Dynamic Ancillary Services & Virtual Power Plant Control

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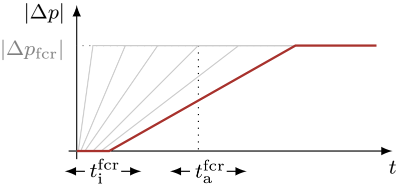
Dynamic ancillary services provided by Dynamic Virtual Power Plant (DVPP)

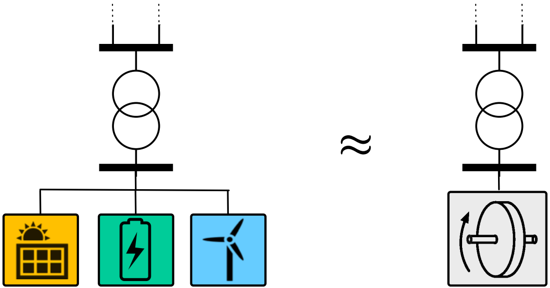
Dynamic ancillary services

- specified as desired **dynamic behavior** / responses
- **ever faster responses** for weaker (low-inertia) grids
- **location** of service provision & grid perception matter



DVPP: coordinate a heterogeneous ensemble of DERs to collectively provide dynamic ancillary services

- sufficiently **heterogeneous** collection of DERs
  - reliably provide services consistently across all power & energy levels & all time scales
  - none of the DERs itself is able to do so
- **coordination** aspect
  - disaggregation of DVPP specifications
  - decentralized control implementation



Problem abstraction in a simple setting

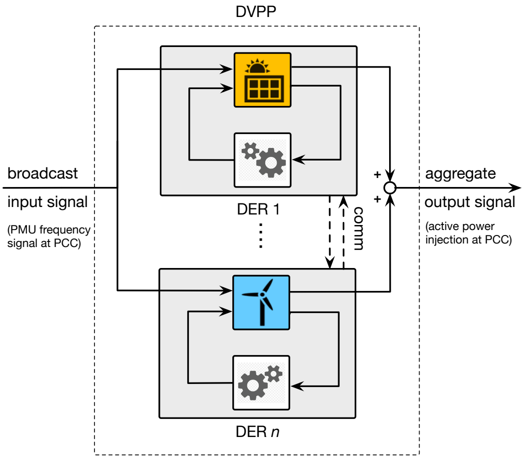
- **DVPP setup** (simplified) consisting of
  - DERs connected at a common bus
  - PMU frequency measurement at PCC broadcasted to all DERs
- **ancillary service** = aggregate DVPP specification:
  - desired grid-following fast frequency response

$$\textit{power} = \underbrace{\big(H\,s + D\big)}_{=T_{\text{des}}(s)} \cdot \textit{frequency}$$

- task: **coordinated model matching**
  - design decentralized DER controls so that DVPP behavior matches the aggregate specification

$$\textstyle\sum_i \textit{power}_i \overset{!}{=} \big(H\,s + D\big) \cdot \textit{PMU-frequency}$$

  - while taking device-level constraints into account



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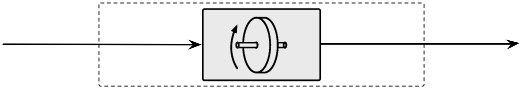
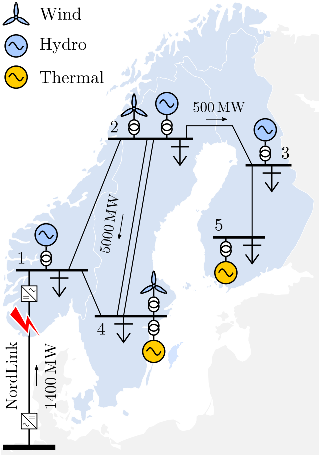


desired aggregate behavior

Nordic case study

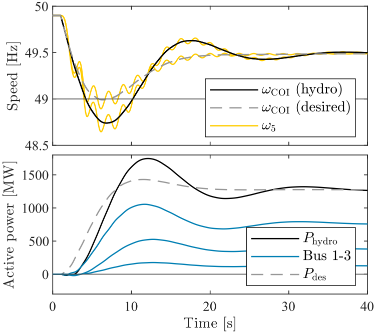


aggregated 5-bus Nordic model

- desired **ancillary service**: FCR-D

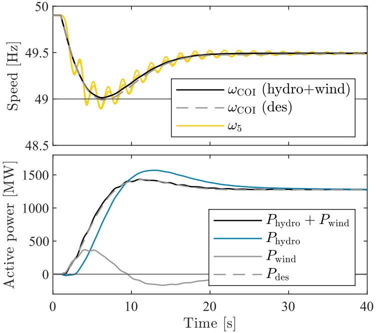
$$\frac{\textit{power}}{\textit{frequency}} = \frac{3100 \cdot (6.5s + 1)}{(2s + 1)(17s + 1)}$$

- well-known **issue:** actuation of hydro via governor is non-minimum phase
  $\rightarrow$ initial power surge opposes control
  $\rightarrow$ highly unsatisfactory response



- **discussed solution**: augment hydro with batteries for fast response
  $\rightarrow$ works but not very economic

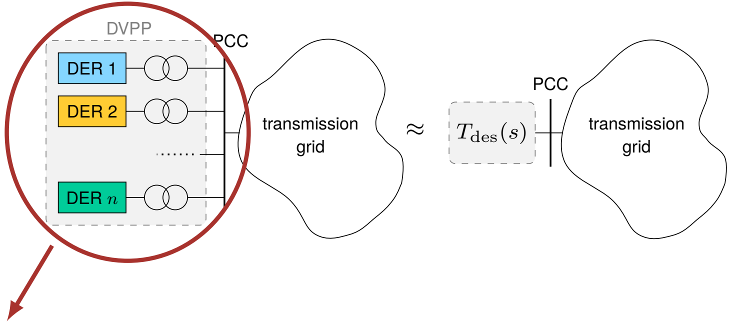
- better **DVPP solution**: coordinate hydro & wind to cover all time scales



remainder of the talk: **how** to do it ?

Björk, Johansson, & Dörfler (2022). *Dynamic virtual power plant design for fast frequency reserves: Coordinating hydro and wind.* IEEE Transactions on Control of Network Systems.

Outline



Part I: DVPP control

- **disaggregation** of desired ancillary service
- **decentralized** device-level model matching **control**
- **case study, experiments**, & sketch of **extensions**

Part II: grid codes & optimal services

- **grid codes** & translation into desired I/O behavior
- **perceive** local grid model via system identification
- **optimize** DER response subject to grid-code flexibility

Decentralized DVPP control setup

- global **broadcast signal** $\begin{bmatrix}\Delta f\\ \Delta v\end{bmatrix}$
- global **aggregated power output**

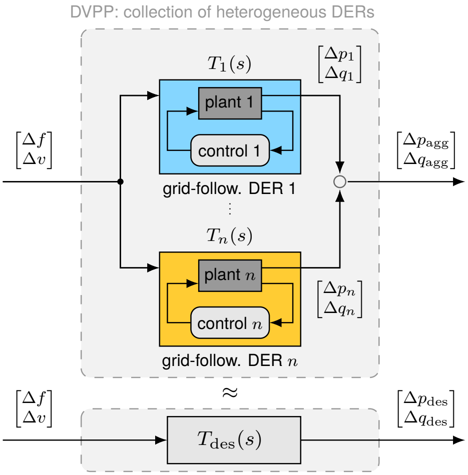
$$\begin{bmatrix}\Delta p_{\text{agg}}\\ \Delta q_{\text{agg}}\end{bmatrix} = \sum_i \begin{bmatrix}\Delta p_i\\ \Delta q_i\end{bmatrix}$$

- DERs with **controllable** closed-loop behaviors $T_i(s)$
- overall/global/aggregate **DVPP behavior**

$$\begin{bmatrix}\Delta p_{\text{agg}}(s)\\ \Delta q_{\text{agg}}(s)\end{bmatrix} = \sum_i T_i(s) \begin{bmatrix}\Delta f(s)\\ \Delta v(s)\end{bmatrix}$$

- **desired DVPP specification**

$$\begin{bmatrix}\Delta p_{\text{des}}(s)\\ \Delta q_{\text{des}}(s)\end{bmatrix} = \underbrace{\begin{bmatrix}T_{\text{des}}^{\text{fp}}(s) & 0\\ 0 & T_{\text{des}}^{\text{vq}}(s)\end{bmatrix}}_{T_{\text{des}}(s)} \begin{bmatrix}\Delta f(s)\\ \Delta v(s)\end{bmatrix}$$

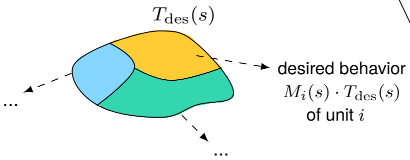


$\rightarrow$ **aggregation condition:** $\sum_i T_i(s) = T_{\text{des}}(s)$

Task: Find local controllers such that the aggregation condition & the local DER constraints are satisfied.

Divide & conquer strategy

1) Disaggregation & pooling



Disaggregate $T_{\text{des}}(s)$ into local desired behaviors via **dynamic participation factors (DPFs)**

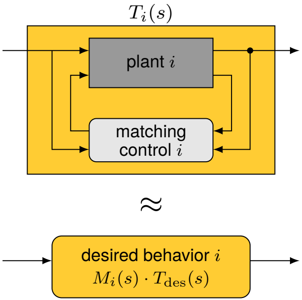
$$M_i(s) = \begin{bmatrix} m_i^{\text{fp}}(s) & 0 \\ 0 & m_i^{\text{vq}}(s) \end{bmatrix}$$

such that

$$\sum_i T_i(s) = T_{\text{des}}(s) = \sum_i M_i(s) \cdot T_{\text{des}}(s)$$

participation condition $\sum_i M_i(s) = I_2$

2) Local matching control



For each unit i, design **local matching control** to match desired behavior i

$$T_i(s) = M_i(s) \cdot T_{\text{des}}(s)$$

Häberle, V., Fisher, M., Prieto, E. & Dörfler, F. (2021). *Control design of dynamic virtual power plants: an adaptive divide-&-conquer approach*. IEEE Transactions on Power Systems.

Dynamic participation factor (DPF) selection

Define DPFs $m_i^{\mathrm{fp}}(s)$ and $m_i^{\mathrm{vq}}(s)$ of the DVPP units as **transfer functions**, among others characterized by

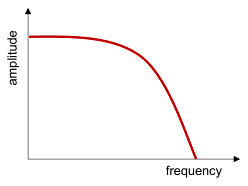
- a **time constant** τ_i for the roll-off frequency
- a **DC gain** $m_i(0) = \mu_i$ to account for power capacity limitations

$\rightarrow$ divide DVPP units into three categories, i.e., we envision

low-pass filter participation

units that can provide regulation on longer time scales including steady-state contributions

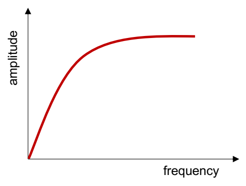
$$m_i(s) = \frac{\mu_i}{\tau_i s+1}$$



high-pass filter participation

units that can provide regulation on very short time scales (fast response capability)

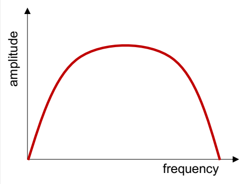
$$m_i(s) = \frac{\tau_i s}{\tau_i s+1}$$



band-pass filter participation

units able to cover the intermediate regime

$$m_i(s) = \frac{(\tau_i - \tau_j)s}{(\tau_i s+1)(\tau_j s+1)}$$



Local matching control

Control objective: for each DVPP unit, find **local matching controllers** such that the local closed-loop behavior matches the local desired specification

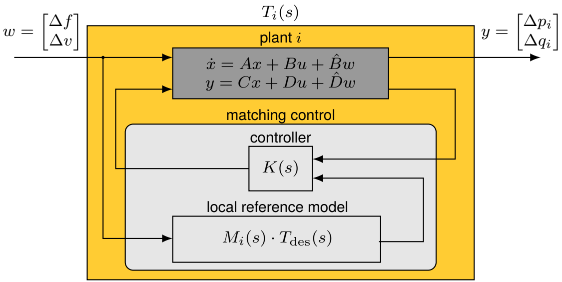
$$T_i(s) = M_i(s) \cdot T_{\text{des}}(s)$$

General setup for matching control of unit i

- incorporate local desired behavior

  $$M_i(s) \cdot T_{\text{des}}(s)$$

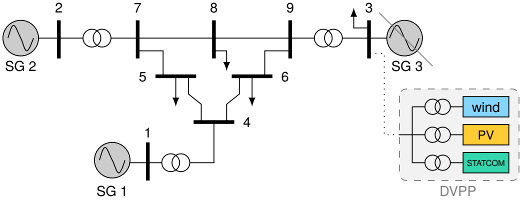
  as **reference model** into conventional converter control architecture
- different **matching control implementations**, e.g., classical PI-based control, robust & optimal $\mathcal{H}_\infty$ methods, etc.



Goal: minimize local matching error!

Case study

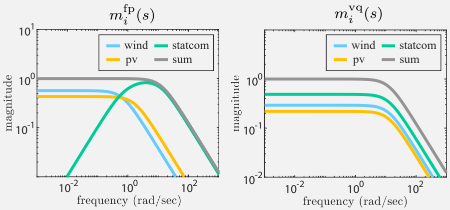
Nonlinear & detailed simulation model



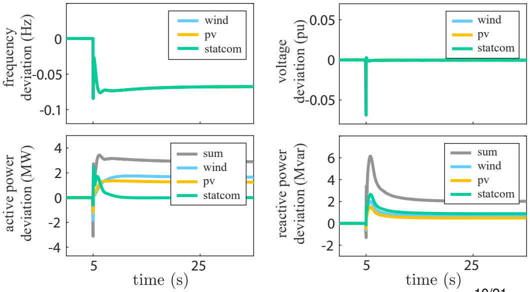
DVPP specification: frequency & voltage control

$$\begin{bmatrix} \Delta p_{\mathrm{des}}(s) \\ \Delta q_{\mathrm{des}}(s) \end{bmatrix} = \underbrace{\begin{bmatrix} \frac{D_{\mathrm{p}}+Ms}{\tau_{\mathrm{p}}s+1} & 0 \\ 0 & \frac{D_{\mathrm{q}}}{\tau_{\mathrm{q}}s+1} \end{bmatrix}}_{=T_{\mathrm{des}}(s)} \begin{bmatrix} \Delta f(s) \\ \Delta v(s) \end{bmatrix}$$

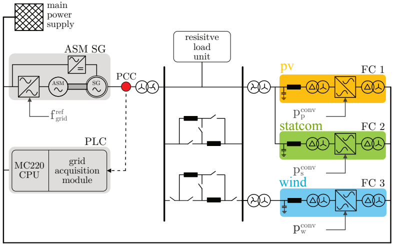
Participation factor selection

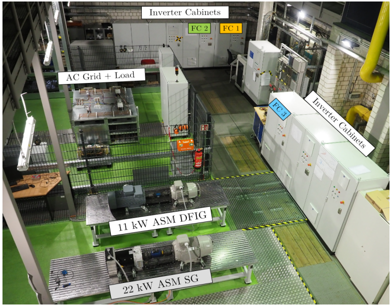


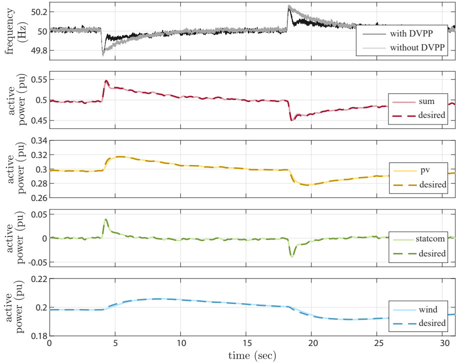
System response during load increase at bus 6



Experimental validation: Multi-converter PHIL testbed







- DVPP (wind, PV, STATCOM) for frequency regulation
- DVPP response during a ± 1kW load jump
- response characteristics according to selected DPFs

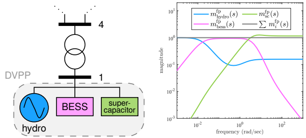
Andrejewski, M., Häberle, V., Goldschmidt, N., Dörfler, F. & Schulte, H. (2023). *Experimental validation of a dynamic virtual power plant control concept based on multi-converter power hardware-in-the-loop test bench*, 22nd Wind and Solar Integration Workshop.

DVPP extensions

coupled $T_{\text{des}}(s)$

$$T_{\text{des}}(s) = \begin{bmatrix} T^{\text{fp}}_{\text{des}}(s) & T^{\text{vp}}_{\text{des}}(s) \\ T^{\text{fq}}_{\text{des}}(s) & T^{\text{vq}}_{\text{des}}(s) \end{bmatrix}$$

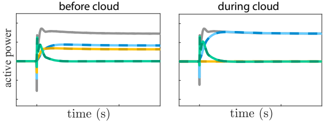
noncontrollable units



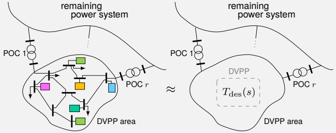
grid-forming DVPP

$$\begin{bmatrix} \Delta f_{\text{des}}(s) \\ \Delta v_{\text{des}}(s) \end{bmatrix} = T_{\text{des}}(s) \begin{bmatrix} \Delta p \\ \Delta q \end{bmatrix}$$

adaptive DPF



spatially distributed

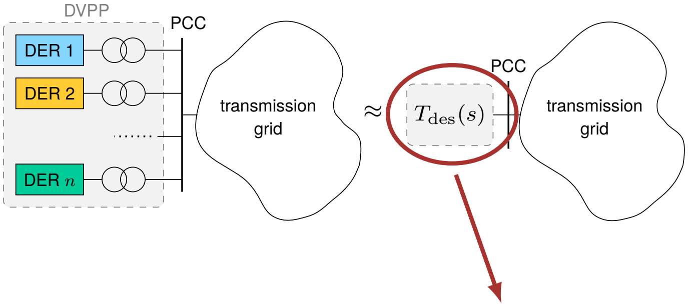


others

- complex-frequency DVPP
- DC DVPP
- ...

Häberle, V., Fisher, M., Prieto, E. & Dörfler, F. (2021). *Control design of dynamic virtual power plants: an adaptive divide-&-conquer approach*. IEEE Transactions on Power Systems.
Häberle, V., Tayyebi, A., He, X., Prieto, E. & Dörfler, F. (2023). *Grid-forming & spatially distributed control design of dynamic virtual power plants*. IEEE Transactions on Smart Grid.
Domingo-Enrich, R., Häberle, V., He, X., Prieto-Araujo, E. & Dörfler, F. (2023). *Complex frequency control of dynamic virtual power plants*. Master Thesis.

Outline



Part I: DVPP control

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Part II: grid codes & optimal services

- **grid codes** & translation into desired I/O behavior
- **perceive** local grid model via system identification
- **optimize** DER response subject to grid-code flexibility

From grid codes to feasible transfer functions

- translate piece-wise linear **time-domain grid code curves** into **parametric transfer functions**

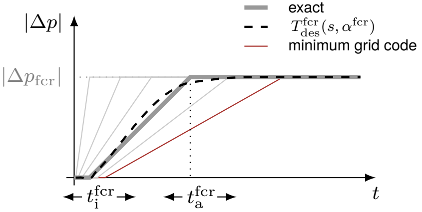
$$\begin{bmatrix}\Delta p(s)\\ \Delta q(s)\end{bmatrix} = \underbrace{\begin{bmatrix}T_{\mathrm{des}}^{\mathrm{fp}}(s,\alpha^{\mathrm{fp}}) & 0\\ 0 & T_{\mathrm{des}}^{\mathrm{vq}}(s,\alpha^{\mathrm{vq}})\end{bmatrix}}_{=T_{\mathrm{des}}(s,\alpha)} \begin{bmatrix}\Delta f(s)\\ \Delta v(s)\end{bmatrix}$$

$\longrightarrow$ parameters α need to satisfy **grid code** requirements & **device-level** constraints

- **superposition** of different ancillary **services**

$$T_{\mathrm{des}}^{\mathrm{fp}}(s,\alpha^{\mathrm{fp}}) = \underbrace{T_{\mathrm{des}}^{\mathrm{fcr}}(s,\alpha^{\mathrm{fcr}})}_{\text{FCR}} + \underbrace{T_{\mathrm{des}}^{\mathrm{ffr}}(s,\alpha^{\mathrm{ffr}})}_{\text{FFR}} + \ldots$$

Goal: optimize response over α & grid perception



Example: FCR Capability Curve (EU 2016/631)

- active power capability curve after frequency drop
- parameterized by time constants $\alpha^{\mathrm{fcr}} := [t_{\mathrm{i}}^{\mathrm{fcr}}, t_{\mathrm{a}}^{\mathrm{fcr}}]$
- **grid code** requirements on FCR capacity $|\Delta p_{\mathrm{fcr}}|$

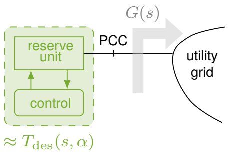
$$0 \le t_{\mathrm{i}}^{\mathrm{fcr}} \le t_{\mathrm{i,max}}^{\mathrm{fcr}} \quad \& \quad t_{\mathrm{i}}^{\mathrm{fcr}} \le t_{\mathrm{a}}^{\mathrm{fcr}} \le t_{\mathrm{a,max}}^{\mathrm{fcr}}$$

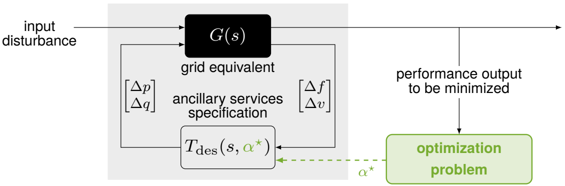
- **device-level** ramping rate constraint

$$|\Delta p_{\mathrm{fcr}}| \le \left(t_{\mathrm{a}}^{\mathrm{fcr}} - t_{\mathrm{i}}^{\mathrm{fcr}}\right) \cdot r_{\mathrm{max}}^{\mathrm{p}}$$

Häberle, V., Huang, L., He, X., Prieto-Araujo, E., & Dörfler, F. (2023). *Dynamic ancillary services: From grid codes to transfer function-based converter control.* arXiv:2310.01552.

Optimal dynamic ancillary services provision: **Perceive & Optimize** (P&O)





"Perceive" unknown & local grid dynamics

$\rightarrow$ **identify** grid dynamic equivalent $G(s)$

$$\begin{bmatrix}\Delta f(s)\\ \Delta v(s)\end{bmatrix} = \underbrace{\begin{bmatrix}G_{11}(s) & G_{12}(s)\\ G_{21}(s) & G_{22}(s)\end{bmatrix}}_{=:G(s)} \begin{bmatrix}\Delta p(s)\\ \Delta q(s)\end{bmatrix}$$

$\rightarrow$ takes into account **local grid** characteristics: sensitivity, short circuit & R/L ratios, etc.

"Optimize" device response subject to constraints

- ensure **grid code & device-level** requirements
- **stable closed-loop interconnection** of grid equivalent $G(s)$ & parametric service $T_{\mathrm{des}}(s,\alpha)$

$\rightarrow$ optimize for feasible $\alpha^\star$ which results in **best closed-loop & system-level performance**

Häberle, V., He, X, Huang, L, Prieto-Araujo, E. & Dörfler, F. (2024). *Optimal dynamic ancillary services provision based on local power grid perception. arXiv:2401.17793.*

Perceive: dynamic grid equivalent identification

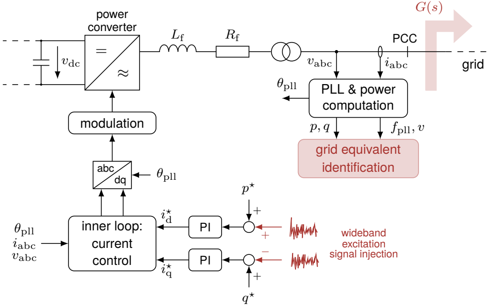
"Perceive"
unknown & local grid dynamics $\rightarrow$ identify $G(s)$

$$\begin{bmatrix} \Delta f(s) \\ \Delta v(s) \end{bmatrix} = \underbrace{\begin{bmatrix} G_{11}(s) & G_{12}(s) \\ G_{21}(s) & G_{22}(s) \end{bmatrix}}_{=:G(s)} \begin{bmatrix} \Delta p(s) \\ \Delta q(s) \end{bmatrix}$$

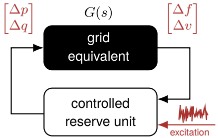
Dynamic grid equivalent identification

- inject uncorrelated **wideband excitation** signals in converter's control loop
- measure & collect f, v, p, q responses at PCC
- apply **parametric system identification** techniques (e.g., PEM methods, subspace methods, etc.) to compute $G(s)$

Practical power converter control setup



Closed-loop identification problem

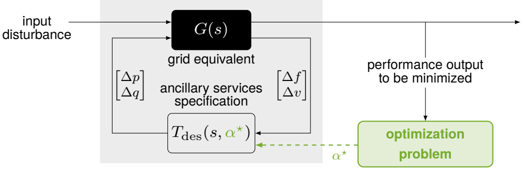


Häberle, V., Huang, L., He, X., Prieto-Araujo, E., Smith, R. S. & Dörfler, F. (2023). *MIMO grid impedance identification of three-phase power systems: parametric vs. nonparametric approaches.* IEEE Conference on Decision and Control.

Optimize: Closed-loop power grid optimization

"Optimize"

- **closed-loop interconnection** of $G(s)$ and parametric $T_{\text{des}}(s,\alpha)$
- optimize for $\alpha^\star$ to get **optimal & stable** closed-loop performance



$$\min_{\alpha} \int \text{frequency deviation} + \text{RoCoF} + \text{voltage peak}$$

s.t. **dynamics:** identified grid equivalent

ancillary services specification

grid-code constraints

device-level constraints

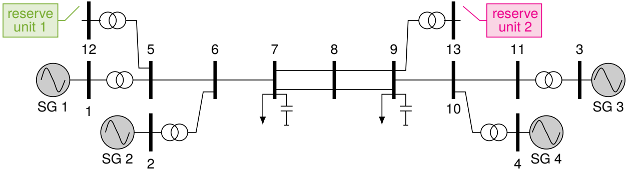
parametric in α

Solution: smooth objective $\rightarrow$ compute explicit gradient + project on constraints + scalable first-order methods

Case studies

2-area Kundur system

- two additional reserve units
- detailed (nonlinear, EMT) models



Case studies to demonstrate the effectiveness of the P&O strategy:

Cheap ancillary services: $T_{\text{des}}(\alpha_0, s)$

- encodes **minimum open-loop grid-code** requirements
- **cheap**, but feasible dynamic ancillary services provision
- **indistinguishable** for any grid **location**

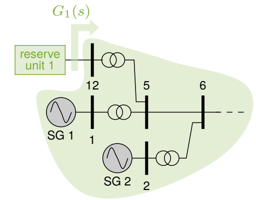
vs.

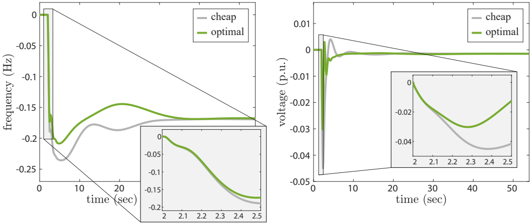
Optimal ancillary services: $T_{\text{des}}(\alpha^\star, s)$

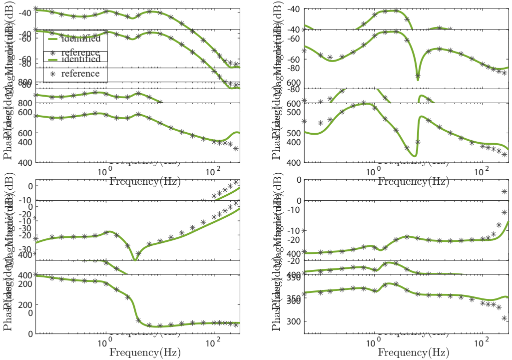
- ensures **optimal and stable** closed-loop performance based on local **grid perception**
- takes **grid-codes & device-level limits** into consideration
- can accommodate **time-varying** grid conditions

Case study I

- **nominal** grid conditions
- apply **P&O strategy for unit 1**, keep unit 2 disconnected
- **initial situation:** cheap ancillary services provision by reserve unit 1







System response during load increase at bus 7

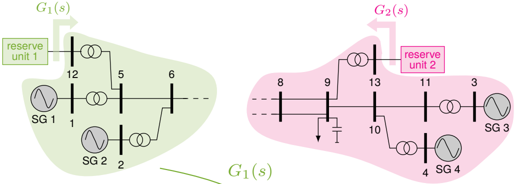
12.6% improvement in RoCoF

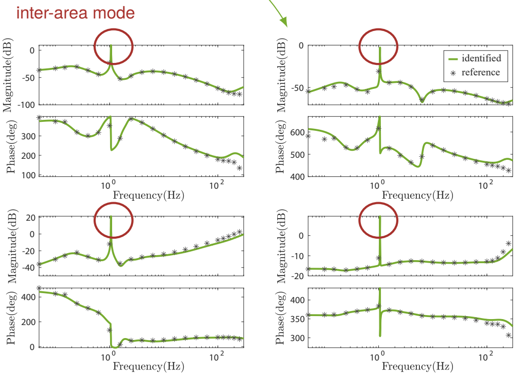
11.6% improvement in frequency nadir

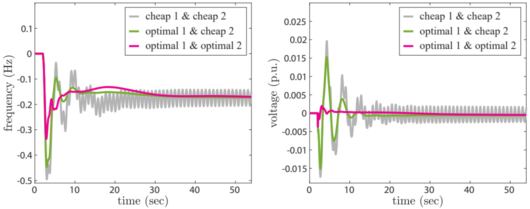
32.9% reduction in voltage peak

Case study II

- **oscillatory** grid with weakly-damped inter-area modes
- sequentially apply **P&O strategy for both units**
- **initial situation:** cheap ancillary services by both units





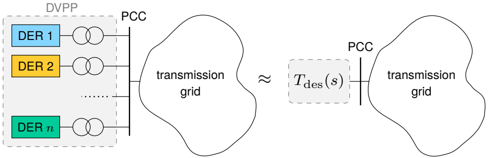


significant improvement of the closed-loop system behavior after **first** & **second** P&O cycle during a load increase at bus 7

Conclusions

Summary

- Part I: **DVPP control**
  - disaggregation via dynamic participation factors
  - decentralized model matching control
  - case study, experiments & extensions
- Part II: **grid codes & optimal services**
  - grid codes & translation into I/O behavior
  - perceive power grid via system identification
  - optimize DER response s.t. grid-code flexibility



Future work

- extension of P&O strategy to **multi-agent scenarios**: what if many DERs learn in parallel ?
- development of **next-generation grid codes**: decentralized stability certificates, service criteria, . . .

link to related publications