual impedance (VVI) and inner limiter (CCL)



- 208 V, 2 kW, 60 Hz, SCR ≈ 7.5
- $m_P = m_Q = 3\%$, w_θ large

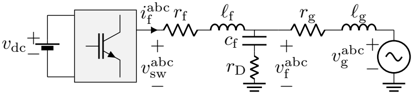


Two-converter system: synchronization, short-circuit fault, & nonlinear load



Can supply 10% (CCL) to 18% (VVI) higher load than state-of-the-art methods

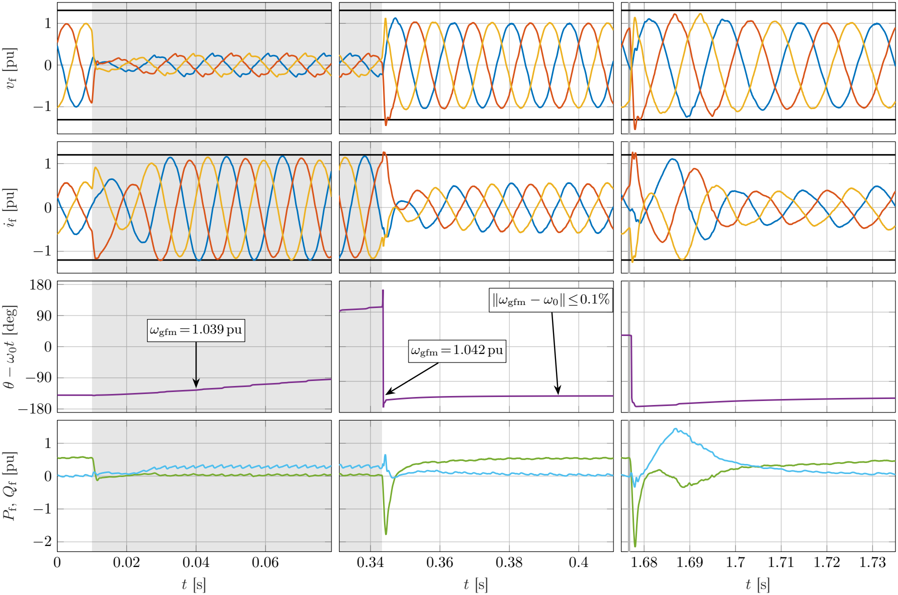
Hardware testbed



Grid		VSC			
V_{base}	186 V	v_{dc}	400 V	r_{D}	0.31 pu
S_{base}	1.788 kW	ℓ_{f}	0.084 pu	$V_{\max}$	1.31 pu
f_{base}	60 Hz	c_{f}	0.08 pu	$i_{\max}$	1.2 pu
GFM control					
m_p	5%	τ_{lp}	5.3 ms	τ_{ctr}	0.1 ms
m_q	5%	w_{ω}^{pu}	0.2	τ_{cyc}	20 ms

- derated 10 kW two-level VSC
- 10 kHz switching frequency
- controller implemented on dSPACE MicroLabBox
- filter parameters
  - nameplate inductance ℓ_f
  - ESR r_f from full load losses
- grid emulator used to simulate
  - symmetric short-circuit faults
  - 180° phase jump

Hardware experiments at SCR $= 6$

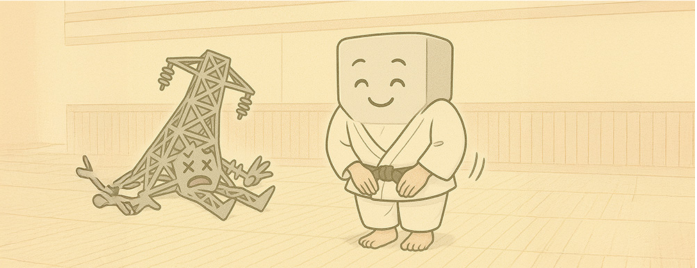


Constraint-aware GFM control

- Minimize deviation from unconstrained GFM control under constraints
- Lightweight prediction model to map constraints to voltage
- Efficient algorithms for real-time implementation

Ongoing work

- Unbalanced systems and faults
- Control barrier functions as more elegant solution



Robustness to filter parameter uncertainty

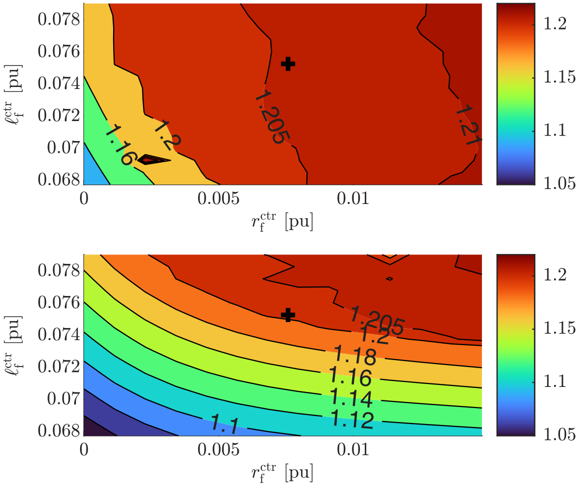


Figure 1: Peak (top) and steady-state (bottom) current during a symmetric short-circuit fault when using ℓ_f^{ctr} and r_f^{ctr} in the controller instead of the true values ℓ_f and r_f (+).