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POSYTYF

Dynamic Virtual Power Plant Control

Autonomous Energy Systems Workshop

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Outline

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1. Introduction & Motivation
2. DVPP Design as Coordinated Model Matching
3. Decentralized Control Design Method
4. Grid-Forming & Spatially Distributed DVPP
5. Conclusions

Selected challenges in future power systems

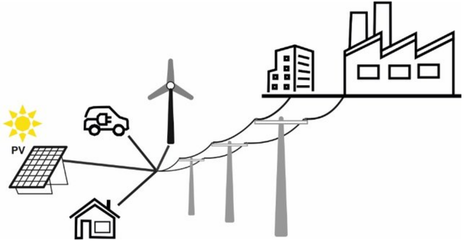
- **conventional power systems**
  - dispatchable generation
  - significant inertial response
  - fast frequency & voltage control

  provided by bulk synchronous generation

- **future power systems**
  - variable generation
  - reduced inertia levels
  - ancillary services for frequency & voltage

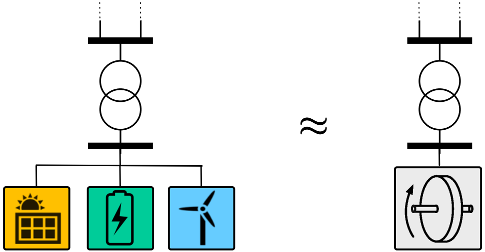
  provided by distributed energy resources (DERs)

- some of the manifold **challenges**
  - **brittle grids:** intermittency & uncertainty of renewables & reduced inertia levels
  - **device fragility:** converter-interfaced DERs limited in energy, power, fault currents, . . .
  - **ancillary services** on ever faster time scales & shouldered by distributed sources



Dynamic Virtual Power Plant (DVPP)

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



- **heterogenous** collection of devices
  - reliable provide services consistently across all power & energy levels and all time scales
  - none of the devices itself is able to do so
- **dynamic** ancillary services
  - fast response (brittle grids), e.g., inertia
  - specified as desired dynamic I/O response
  - robustly implementable on fragile devices
- **coordination** aspect
  - decentralized control implementation
  - real-time adaptation to variable DVPP generation & ambient grid conditions

motivating examples

- frequency containment provided by non-minimum phase hydro & on-site batteries (for fast response)
- wind providing fast frequency response & voltage support augmented with storage to recharge turbine
- hybrid power plants, e.g., PV + battery + supercap
- load / generation aggregators & balancing groups

Abstraction: coordinated model matching

- **setup** (simplified): DVPP consisting of
  - DERs connected at a common bus
  - PMU frequency measurement at point of common coupling broadcasted to all DERs

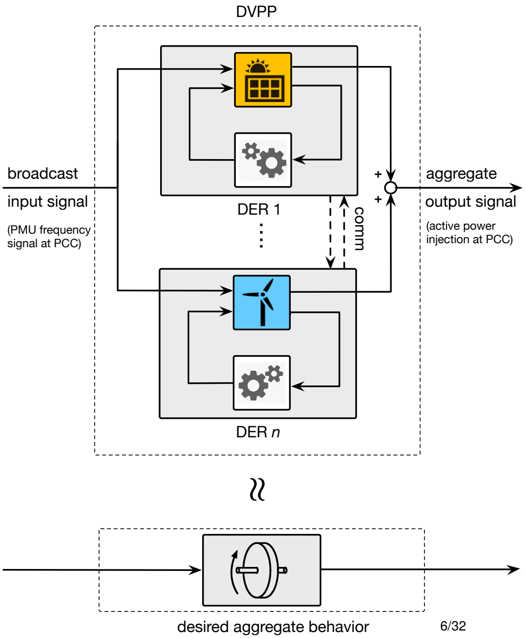
- DVPP **aggregate specification** (ancillary service):
  - grid-following fast frequency response (inertia & damping)

    power = $\big(H\,s + D\big)$ · *frequency*

    (later: also forming + distributed + voltage . . .)

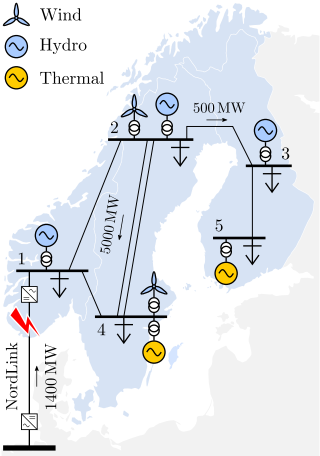
- task: **coordinated model matching**
  - design decentralized DER controls so that the aggregate behavior matches specification

    $\sum_i \text{power}_i = \big(H\,s + D\big) \cdot$ *PMU-frequency*
  - while taking device-level constraints into account
  - & online adapting to variable DVPP generation



Nordic case study

with J. Björk (Svenska kraftnät)
& K.H. Johansson (KTH)

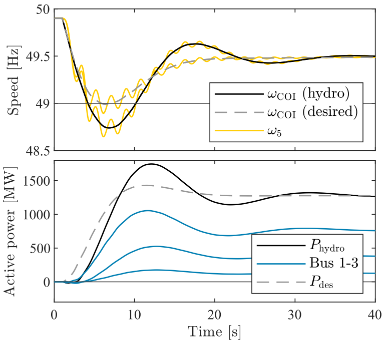


aggregated 5-bus Nordic model

- **FCR-D service** → desired behavior

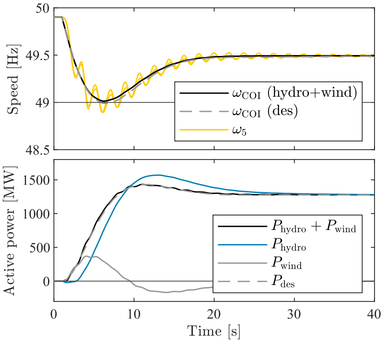
$$\frac{\textit{power}}{\textit{frequency}} = \frac{3100 \cdot (6.5s + 1)}{(2s+1)(17s+1)}$$

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



- **discussed solution**: augment hydro with batteries for faster response
  → works but not very economic

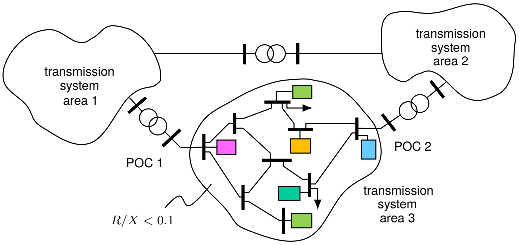
- better **DVPP solution**: coordinate hydro & wind to cover all time scales



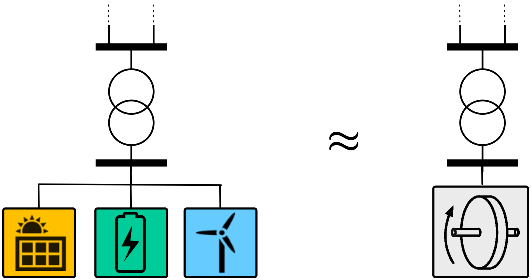
remainder of the talk: **how** to do it ?

Outline

Problem setup & variations



one can conceive **complex problem setups** with DVPPs spanning transmission / distribution, multiple areas, forming / following . . . → **start simple for now**



- DVPP consists of **controllable & non-controllable devices** (whose I/O behavior cannot be altered)
- **topology**: all DVPP devices at common bus bar (later also spatially distributed setup)
- **grid-following** signal causality: power injection controlled as function of voltage measurement (later also grid-forming setup)

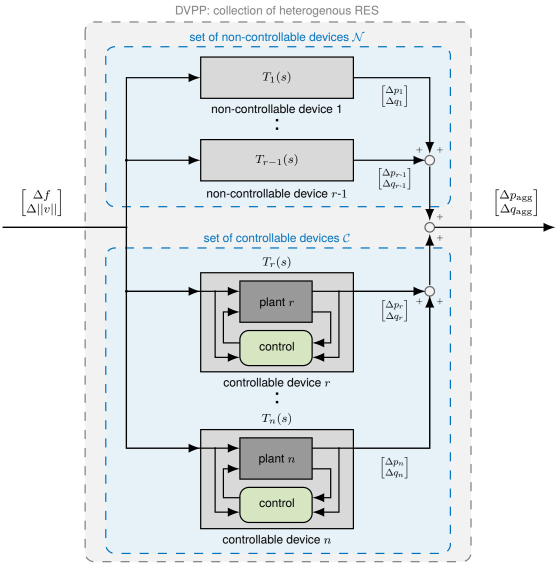
DVPP control setup

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

$$\begin{bmatrix}\Delta p_{\text{agg}} \\ \Delta q_{\text{agg}}\end{bmatrix} = \sum_{i\in\mathcal{N}\cup\mathcal{C}} \begin{bmatrix}\Delta p_i \\ \Delta q_i\end{bmatrix}$$

- fixed local closed-loop behaviors $T_i(s)$ of **non-controllable devices** $i \in \mathcal{N}$ (e.g., closed-loop hydro/governor model)
- devices $i \in \mathcal{C}$ with **controllable** closed-loop behaviors $T_i(s)$ (e.g., battery sources)
- overall **aggregate DVPP behavior**

$$\begin{bmatrix}\Delta p_{\text{agg}}(s) \\ \Delta q_{\text{agg}}(s)\end{bmatrix} = \sum_{i\in\mathcal{N}\cup\mathcal{C}} T_i(s) \begin{bmatrix}\Delta f(s) \\ \Delta||v||(s)\end{bmatrix}$$



Coordinated model matching

- overall **aggregate DVPP behavior**

$$\begin{bmatrix}\Delta p_{\text{agg}}(s)\\ \Delta q_{\text{agg}}(s)\end{bmatrix} = \sum\nolimits_{i\in\mathcal{N}\cup\mathcal{C}} T_i(s)\begin{bmatrix}\Delta f(s)\\ \Delta\|v\|(s)\end{bmatrix}$$

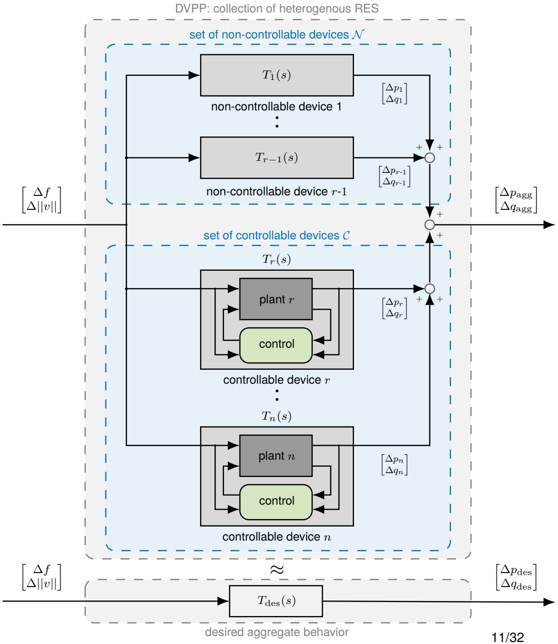
- **desired DVPP specification**: decoupled f-p & v-q control (later: also consider couplings)

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

→ **aggregation condition**: $\sum_{i\in\mathcal{N}\cup\mathcal{C}} T_i(s) \overset{!}{=} T_{\text{des}}(s)$

DVPP control problem

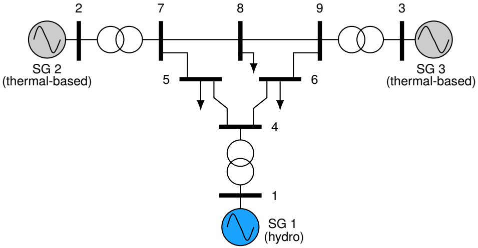
Find local controllers such that the DVPP aggregation condition & local device-level specifications are satisfied.



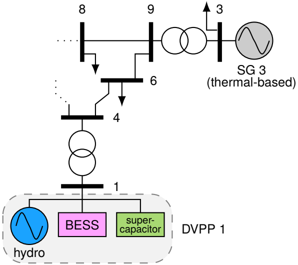
Outline

Running case studies

Original 9 bus system setup



Case study I: hydro supplementation

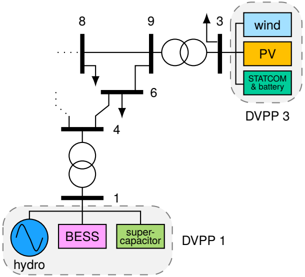


DVPP 1 for freq. control

$$\Delta p = T_{\mathrm{des}}(s)\, \Delta f$$

$$T_{\mathrm{des}}(s) = \frac{-D}{\tau s + 1},$$

Case study II: synchronous generator replacement



DVPP 3 for freq. & volt. control

$$\begin{bmatrix} \Delta p \\ \Delta q \end{bmatrix} = T_{\mathrm{des}}(s) \begin{bmatrix} \Delta f \\ \Delta \|v\| \end{bmatrix}$$

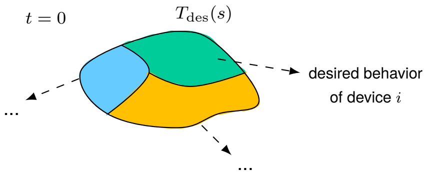
$$T_{\mathrm{des}}(s) = \begin{bmatrix} \frac{-D_{\mathrm{p}} - H s}{\tau_{\mathrm{p}} s + 1} & 0 \\ 0 & \frac{-D_{\mathrm{q}}}{\tau_{\mathrm{q}} s + 1} \end{bmatrix}$$

Divide & conquer strategy

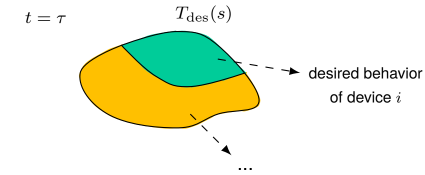
with V. Häberle (ETH Zürich), M. W. Fisher (Univ. Waterloo), & E. Prieto (UPC)

aggregation condition: $\sum_{i \in \mathcal{N} \cup \mathcal{C}} T_i(s) \stackrel{!}{=} T_{\text{des}}(s)$

1) Disaggregation & pooling

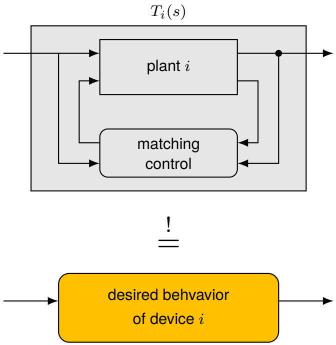


Disaggregate $T_{\text{des}}(s)$ into local desired behaviors for each device (taking local constraints into account).



Disaggregation can be adaptive (later).

2) Local matching control



For each device i, design a local matching controller to match the desired behavior.

Disaggregation & pooling

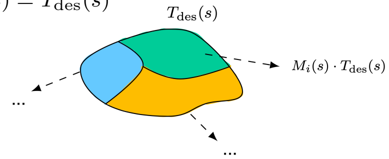
- disaggregation of DVPP specification via **dynamic participation matrices**

$$\boldsymbol{T_i(s) = M_i(s) \cdot T_{\mathrm{des}}(s)} \qquad M_i(s) = \begin{bmatrix} m_i^{\mathrm{fp}}(s) & 0 \\ 0 & m_i^{\mathrm{vq}}(s) \end{bmatrix}$$

where diagonals $m_i^{\mathrm{fp}}, m_i^{\mathrm{vq}}$ are **dynamic participation factors (DPFs)** for f-p & v-q channels

- resulting DVPP **aggregation condition**:

$$\sum\nolimits_{i \in \mathcal{N} \cup \mathcal{C}} T_i(s) \stackrel{!}{=} \sum\nolimits_{i \in \mathcal{N} \cup \mathcal{C}} M_i(s) \cdot T_{\mathrm{des}}(s) = T_{\mathrm{des}}(s)$$



- **participation condition**: $\sum\nolimits_{i \in \mathcal{N} \cup \mathcal{C}} M_i(s) \stackrel{!}{=} I_2$

or element-wise for the DPFs: $\sum\nolimits_{i \in \mathcal{N} \cup \mathcal{C}} m_i^{\mathrm{fp}}(s) \stackrel{!}{=} 1$ & $\sum\nolimits_{i \in \mathcal{N} \cup \mathcal{C}} m_i^{\mathrm{vq}}(s) \stackrel{!}{=} 1$

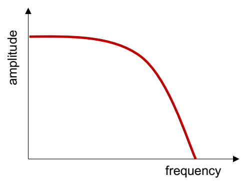
Dynamic participation factor (DPF) selection

- fixed DPFs $M_i(s) = (T_{\text{des}}(s))^{-1} \cdot T_i(s)$ for non-controllable devices $\rightarrow T_i(s)$ unchanged
- DPFs of controllable devices $=$ transfer functions $m_i(s)$ for f-p & v-q channels with
  - **time constant** τ_i for the roll-off frequency to account for bandwidth
  - **DC gain** $m_i(0) = \mu_i$ to account for peak power limitations

low-pass filter participation

for devices providing regulation on longer time-scale & steady -state contributions (e.g., RES)

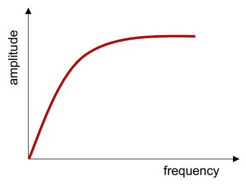
$$m_i(s) = \frac{\mu_i}{\tau_i s+1}$$



high-pass filter participation

for devices providing very fast response (e.g., super-caps)

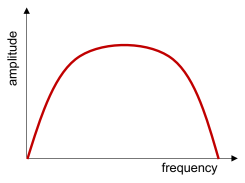
$$m_i(s) = \frac{\tau_i s}{\tau_i s+1}$$



band-pass filter participation

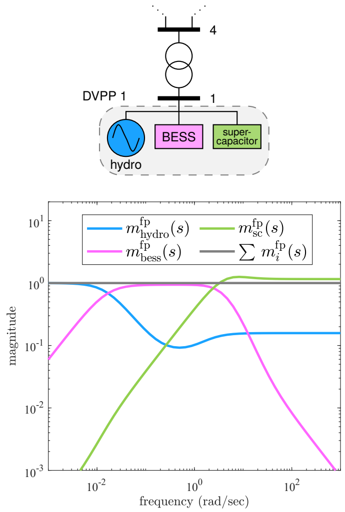
for devices covering the inter-mediate regime (e.g., batteries)

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

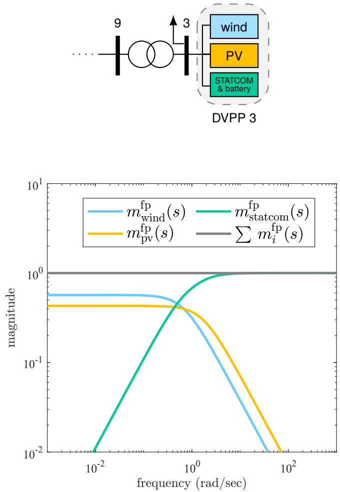


Running case studies - DPF selection for f-p channel

Case study I: hydro supplementation



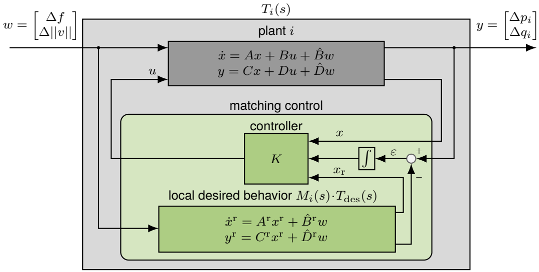
Case study II: sync. generator replacement



Local matching control

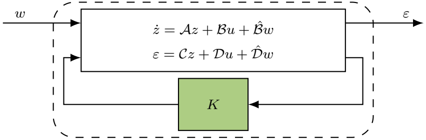
control objective: for each controllable device, design a local matching controllers such that the local closed-loop behavior matches the local desired specification $T_i(s) \overset{!}{=} M_i(s) \cdot T_{\text{des}}(s)$

- setup for **matching control design** of device i: either feed tracking error into standard cascaded converter loops…or better go for principled design



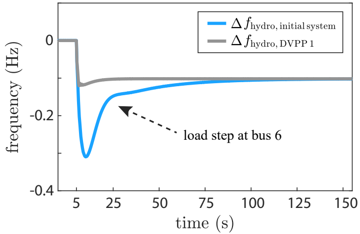
- consider **augmented state** $z = \begin{bmatrix} x & x^r & \int \varepsilon \end{bmatrix}$ with integrated matching error $\varepsilon = y - y^r$ for tracking

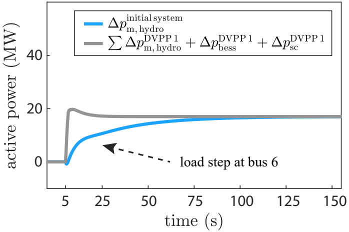
- $\mathcal{H}_\infty$ **optimal static feedback control** K obtained by minimizing the matching error

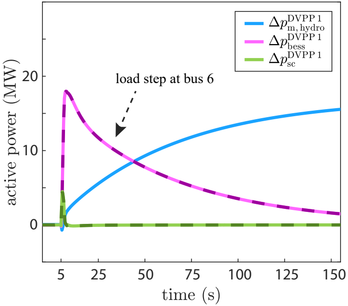


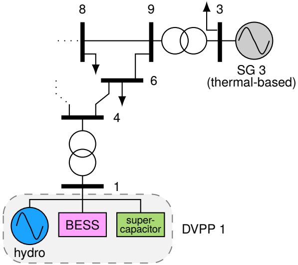
- include **ellipsoidal constraints** for transient device limitations, e.g., hard current constraints

Case study I - simulation results





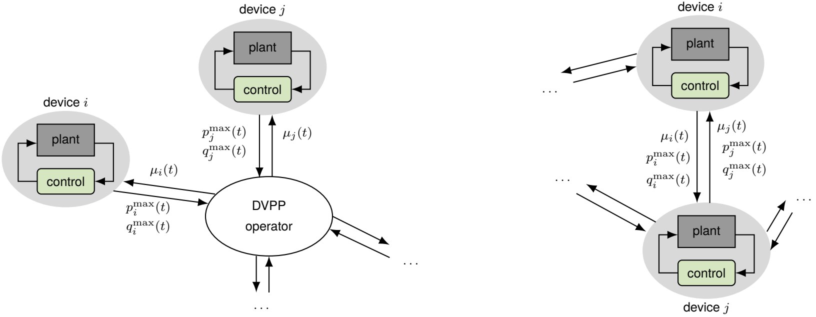




- poor frequency response of stand-alone hydro unit
- significant improvement by DVPP 1
- good matching of desired active power injections (dashed lines)

Online adaptation accounting for fluctuating power capacity limits

- **adaptive** dynamic participation factors (ADPF) with time-varying DC gains: $m_i(0) = \mu_i(t)$
- **online update** of DC gains proportionately to time-varying power capacity limits of variable sources
- requires **centralized (broadcast)** or **distributed peer-to-peer (consensus)** communication

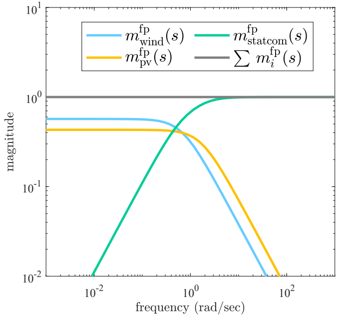


- **LPV $\mathcal{H}_\infty$ control** to account for parameter-varying local reference models $M_i(s) \cdot T_{\text{des}}(s)$

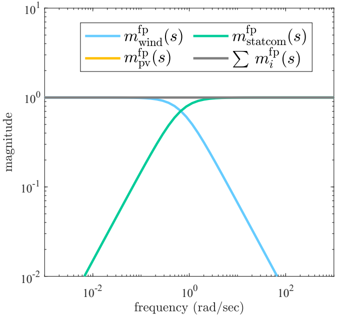
Online adaptation accounting for fluctuating power capacity limits

Running case study II - ADPFs of f-p channel before & during cloud

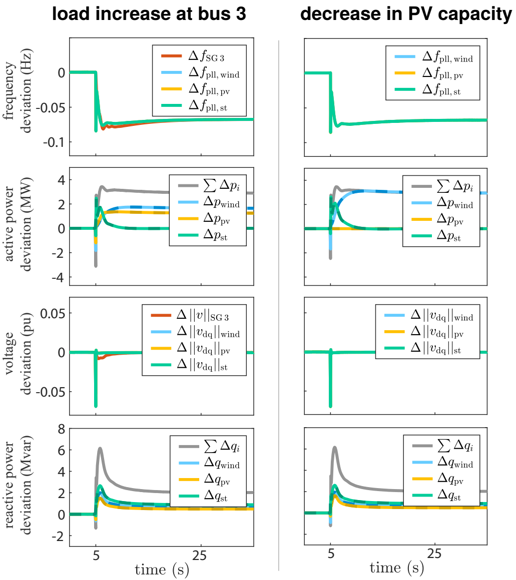
before cloud (nominal)

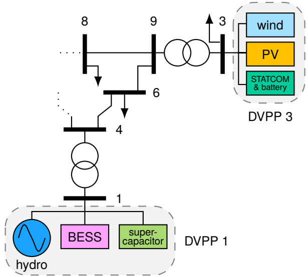


during cloud



Case study II - simulation results



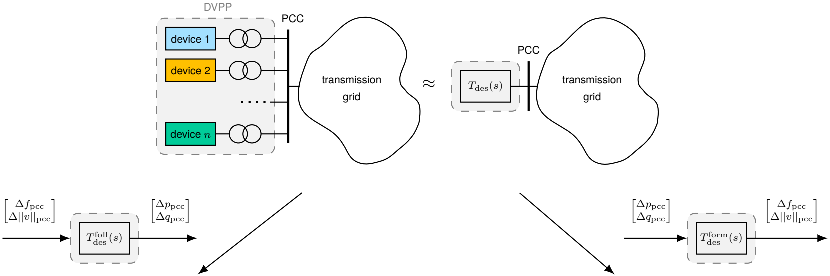


- adequate replacement of frequency & voltage control of prior SG 3
- good matching of desired active & reactive power injections (dashed lines)
- unchanged overall DVPP behavior during step decrease in PV capacity

Outline

Grid-forming DVPP control

with V. Häberle & X. He (ETH Zürich), E. P. Araujo (UPC), & Ali Tayyebi (Hitachi Energy)



grid-following signal causality

$$\begin{bmatrix}\Delta p_{\text{pcc}}(s)\\ \Delta q_{\text{pcc}}(s)\end{bmatrix} \overset{!}{=} \underbrace{\begin{bmatrix}T^{\text{fp}}_{\text{des}}(s) & 0\\ 0 & T^{\text{vq}}_{\text{des}}(s)\end{bmatrix}}_{=T^{\text{foll}}_{\text{des}}(s)} \begin{bmatrix}\Delta f_{\text{pcc}}(s)\\ \Delta\|v\|_{\text{pcc}}(s)\end{bmatrix}$$

→ power injection controlled as function of frequency & voltage measurement

grid-forming signal causality

$$\begin{bmatrix}\Delta f_{\text{pcc}}(s)\\ \Delta\|v\|_{\text{pcc}}(s)\end{bmatrix} \overset{!}{=} \underbrace{\begin{bmatrix}T^{\text{pf}}_{\text{des}}(s) & 0\\ 0 & T^{\text{qv}}_{\text{des}}(s)\end{bmatrix}}_{=T^{\text{form}}_{\text{des}}(s)} \begin{bmatrix}\Delta p_{\text{pcc}}(s)\\ \Delta q_{\text{pcc}}(s)\end{bmatrix}$$

→ frequency & voltage imposition controlled as function of power measurement

Grid-forming DVPP frequency control architecture

- local **controllable** closed-loop behaviors $T_i^{\mathrm{pf}}(s)$ (extendable to non-controllable behaviors)
- explicitly model **interconnection** of DVPP devices (e.g., via LV network & transformers)
- **linearized power flow** with Laplacian L_{dvpp}

$$\Delta p_{\mathrm{e}}(s) = \frac{L_{\mathrm{dvpp}}}{s} \Delta f(s)$$

- assume **coherent response** for DVPP design:

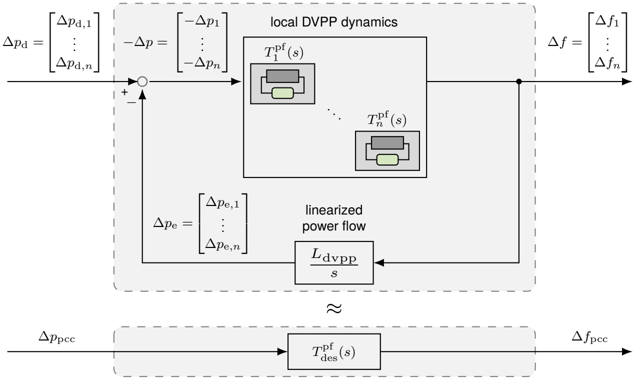
$$\Delta f_i(s) \approx \left(\sum T_i^{\mathrm{pf}}(s)^{-1}\right)^{-1} \sum_i \Delta p_{\mathrm{d},i}(s)$$

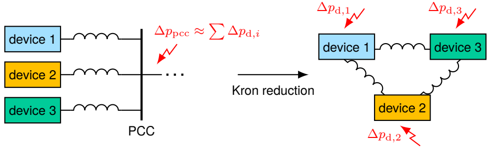
- **desired synchronized PCC dynamics**

$$\Delta f_{\mathrm{pcc}} = T_{\mathrm{des}}^{\mathrm{pf}}(s)\, \Delta p_{\mathrm{pcc}}$$

→ **aggregation condition**:

$$\left(\sum_i T_i^{\mathrm{pf}}(s)^{-1}\right)^{-1} \overset{!}{=} T_{\mathrm{des}}^{\mathrm{pf}}(s)$$





Grid-forming DVPP voltage control architecture

- no coherent behavior of local voltage magnitudes
  $\rightarrow$ no analogy to DVPP frequency control setup
- common global **input signal** $\Delta||v||_{\text{pcc}}$
- **aggregate reactive power** injection

$$\Delta q_{\text{agg}} = \sum_{i=1}^{n} \Delta q_i$$

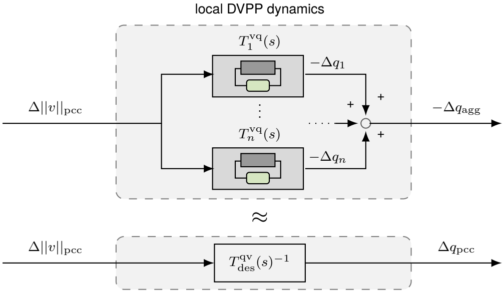
- local **controllable** closed-loop behaviors $T_i^{\text{vq}}(s)$
  (extendable to non-controllable behaviors)
- **aggregate DVPP behavior**

$$\Delta q_{\text{agg}}(s) = -\sum_{i=1}^{n} T_i^{\text{vq}}(s)\Delta||v||_{\text{pcc}}(s)$$

- approximate $\Delta q_{\text{pcc}} \approx -\Delta q_{\text{agg}}$ (loss compensation)

$\rightarrow$ **aggregation condition**:

$$\sum_{i=1}^{n} T_i^{\text{vq}}(s) \overset{!}{=} T_{\text{des}}^{\text{qv}}(s)^{-1}$$



$$\begin{bmatrix} \Delta f_{\text{pcc}}(s) \\ \Delta||v||_{\text{pcc}}(s) \end{bmatrix} \overset{!}{=} \underbrace{\begin{bmatrix} T_{\text{des}}^{\text{pf}}(s) & 0 \\ 0 & T_{\text{des}}^{\text{qv}}(s) \end{bmatrix}}_{=T_{\text{des}}^{\text{form}}(s)} \begin{bmatrix} \Delta p_{\text{pcc}}(s) \\ \Delta q_{\text{pcc}}(s) \end{bmatrix}$$

Adaptive divide & conquer strategy for grid-forming DVPP

- **disaggregation** of $T_{\mathrm{des}}^{\mathrm{form}}$ via ADPFs

$$T_{\mathrm{des}}^{\mathrm{pf}}(s)^{-1} = \sum_{i=1}^{n} m_i^{\mathrm{fp}}(s) T_{\mathrm{des}}^{\mathrm{pf}}(s)^{-1} \overset{!}{=} \sum_{i=1}^{n} T_i^{\mathrm{pf}}(s)^{-1},$$
$$T_{\mathrm{des}}^{\mathrm{qv}}(s)^{-1} = \sum_{i=1}^{n} m_i^{\mathrm{vq}}(s) T_{\mathrm{des}}^{\mathrm{qv}}(s)^{-1} \overset{!}{=} \sum_{i=1}^{n} T_i^{\mathrm{vq}}(s),$$

- **participation condition**

$$\sum_{i=1}^{n} m_i^{\mathrm{fp}}(s) \overset{!}{=} 1 \quad \& \quad \sum_{i=1}^{n} m_i^{\mathrm{vq}}(s) \overset{!}{=} 1$$

- **online adaptation** of LPF DC gains $m_i^k(0) = \mu_i^k(t), \quad k \in \{\mathrm{fp}, \mathrm{vq}\}$

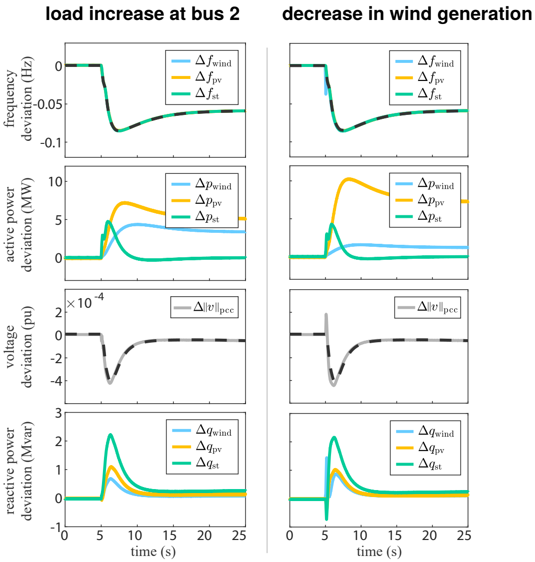
- **local model matching condition**

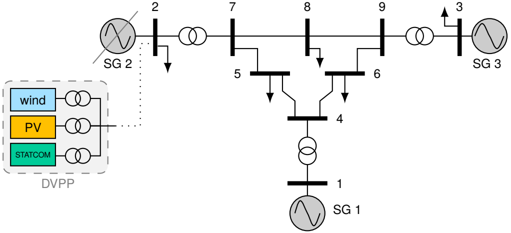
$$T_i^{\mathrm{pf}}(s) \overset{!}{=} m_i^{\mathrm{fp}}(s)^{-1} T_{\mathrm{des}}^{\mathrm{pf}}(s),$$
$$T_i^{\mathrm{vq}}(s) \overset{!}{=} m_i^{\mathrm{vq}}(s) T_{\mathrm{des}}^{\mathrm{qv}}(s)^{-1}.$$

- compute **local LPV $\mathcal{H}_\infty$ matching controllers**

same as before ...

Numerical case study





- specify decoupled p-f & q-v control

$$\begin{bmatrix} \Delta f_{\mathrm{pcc}}(s) \\ \Delta v_{\mathrm{pcc}}(s) \end{bmatrix} = T_{\mathrm{des}}(s) \begin{bmatrix} \Delta p_{\mathrm{pcc}} \\ \Delta q_{\mathrm{pcc}} \end{bmatrix}, \quad T_{\mathrm{des}} = \begin{bmatrix} \frac{1}{H_{\mathrm{p}} s + D_{\mathrm{p}}} & 0 \\ 0 & D_{\mathrm{q}} \end{bmatrix}$$

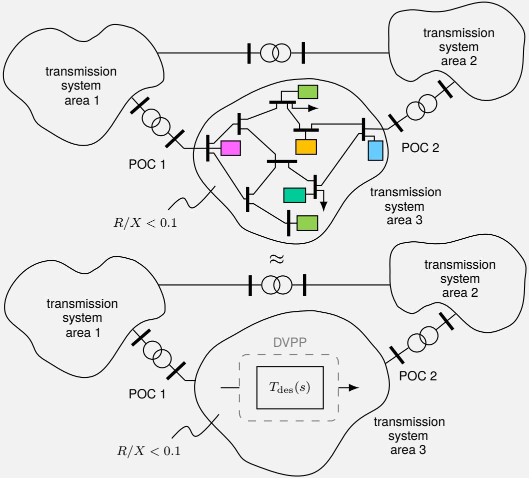
- good matching of desired behavior (dashed lines)
- unchanged aggregate DVPP behavior during decrease in wind generation

→ also possible: **hybrid DVPPs** including grid-forming + grid-following devices (. . . same as before)

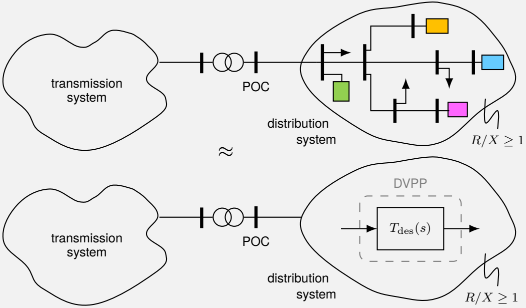
Spatially distributed DVPP

with V. Häberle & X. He (ETH), Ali Tayyebi (Hitachi Energy), & E. Prieto (UPC)

Transmission system DVPP



Distribution system DVPP

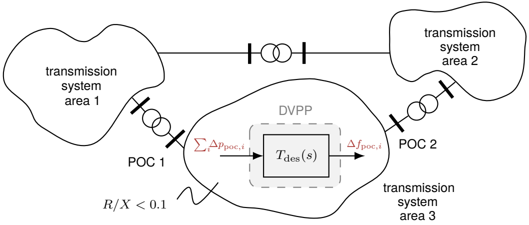


Assumptions

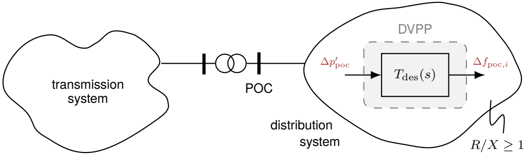
- only constant power loads within DVPP area
- all devices in the DVPP area with dynamic ancillary services provision are part of the DVPP

Key ingredient: rotational power control

transmission system DVPP



distribution system DVPP



→ rotational powers to decouple power flow equations

$$\begin{bmatrix} p' \\ q' \end{bmatrix} = \begin{bmatrix} X/Z & -R/Z \\ R/Z & X/Z \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix}$$

- lossless p (*or* p') transmission → p-f (*or* **modified** p'-f) control setup for DVPP at one bus still valid
- **limitation 1:** (p,q) device constraints need to be mapped (possibly conservatively) to (p',q') constraints
- **limitation 2:** lossy q (*or* q') transmission → DVPP control requires omniscient & centralized coordination

solution: consider global p-f (*or* p'-f) DVPP control at the POCs & use independent local q-v (*or* q'-v) controllers

Outline

1. Introduction & Motivation
2. DVPP Design as Coordinated Model Matching
3. Decentralized Control Design Method
4. Grid-Forming & Spatially Distributed DVPP
5. Conclusions

Conclusions

DVPP control

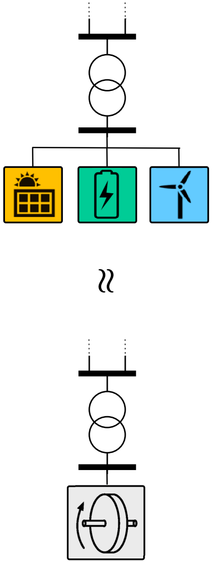
- coordinate heterogeneous RES to provide dynamic ancillary services
- heterogeneity: different device characteristics complement each other
- reduce the need of conventional generation for dynamic ancillary services

adaptive divide & conquer strategy

- disaggregation of desired aggregate input / output specification via DPFs
- local LPV $\mathcal{H}_\infty$ model matching taking device constraints into account
- online-update of DPFs & matching control to adapt to variable generation

extensions & ongoing research

- grid-forming, hybrid, & spatially distributed DVPP setups
- globally optimal model-matching via modified system level synthesis
- complex frequency & power notions to specify future ancillary services



References

Björk, J., Johansson, K. H., & Dörfler, F. (2021). Dynamic virtual power plant design for fast frequency reserves: Coordinating hydro and wind. IEEE Transactions on Control of Network Systems.

Häberle, V., Fisher, M. W., Prieto, E., & Dörfler, F. (2021). Control Design of Dynamic Virtual Power Plants: An Adaptive Divide-and-Conquer Approach. IEEE Transactions on Power Systems.

Fisher, M.W., Hug, G., & Dörfler, F. (2022). Approximation by Simple Poles – Parts I & II. Submitted (arXiv preprint arXiv:2203.16765).

Häberle, V., Tayyebi, A., Prieto, E., & Dörfler, F. (2022). Grid-Forming Control Design of Dynamic Virtual Power Plants. Extended Abstract IFAC Workshop on Networked Systems.

Häberle, V., Tayyebi, A., He, X., Prieto, E., & Dörfler, F. (2022) Grid-Forming and Spatially Distributed Control Design of Dynamic Virtual Power Plants. To be submitted.