ETH zürich

POSYTYF

Dynamic Virtual Power Plant Control

POSYTYF Internal Webinar, WP 4

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Acknowledgements

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Outline

Outline

Challenges in future power systems

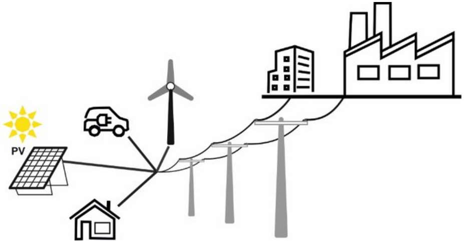
- **conventional power systems**
  - dispatchable generation
  - significant inertial response
  - fast frequency & voltage control

  provided by bulk synchronous generation

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

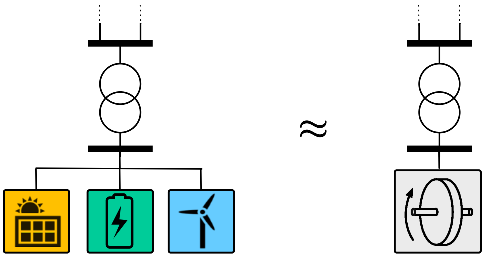
  provided by distributed energy resources (DERs)

- some of the manifold **challenges**
  - **grid fragility:** 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



- sufficiently **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** & robustly ancillary services
  - fast response (grid fragility), 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 . . .

Abstraction: coordinated model matching

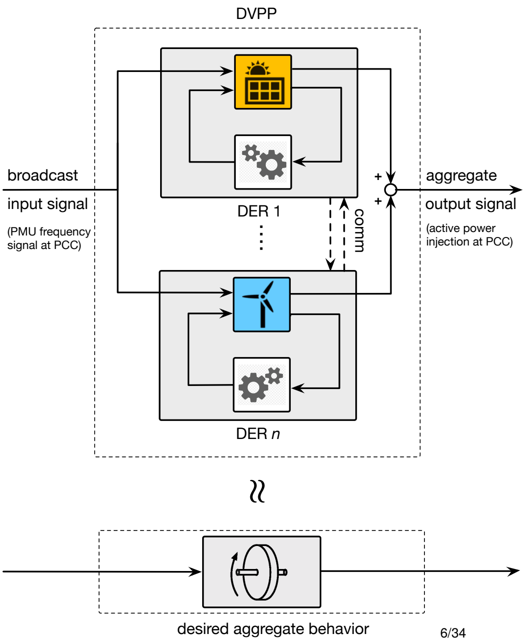
- **setup** (simplified): DVPP consisting of
  - DERs connected at a common bus
  - PMU frequency measurement at point of common coupling broadcasted to all DERs
- DVPP **aggregate specification** (ancillary service):
  - grid-following fast frequency response (virtual inertia & damping)

    $$\textit{power} = \big(H\,s + D\big)\cdot \textit{frequency}$$

    (later: forming + distributed + voltage . . .)
- task: **coordinated model matching**
  - design decentralized DER controls so that the aggregate behavior matches specification

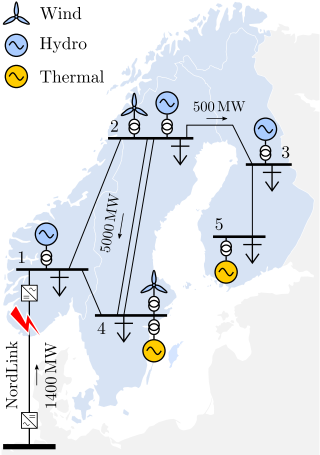
    $$\textstyle\sum_i \text{power}_i \;=\; \big(H\,s + D\big)\cdot \textit{PMU-frequency}$$

  - 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)

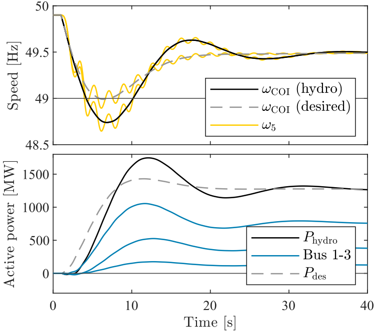


aggregated 5-bus Nordic model

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

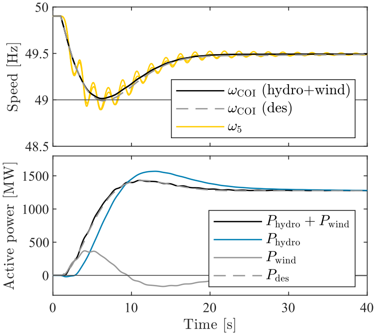
$$\frac{\textit{power}}{\textit{frequency}} = \frac{3100 \cdot (6.5s + 1)}{(2s+1)(17s+1)}$$

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



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

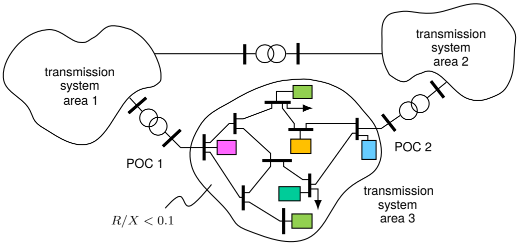
- better **DVPP solution**: coordinate hydro & wind to cover all time scales

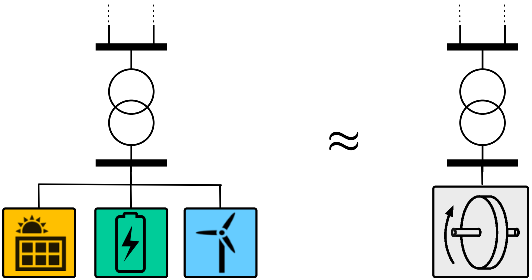


remainder of the talk: **how** to do it ?

Outline

Problem setup & variations





obviously . . . one can conceive **quite complex problem setups** with a DVPP spanning transmission/distribution, multiple areas, forming/following controls, all sorts of devices $\rightarrow$ need to make choices: **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**

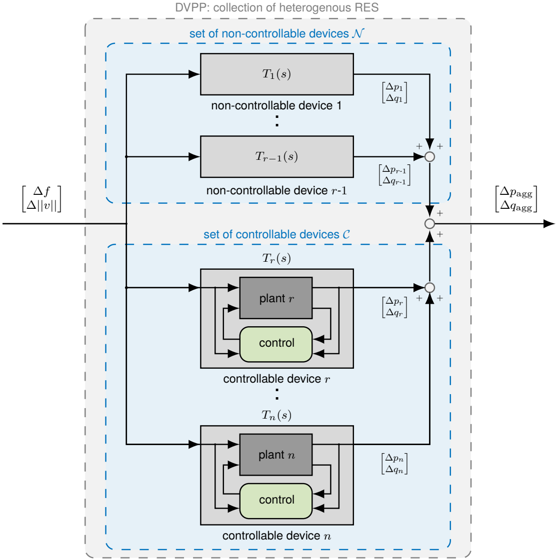
$$\begin{bmatrix} \Delta p_{\text{agg}} \\ \Delta q_{\text{agg}} \end{bmatrix} = \sum_{i \in \mathcal{N} \cup \mathcal{C}} \begin{bmatrix} \Delta p_i \\ \Delta q_i \end{bmatrix}$$

- fixed local closed-loop behaviors of **non-controllable devices** $T_i(s), i \in \mathcal{N}$ (e.g., closed-loop hydro/governor model)

- devices with **controllable** closed-loop behaviors $T_i(s), i \in \mathcal{C}$ (e.g., battery sources)

- overall/global/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/global/aggregate **DVPP behavior**

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

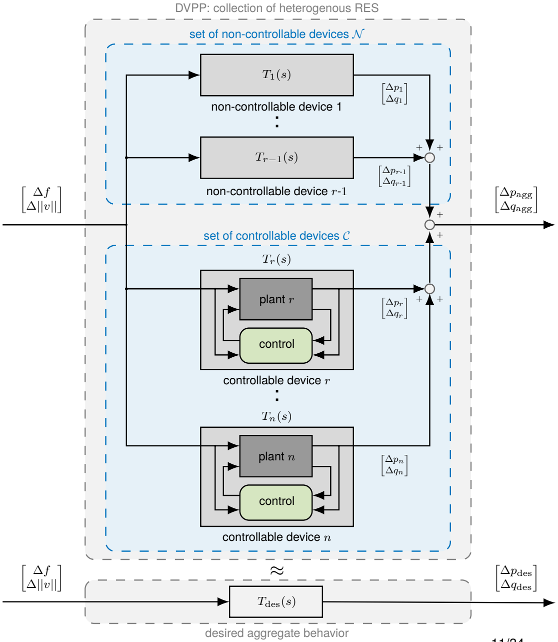
- **desired DVPP specification**: decoupled f-p & v-q control (later: consider couplings)

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

$\rightarrow$ **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.

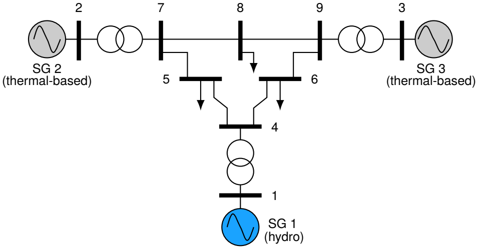


Outline

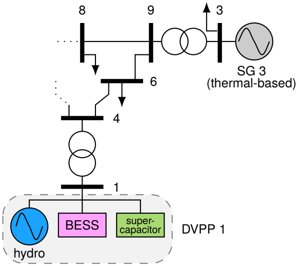
1. Introduction & Motivation
2. DVPP Design as Coordinated Model Matching
3. Decentralized Control Design Method
4. Extensions & Ongoing Research
5. Conclusions

Running case studies

Original 9 bus system setup



Case study I: hydro supplementation

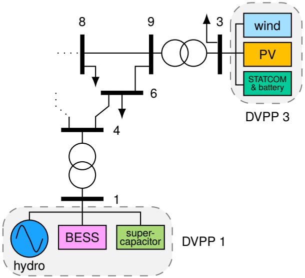


DVPP 1 for freq. control

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

$$T_{\text{des}}(s) := \tfrac{-D}{\tau s+1},$$

Case study II: synchronous generator replacement



DVPP 3 for freq. & volt. control

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

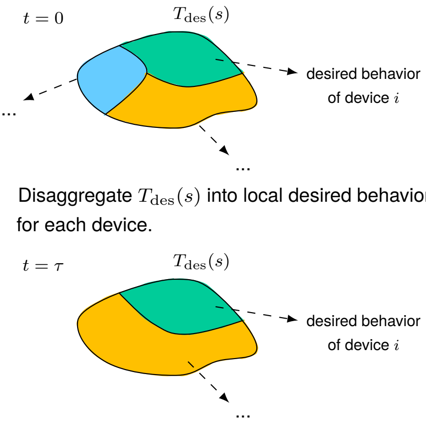
$$T_{\text{des}}(s) := \begin{bmatrix} \frac{-D_{\text{p}}-Hs}{\tau_{\text{p}}s+1} & 0 \\ 0 & \frac{-D_{\text{q}}}{\tau_{\text{q}}s+1} \end{bmatrix}$$

Divide & conquer strategy

with M. W. Fisher (University of Waterloo), E. Prieto-Araujo (UPC)

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

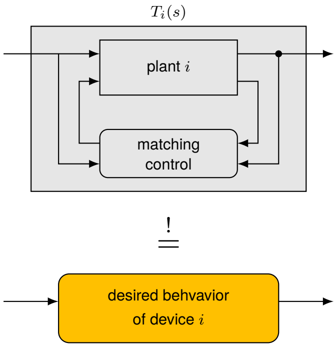
1) Disaggregation & pooling



Disaggregate $T_{\mathrm{des}}(s)$ into local desired behaviors for each device.

Disaggregation can be adaptive (later).

2) Local matching control



For each device i, design local matching control to match desired behavior.

Disaggregation & pooling

- disaggregation of DVPP specification via **dynamic participation matrices (DPMs)**

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

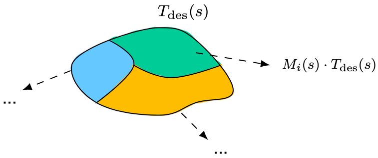
$\rightarrow$ diagonal elements $m_i^{\mathrm{fp}}, m_i^{\mathrm{vq}}$ are **dynamic participation factors (DPFs)** for the f-p & v-q channel
(selection of DPFs on next slide!)

- 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** of DPMs

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



- **participation condition** of DPFs

$$\sum\nolimits_{i \in \mathcal{N} \cup \mathcal{C}} m_i^{\mathrm{fp}}(s) \stackrel{!}{=} 1, \qquad\qquad \sum\nolimits_{i \in \mathcal{N} \cup \mathcal{C}} m_i^{\mathrm{vq}}(s) \stackrel{!}{=} 1,$$

DPF selection

(same principle for f-p and v-q channel; omit superscripts in the following)

- fixed DPFs of non-controllable devices $\mathcal{N}$ with fixed $T_i(s)$

$$m_i(s) := (T_{\text{des}}(s))^{-1} T_i(s)$$

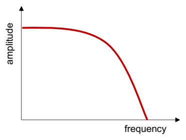
- define DPFs of the controllable deivces $\mathcal{C}$ as transfer functions, each characterized by
  - a **time constant** τ_i for the roll-off frequency
  - a **DC gain** $m_i(0) = \mu_i$ to account for power capacity limitations

$\rightarrow$ divide the controllable devices into three categories, i.e., we envision

low-pass filter participation

for devices that can provide regulation on longer time scales including steady-state contri-butions

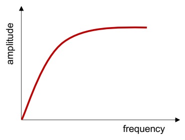
$$m_i(s) = \frac{\mu_i}{\tau_i s + 1}$$



high-pass filter participation

for devices able to provide regulation on very short time scales

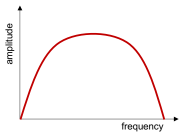
$$m_i(s) = \frac{\tau_i s}{\tau_i s + 1}$$



band-pass filter participation

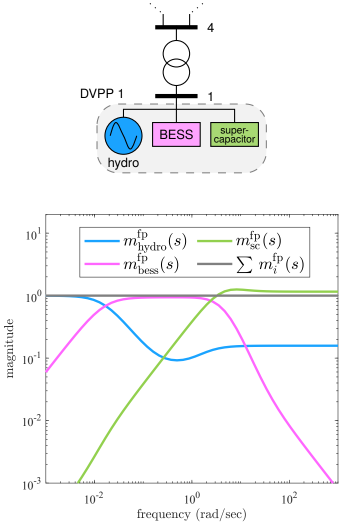
for devices able to cover the intermediate regime

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

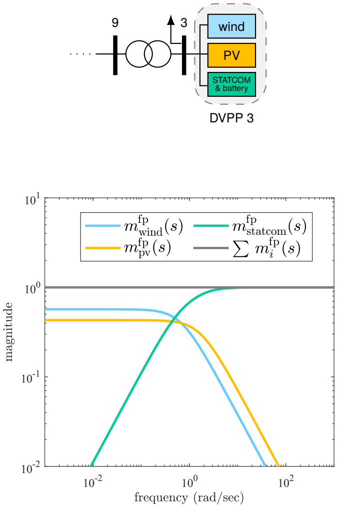


Running case studies - DPF selection for f-p channel

Case study I: hydro supplementation



Case study II: sync. generator replacement

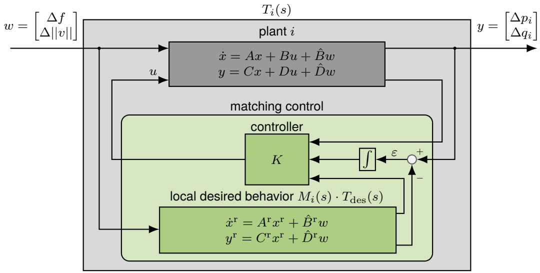


Local matching control

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

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

- setup for matching control design of device i

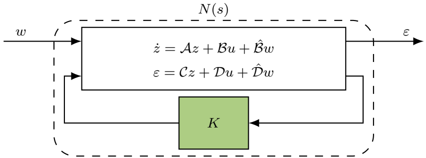


- consider the augmented system with state $z = [x \quad x^{\text{r}} \ \int \varepsilon]'$

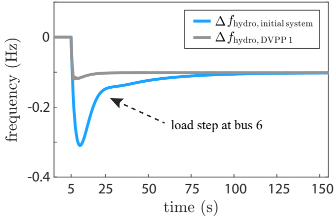
- the state-feedback controller K is obtained by minimizing the matching error $\varepsilon(s) = N(s)w(s)$ in the $\mathcal{H}_\infty$-norm as

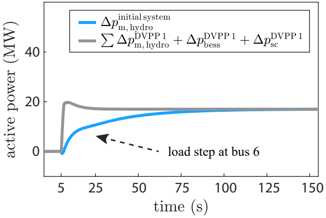
$$\underset{K}{\text{minimize}} \quad ||N(s)||_\infty$$

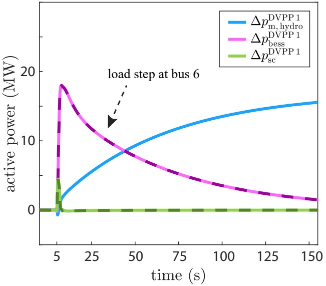
- include ellipsoidal constraints for transient device limitations, e.g., converter current constraints

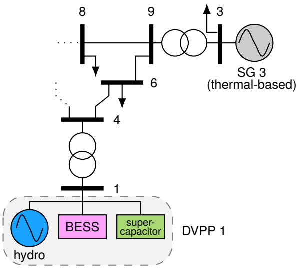


Case study I - simulation results





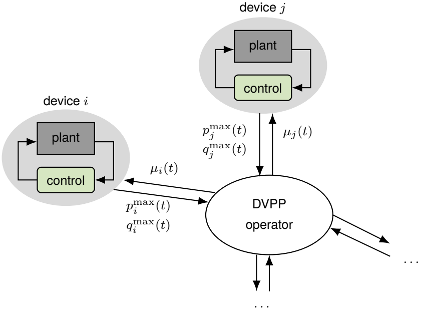


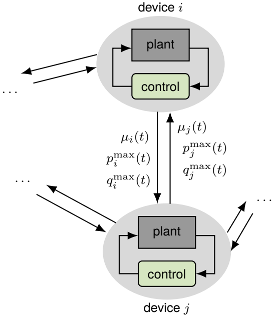


- poor frequency response of stand-alone hydro unit
- significant improvement by DVPP 1
- good matching of desired active power injections (dashed lines)

Online adaptation accounting for fluctuating power capacity limits

- adaptive (i.e., time-varying) DC gains of LPF DPFs, i.e., $m_i(0) = \mu_i(t)$
  $\rightarrow$ **adaptive** dynamic participation factors (ADPF)
- update DC gains proportionately to the power capacity limit of the devices
- requires **centralized (broadcast)** communication or **distributed peer-to-peer** communication



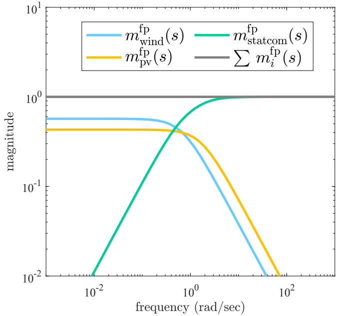


- LPV $\mathcal{H}_\infty$ control to account for parameter-varying local reference models $M_i(s) \cdot T_{\text{des}}(s)$

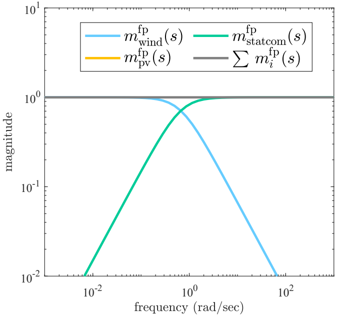
Online adaptation accounting for fluctuating power capacity limits

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

before cloud (nominal)

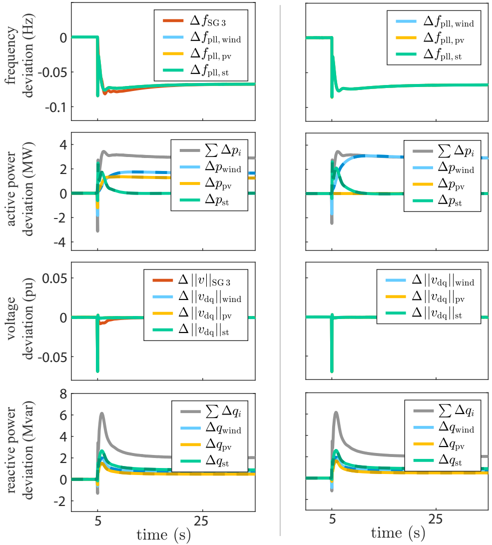


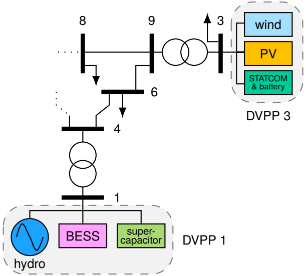
during cloud



Case study II - simulation results

load increase at bus 3 **decrease in PV capacity**





- 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

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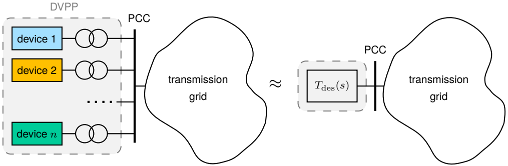
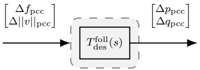
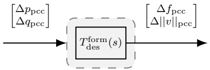
Grid-forming DVPP control

with E. Prieto-Araujo (UPC), Ali Tayyebi (Hitachi Energy)







grid-following signal causality

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

$\rightarrow$ power injection controlled as function of frequency & voltage measurement

grid-forming signal causality

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

$\rightarrow$ frequency & voltage imposition controlled as function of power measurement

Grid-forming DVPP frequency control architecture

- **feedback interconnection:** local DVPP dynamics & dynamics of DVPP interconnection network (e.g., via LV/MV transformers)
- local **controllable** closed-loop behaviors $T_i^{\mathrm{pf}}(s)$ ($\rightarrow$ extendable to non-controllable behaviors)
- linearized power flow of DVPP interconnection network (L_{dvpp}: Laplacian matrix)

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

- **coherent response** [Jiang et. al (2021)]

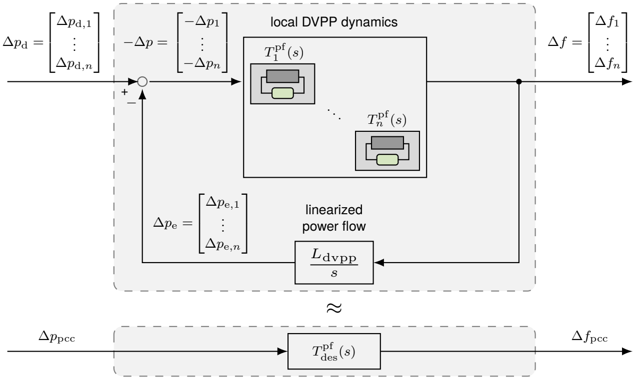
$$\Delta f(s) = \left(\sum_{i=1}^{n} T_i^{\mathrm{pf}}(s)^{-1}\right)^{-1} \mathbb{1}_n \mathbb{1}_n^\top \Delta p_{\mathrm{d}}(s)$$

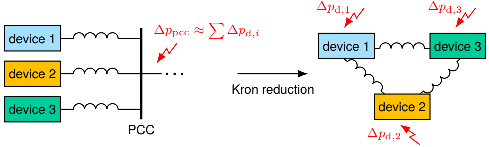
- synchronized frequency dynamics at PCC

$$\Delta f_{\mathrm{pcc}} = \left(\sum_{i=1}^{n} T_i^{\mathrm{pf}}(s)^{-1}\right)^{-1} \Delta p_{\mathrm{pcc}},$$

$\rightarrow$ **aggregation condition:**

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



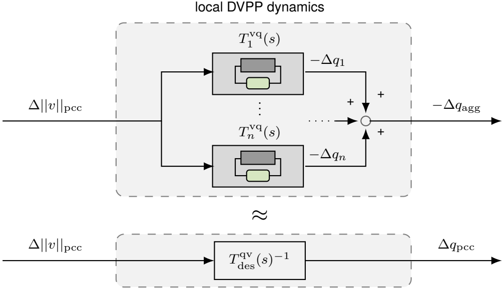


Grid-forming DVPP voltage control architecture

- no coherent dynamic behavior of local voltage magnitudes $\rightarrow$ no analogy between frequency & voltage control setup!
- common **input signal** $\Delta||v||_{\mathrm{pcc}}$
- **aggregate reactive power output**
$$\Delta q_{\mathrm{agg}} = \sum_{i=1}^{n} \Delta q_i$$
- local **controllable** closed-loop behaviors $T_i^{\mathrm{vq}}(s)$
(→ extendable to non-controllable behaviors)
- **aggregate DVPP behavior**
$$\Delta q_{\mathrm{agg}}(s) = -\sum_{i=1}^{n} T_i^{\mathrm{vq}}(s)\Delta||v||_{\mathrm{pcc}}(s)$$
- approximate $\Delta q_{\mathrm{pcc}} \approx -\Delta q_{\mathrm{agg}}$
(or compensate reactive losses)

→ **aggregation condition:**
$$\sum_{i=1}^{n} T_i^{\mathrm{vq}}(s) \stackrel{!}{=} T_{\mathrm{des}}^{\mathrm{qv}}(s)^{-1}$$

Note: $T_{\mathrm{des}}^{\mathrm{qv}}$ needs to be invertible.



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

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**

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

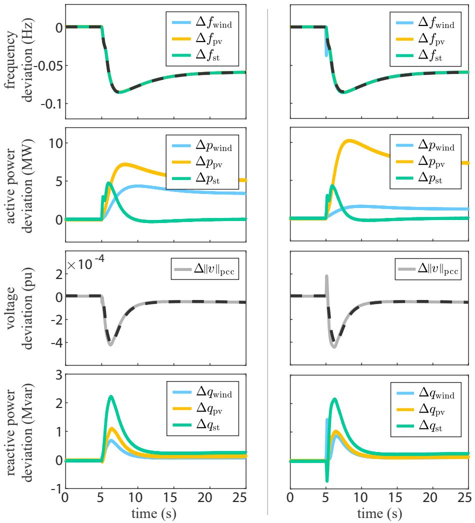
$$T_i^{\mathrm{vq}}(s) \overset{!}{=} m_i^{\mathrm{vq}}(s) T_{\mathrm{des}}^{\mathrm{qv}}(s)^{-1}.$$

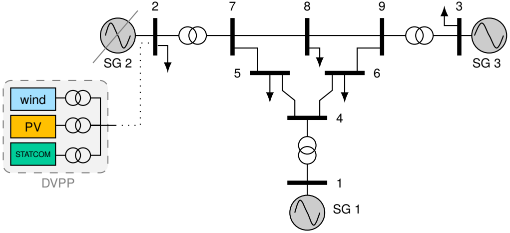
$\rightarrow$ compute local LPV $\mathcal{H}_\infty$ matching controllers!

same as before ...

Numerical case study

load increase at bus 2 | **decrease in wind generation**





- specify decoupled p-f & q-v control

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

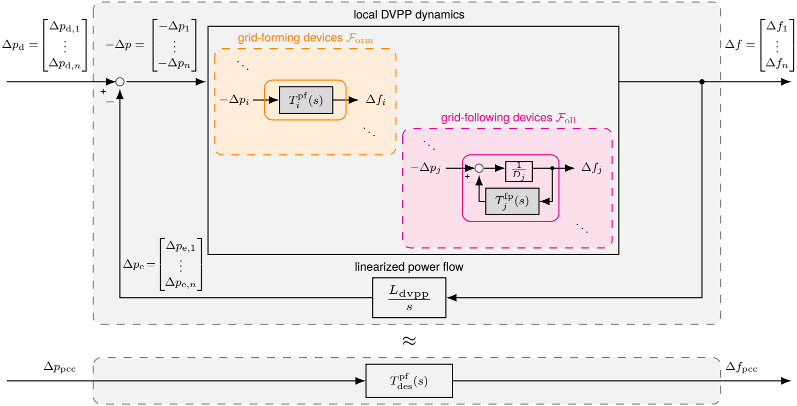
- good matching of desired frequency & voltage behavior (dashed lines)
- unchanged overall DVPP behavior during decrease in wind generation

Next level: hybrid DVPPs - aggregating grid-forming & grid-following devices

Frequency control setup

- include grid-following devices via fictitious frequency dependent load, where $D_j = 0$, such that
$$\Delta f_j = -\frac{1}{D_j + T_j^{\text{fp}}(s)} \Delta p_j$$
$$= -\frac{1}{T_j^{\text{fp}}(s)} \Delta p_j$$

- local **controllable** closed-loop behaviors T_i^{pf}, T_j^{fp}
(→ extendable to non-controllable behaviors)



coherent closed-loop dynamics [Jiang et al. (2021)]

$$\Delta f = \left(\sum_{i \in \mathcal{F}_{\text{orm}}} T_i^{\text{pf}}(s)^{-1} + \sum_{j \in \mathcal{F}_{\text{oll}}} T_j^{\text{fp}}(s) \right)^{-1} \mathbb{1}_n \mathbb{1}_n^\top \Delta p_{\text{d}}(s)$$

→ **aggregation condition:**

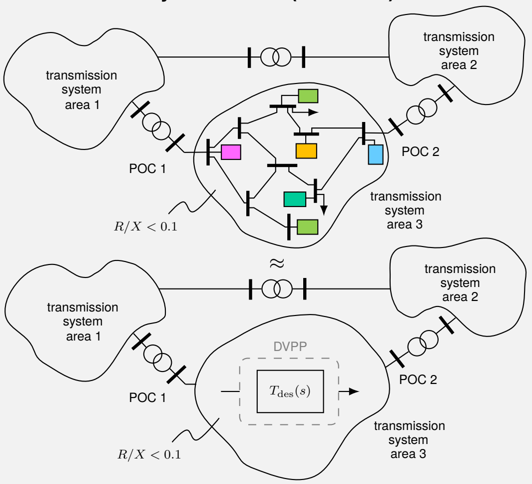
$$\left(\sum_{i \in \mathcal{F}_{\text{orm}}} T_i^{\text{pf}}(s)^{-1} + \sum_{j \in \mathcal{F}_{\text{oll}}} T_j^{\text{fp}}(s) \right)^{-1} \overset{!}{=} T_{\text{des}}^{\text{pf}}(s)$$

(voltage control setup similar to before)

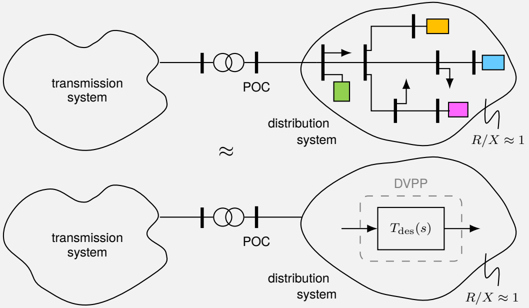
Preview: spatially distributed DVPP

with X. He (ETH), Ali Tayyebi (Hitachi Energy), E. Prieto-Araujo (UPC)

Transmission system DVPP (TS-DVPP)



Distribution system DVPP (DS-DVPP)



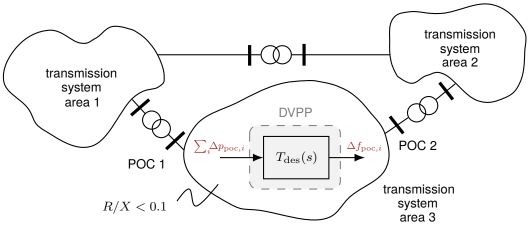
Assumptions

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

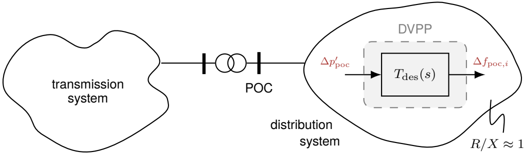
Preview: spatially distributed DVPP

with X. He (ETH), Ali Tayyebi (Hitachi Energy), E. Prieto-Araujo (UPC)

Transmission system DVPP (TS-DVPP)



Distribution system DVPP (DS-DVPP)



→ rotational powers to decouple power flow equations

$$\begin{bmatrix} p' \\ q' \end{bmatrix} = \begin{bmatrix} X/Z & -R/Z \\ R/Z & X/Z \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix}, \; Z^2 = X^2 + R^2$$

- lossless p (*or* p') transmission → p-f (*or* **modified** p'-f) control setup for DVPP at one bus still valid!
- **limitations:** lossy q (*or* q') transmission → DVPP control would require full network information during real-time operation & 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. Extensions & Ongoing Research
5. Conclusions

Conclusions

DVPP control

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

Adaptive divide & conquer strategy

- fully decentralized control strategy
  1. disaggregation & pooling
  2. local model matching
- incorporation of DVPP internal constraints
- online-adaptation towards fluctuating device capacities

Alternative DVPP control design approach based on centralized optimization problem [M.W.Fisher et. al (2022)]

Extensions & ongoing research

- grid-forming DVPP control, hybrid DVPP control
- spatially distributed DVPP devices in transmission & distribution grid

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