Dynamic Virtual Power Plant Control

Autonomous Energy Systems Workshop

Florian Dörfler

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Verena Häberle
(ETH Zürich)

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(ETH Zürich)

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(UP Catalunya)

Joakim Björk
Svenska Kraftnät

Further: Gabriela Hug, Karl Henrik Johansson, & POSYTYF partners

Outline

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

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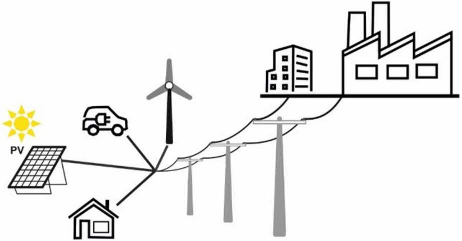
Selected challenges in future power systems

- **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)



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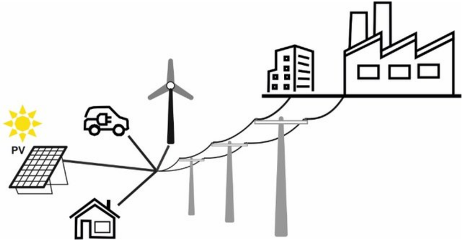
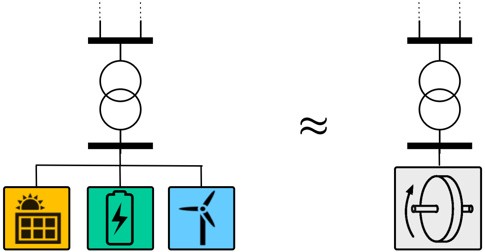
- some of the manifold **challenges**
  - **brittle grids:** intermittency & uncertainty of renewables & reduced inertia levels
  - **device fragility:** converter-interfaced DERs limited in energy, power, fault currents, . . .
  - **ancillary services** on ever faster time scales & shouldered by distributed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



Dynamic Virtual Power Plant (DVPP)

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



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  - reliable provide services consistently across all power & energy levels and all time scales
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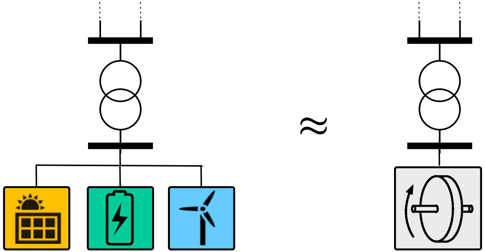

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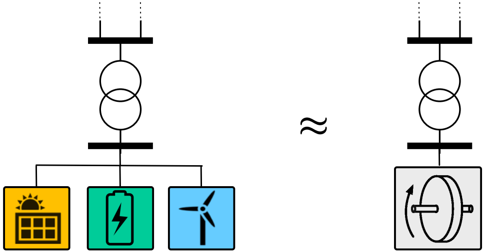

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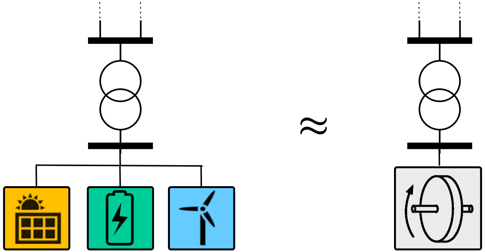

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  - decentralized control implementation
  - real-time adaptation to variable DVPP generation & ambient grid conditions

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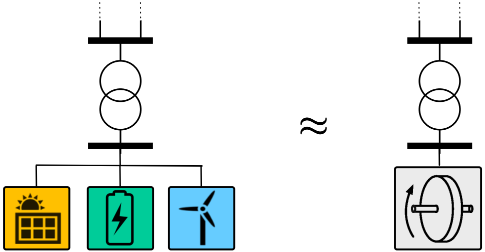

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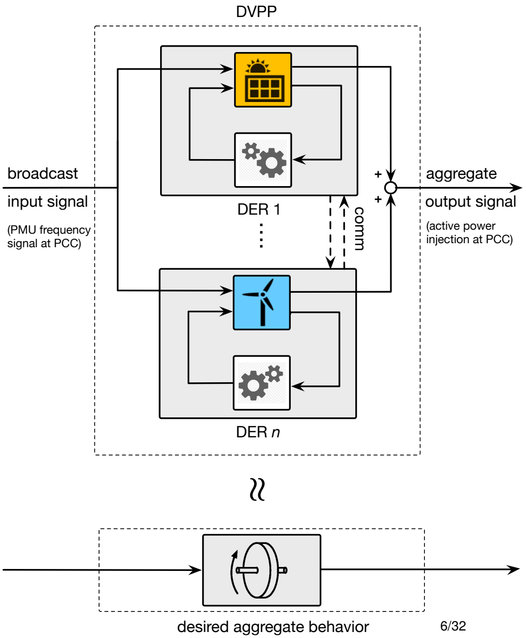
motivating examples

- 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



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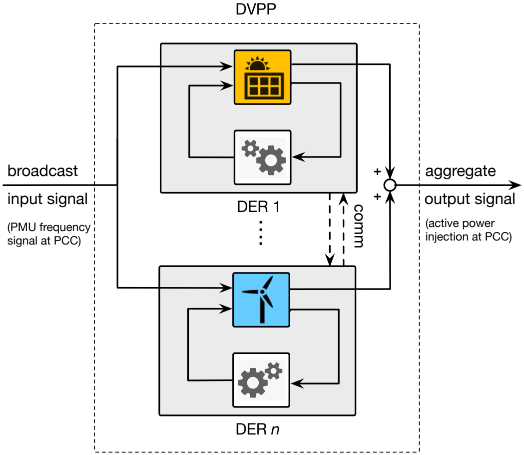
    $$\textit{power} = \left(H\,s + D\right) \cdot \textit{frequency}$$

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



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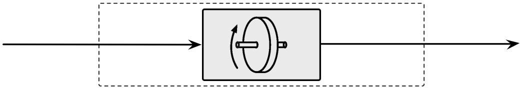

desired aggregate behavior

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

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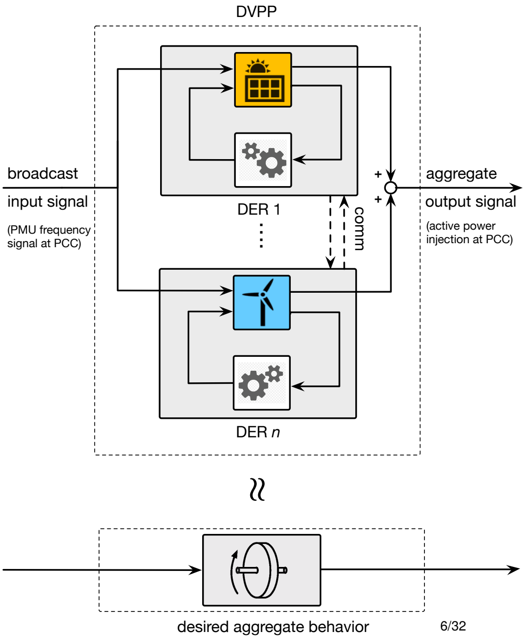
- task: **coordinated model matching**
  - design decentralized DER controls so that the aggregate behavior matches specification

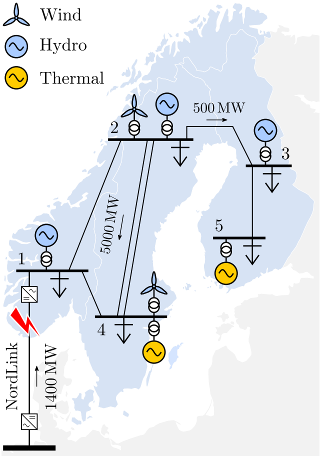
    $$\sum_i \text{power}_i \;=\; \big(H\,s + D\big) \cdot \textit{PMU-frequency}$$

  - 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

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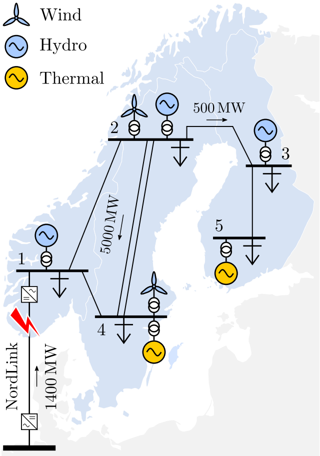

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- **FCR-D service** → desired behavior

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

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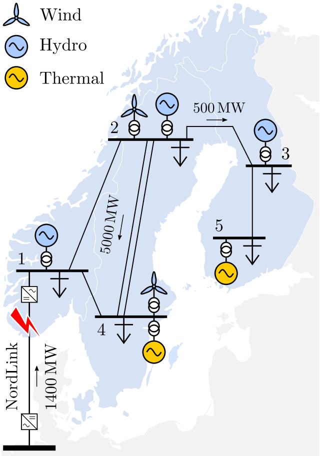

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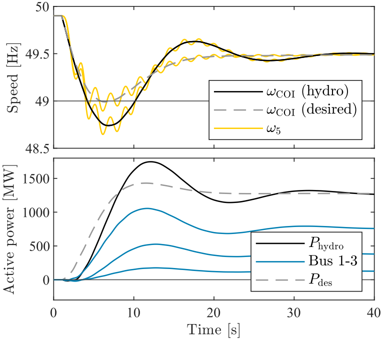
  $\rightarrow$ initial power surge opposes control
  $\rightarrow$ highly unsatisfactory response



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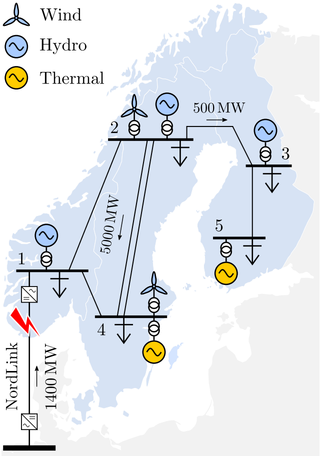

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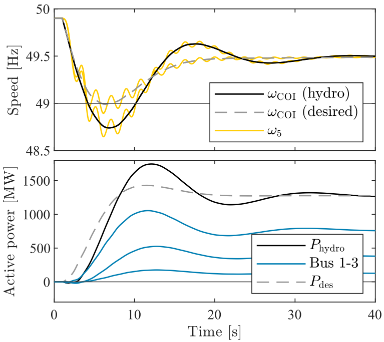

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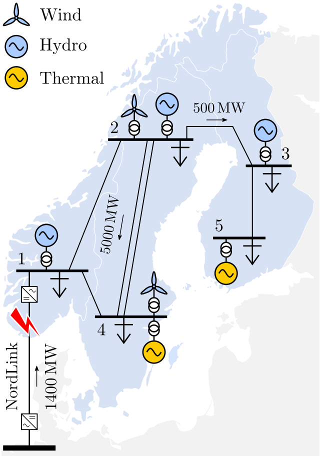

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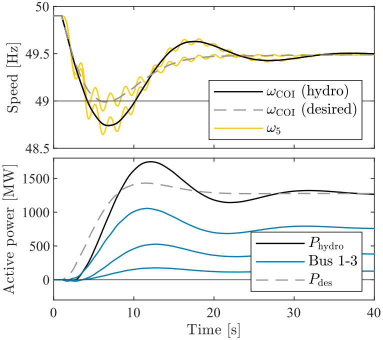

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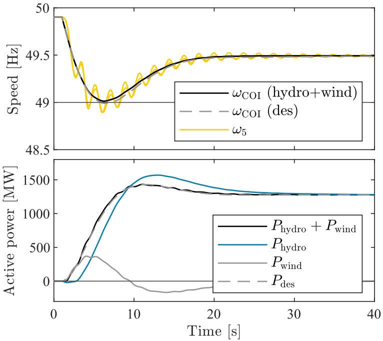

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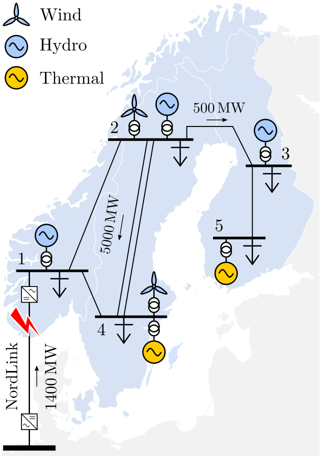

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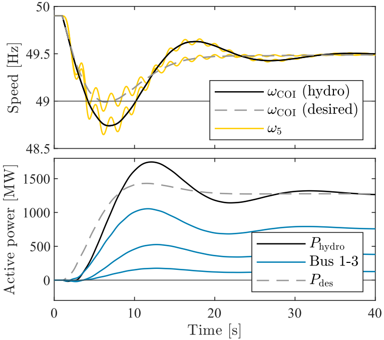

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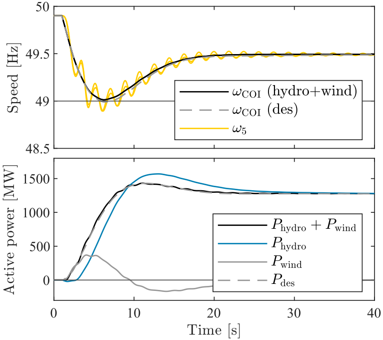

remainder of the talk: **how** to do it ?

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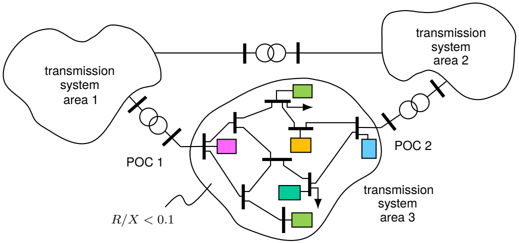
Problem setup & variations



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

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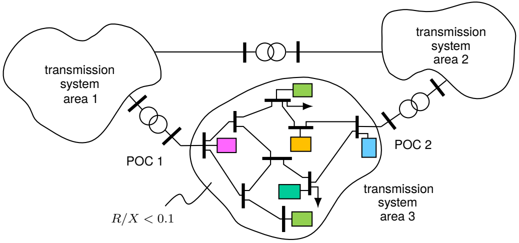

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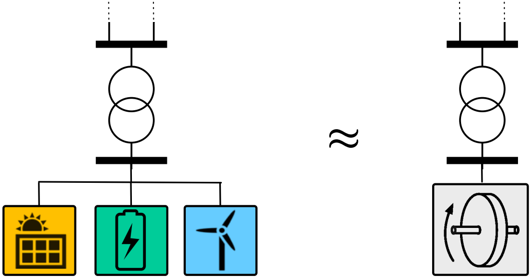
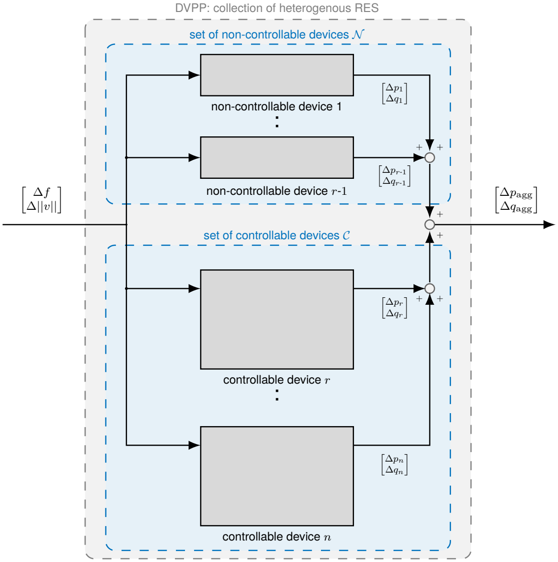


- DVPP consists of **controllable & non-controllable devices** (whose I/O behavior cannot be altered)
- **topology**: all DVPP devices at common bus bar (later also spatially distributed setup)
- **grid-following** signal causality: power injection controlled as function of voltage measurement (later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

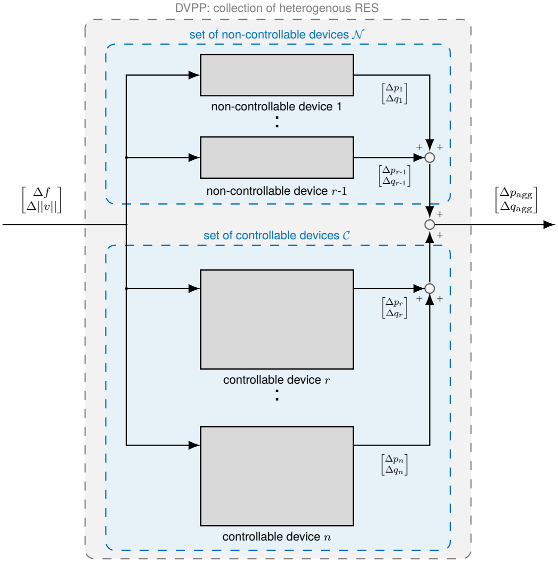
DVPP control setup



DVPP control setup

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

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



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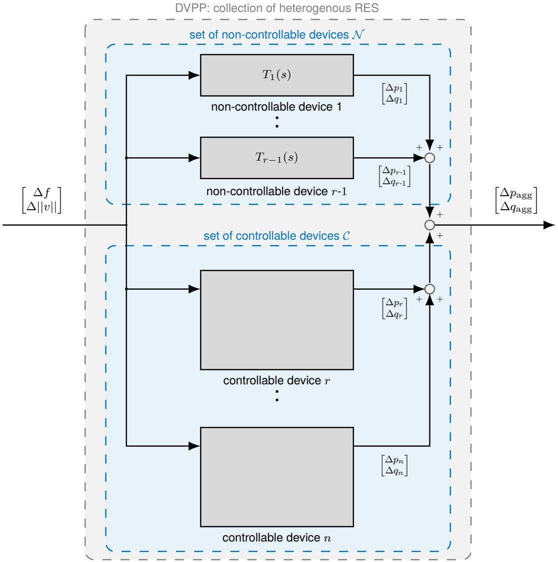
  (e.g., closed-loop hydro/governor model)



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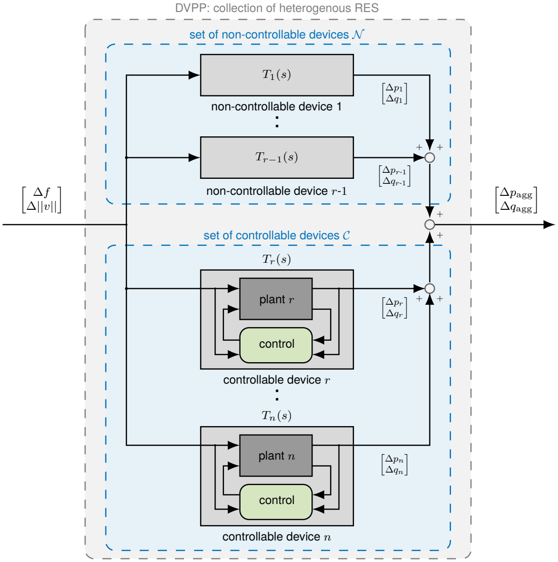

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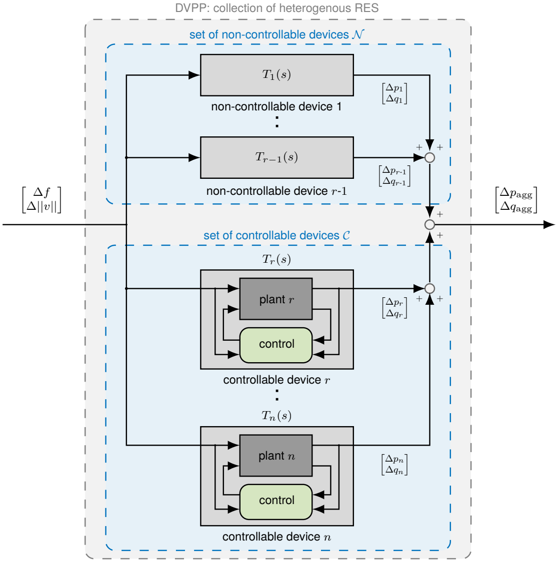
- overall **aggregate DVPP behavior**

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



Coordinated model matching

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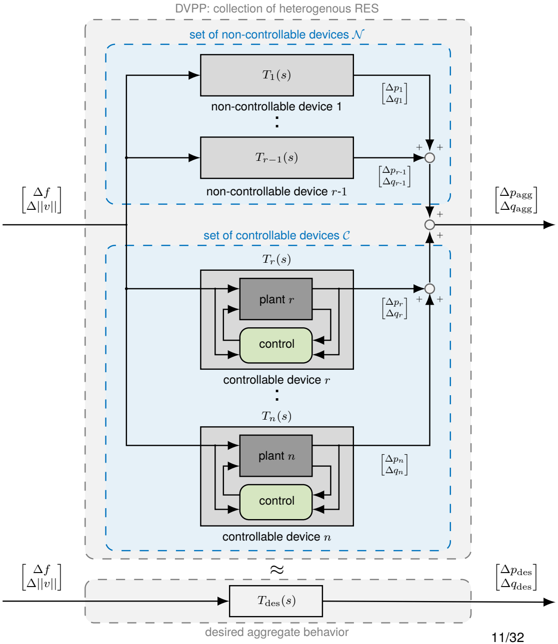
- **desired DVPP specification**: decoupled f-p & v-q control (later: also consider couplings)

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



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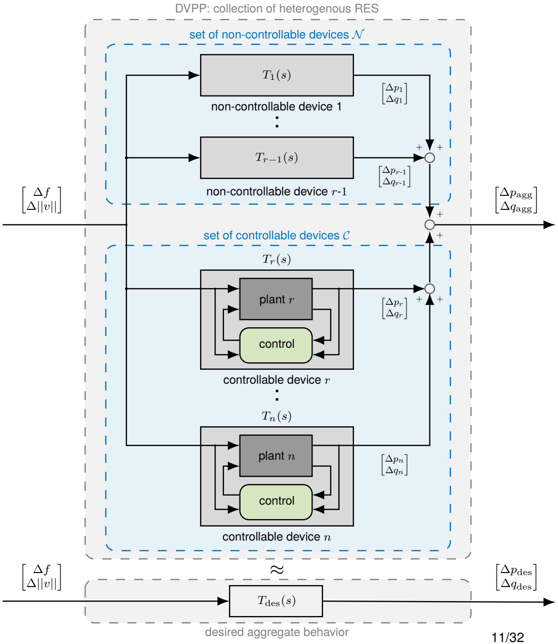
→ **aggregation condition**: $\sum_{i\in\mathcal{N}\cup\mathcal{C}} T_i(s) \overset{!}{=} T_{\text{des}}(s)$



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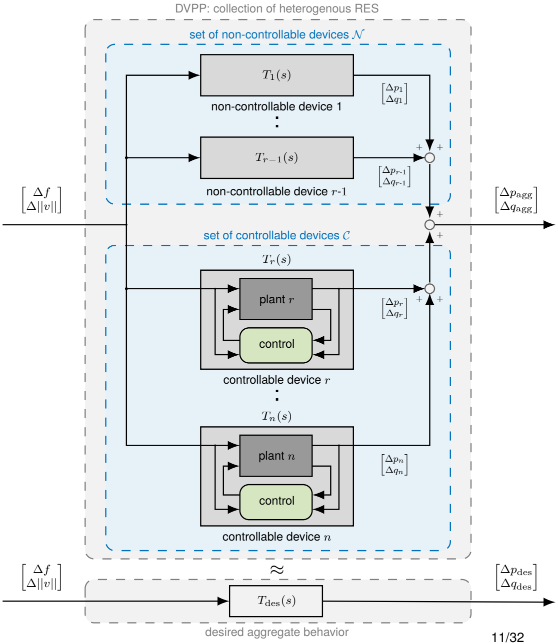
DVPP control problem

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



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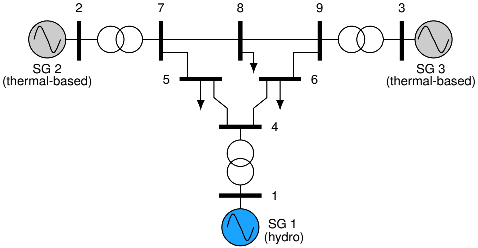
Running case studies

Original 9 bus system setup



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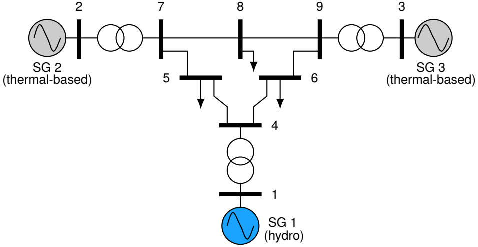
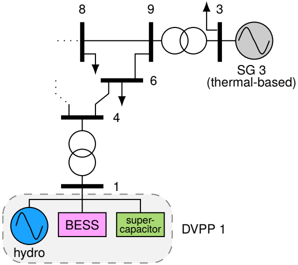


Case study I: hydro supplementation



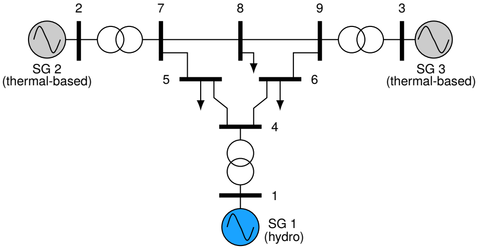
DVPP 1 for freq. control

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

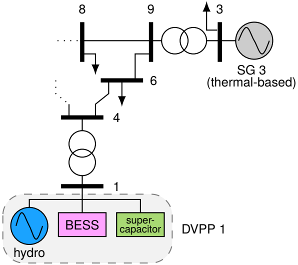
$$T_{\text{des}}(s) = \frac{-D}{\tau s+1},$$

Running case studies

Original 9 bus system setup



Case study I: hydro supplementation

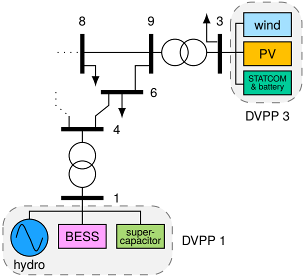


DVPP 1 for freq. control

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

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

Case study II: synchronous generator replacement



DVPP 3 for freq. & volt. control

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

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

Divide & conquer strategy

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

1) Disaggregation & pooling

2) Local matching control

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

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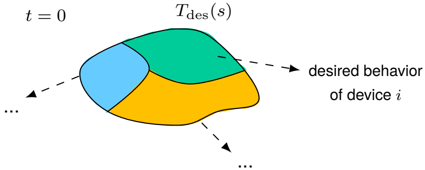

Disaggregate $T_{\text{des}}(s)$ into local desired behaviors for each device (taking local constraints into account).

2) Local matching control

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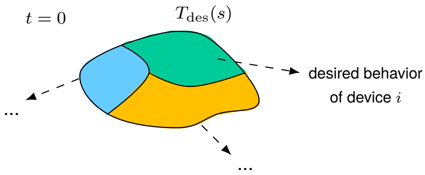

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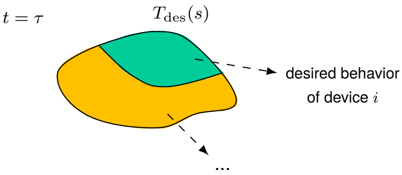

Disaggregation can be adaptive (later).

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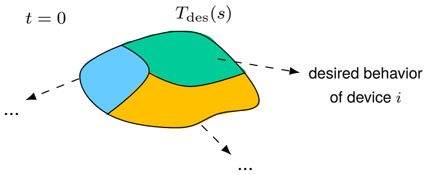

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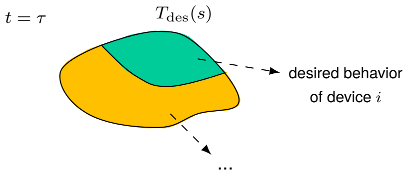

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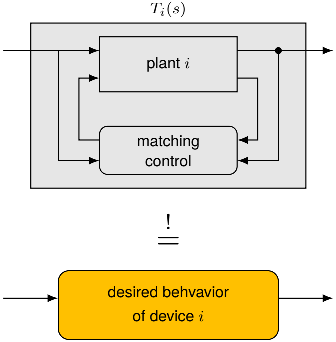


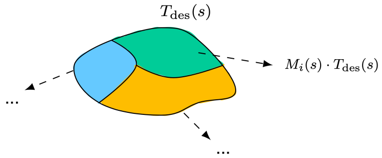
For each device i, design a local matching controller to match the desired behavior.

Disaggregation & pooling

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

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

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



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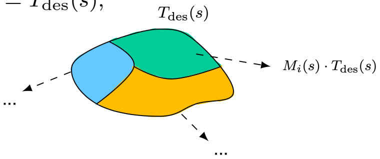

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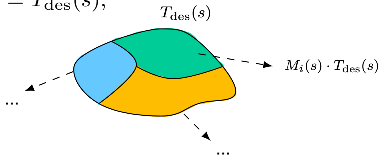

- **participation condition**: $\sum\nolimits_{i \in \mathcal{N} \cup \mathcal{C}} M_i(s) \overset{!}{=} I_2$

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

Dynamic participation factor (DPF) selection (subscripts f-p and v-q channel omitted)

- fixed DPFs $m_i(s) = (T_{\mathrm{des}}(s))^{-1} \cdot T_i(s)$ for non-controllable devices $\rightarrow T_i(s)$ unchanged

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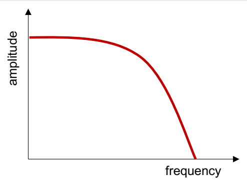
low-pass filter participation

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

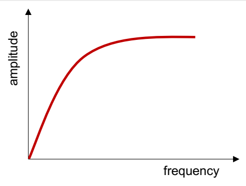
$$m_i(s) = \frac{\mu_i}{\tau_i s+1}$$



high-pass filter participation

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

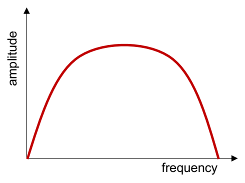
$$m_i(s) = \frac{\tau_i s}{\tau_i s+1}$$



band-pass filter participation

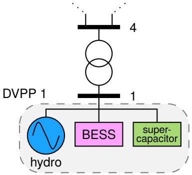
for devices covering the inter-mediate regime (e.g., batteries)

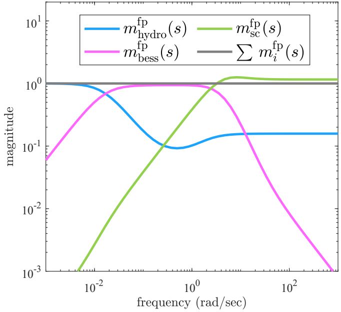
$$m_i(s) = \frac{(\tau_i - \tau_j)s}{(\tau_i s+1)(\tau_j s+1)}$$



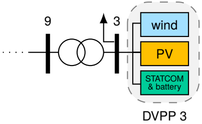
Running case studies - DPF selection for f-p channel

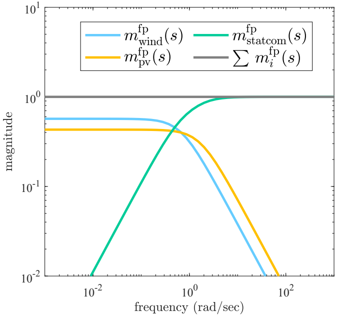
Case study I: hydro supplementation





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

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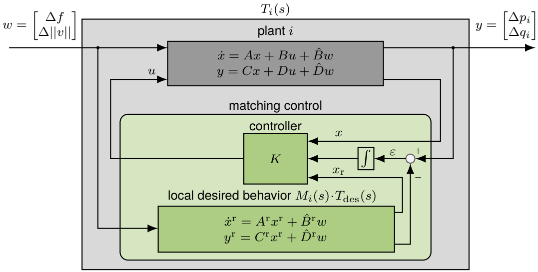

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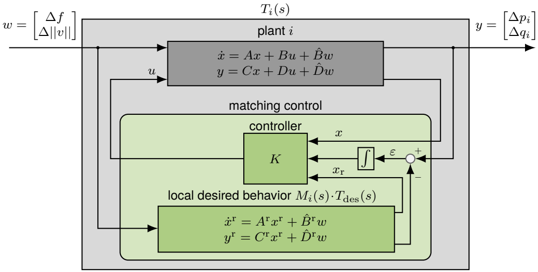

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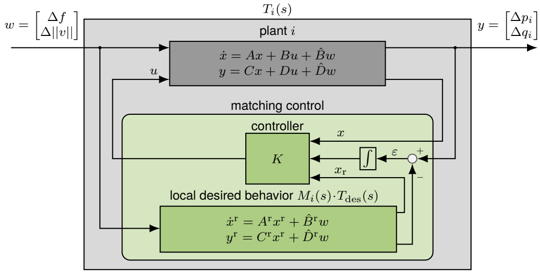

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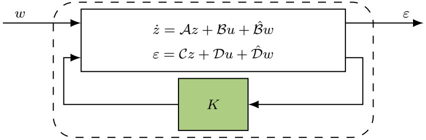
- $\mathcal{H}_\infty$ **optimal static feedback control** K obtained by minimizing the matching error



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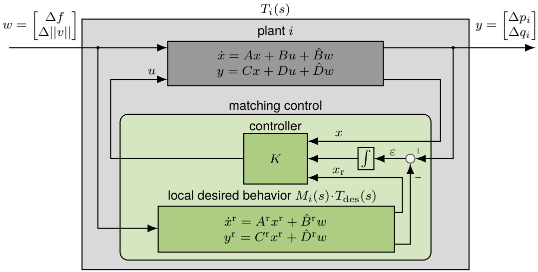

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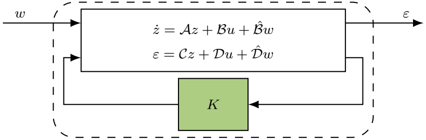
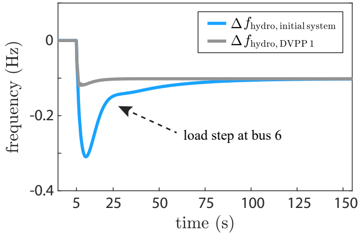
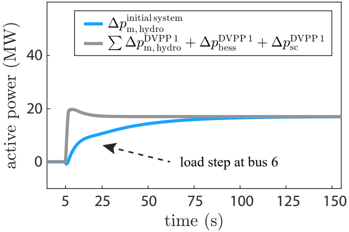
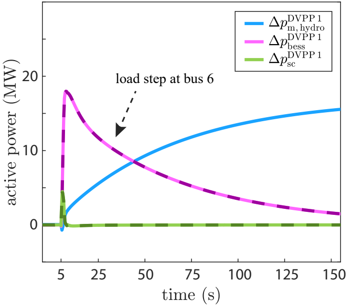


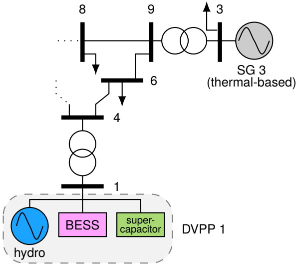
- include **ellipsoidal constraints** for transient device limitations, e.g., hard current constraints

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

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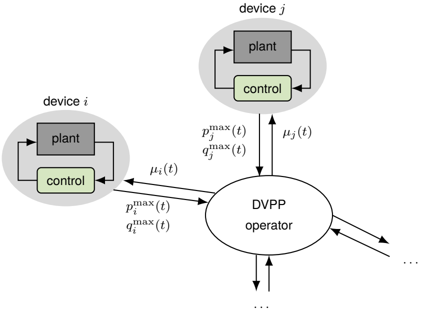

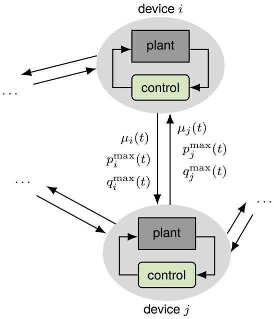

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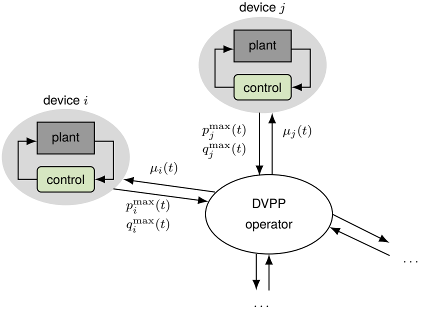
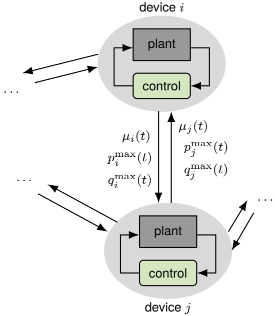


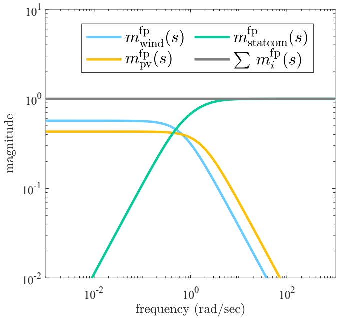


- **LPV $\mathcal{H}_\infty$ control** to account for parameter-varying local reference models $M_i(s) \cdot T_{\text{des}}(s)$

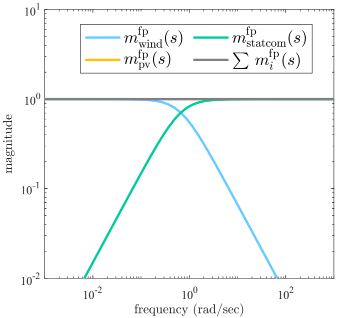
Online adaptation accounting for fluctuating power capacity limits

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

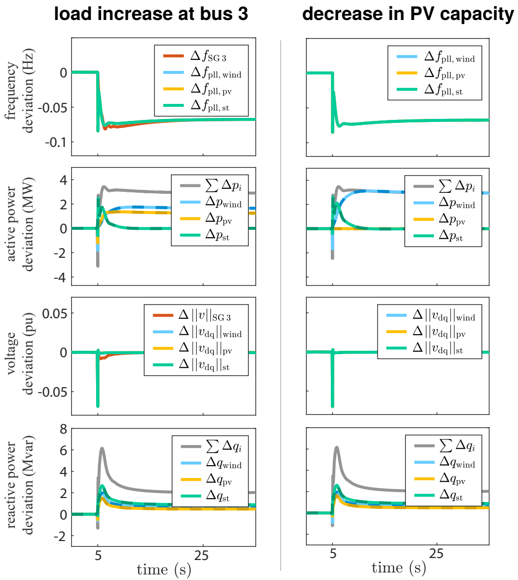
before cloud (nominal)

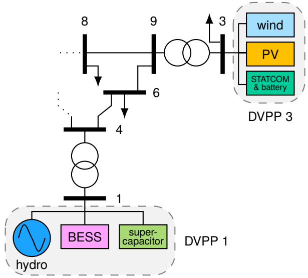


during cloud



Case study II - simulation results





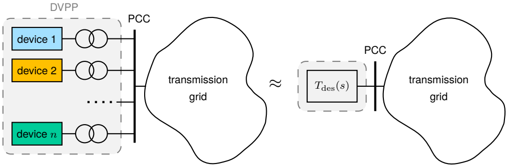
- adequate replacement of frequency & voltage control of prior SG 3
- good matching of desired active & reactive power injections (dashed lines)
- unchanged overall DVPP behavior during step decrease in PV capacity

Outline

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

Grid-forming DVPP control

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



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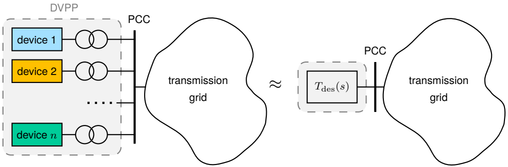

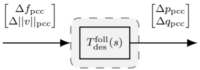

grid-following signal causality

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

→ power injection controlled as function of frequency & voltage measurement

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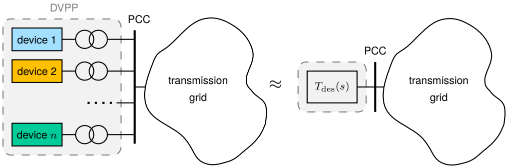

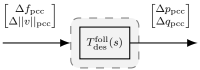

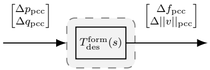

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grid-forming signal causality

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

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Grid-forming DVPP frequency control architecture

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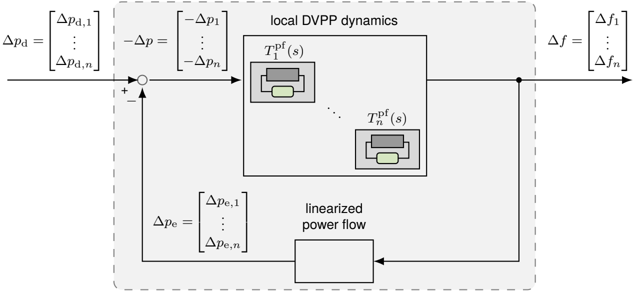

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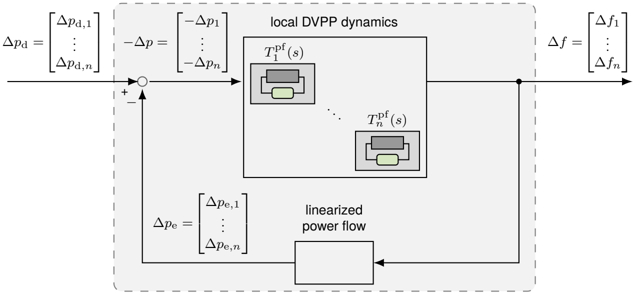

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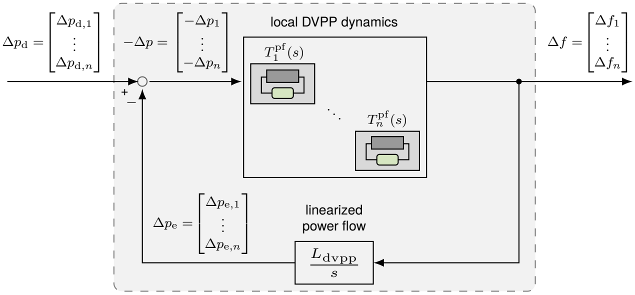

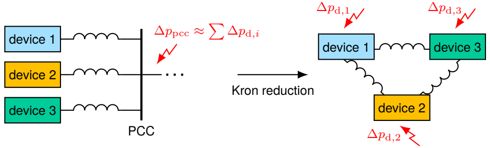

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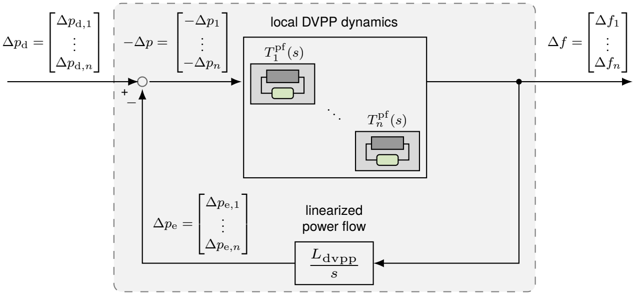

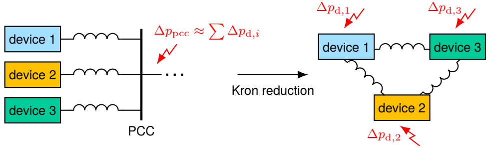

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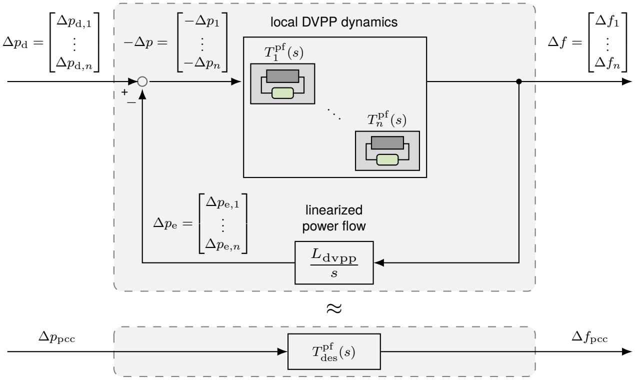

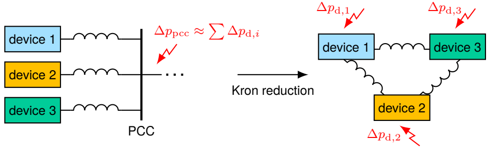

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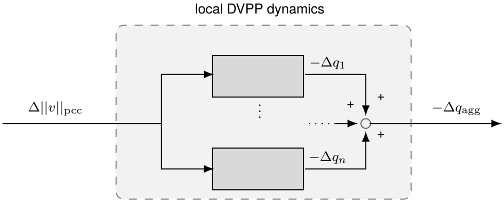

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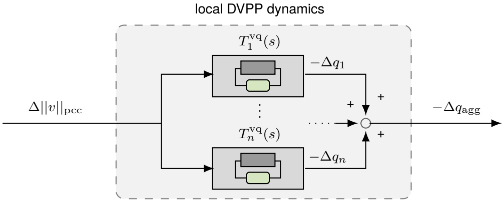

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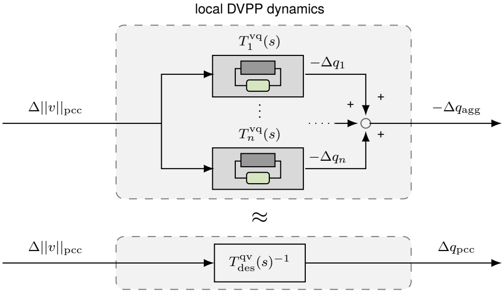

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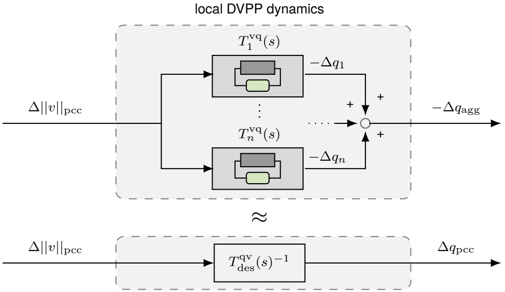

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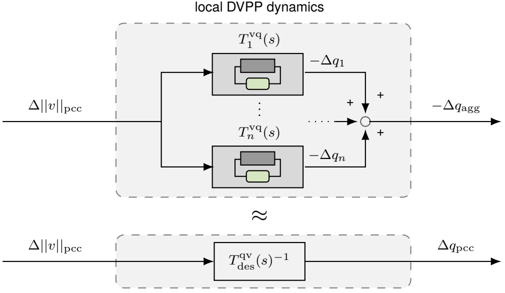

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Adaptive divide & conquer strategy for grid-forming DVPP

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

$$T_{\text{des}}^{\text{pf}}(s)^{-1} = \sum_{i=1}^{n} m_i^{\text{fp}}(s) T_{\text{des}}^{\text{pf}}(s)^{-1} \stackrel{!}{=} \sum_{i=1}^{n} T_i^{\text{pf}}(s)^{-1},$$

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

- **participation condition**

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

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

- **local model matching condition**

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

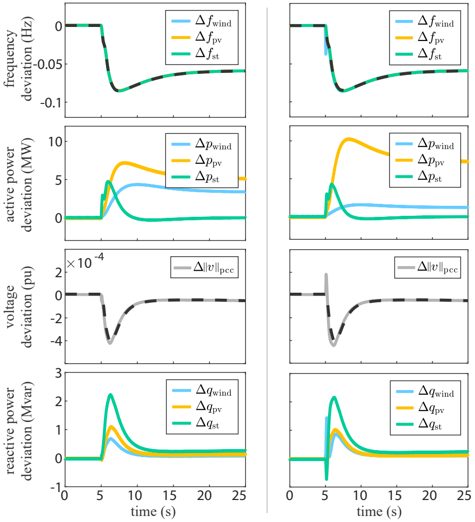
$$T_i^{\text{vq}}(s) \stackrel{!}{=} m_i^{\text{vq}}(s) T_{\text{des}}^{\text{qv}}(s)^{-1}.$$

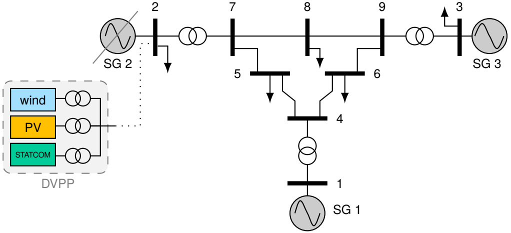
- compute **local LPV $\mathcal{H}_\infty$ matching controllers**

same as before ...

Numerical case study

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





- specify decoupled p-f & q-v control

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

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

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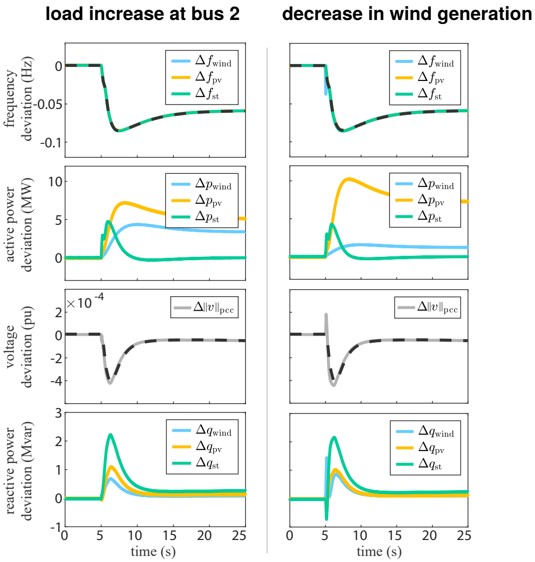

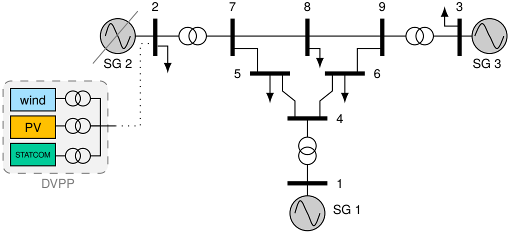

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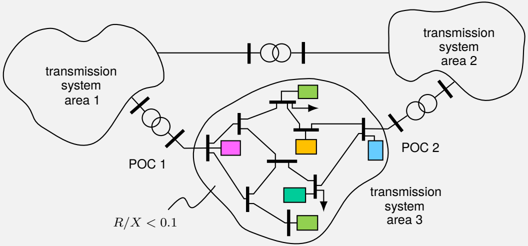
→ also possible: **hybrid DVPPs** including grid-forming + grid-following devices (. . . same as before)

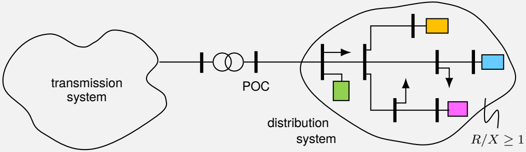
Spatially distributed DVPP

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

Transmission system DVPP



Distribution system DVPP



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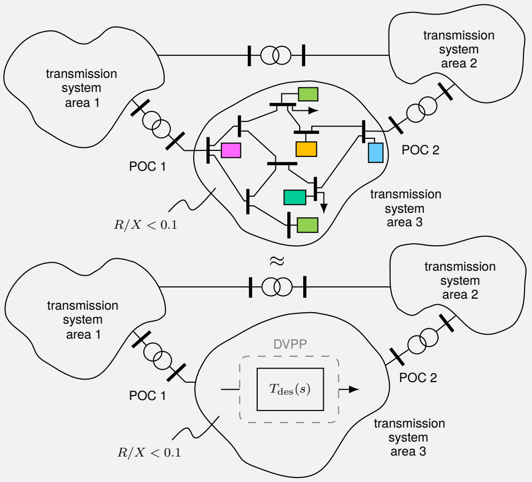

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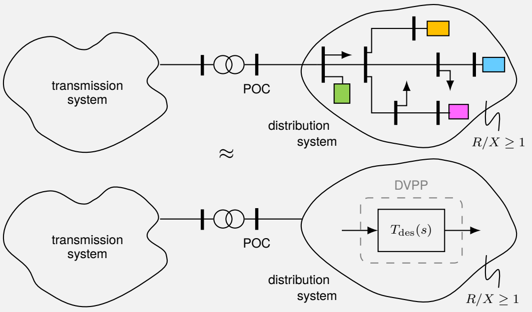

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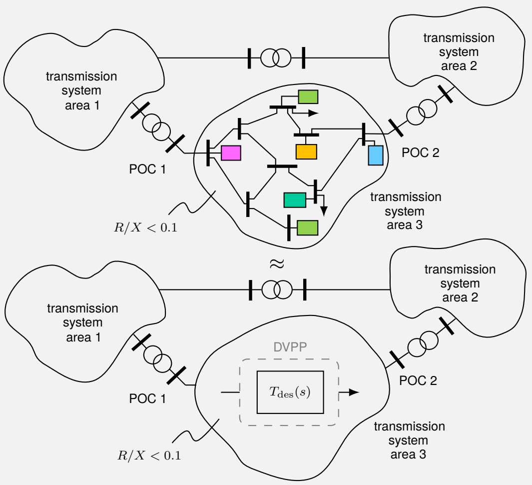

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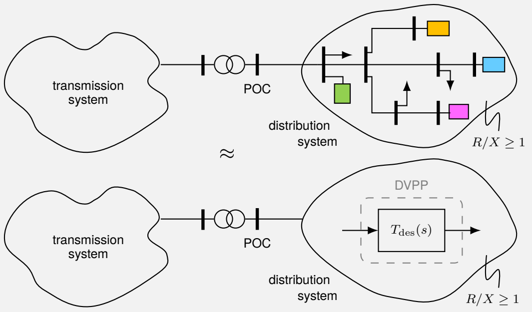
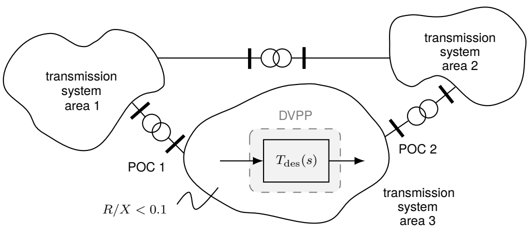


Assumptions

- 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



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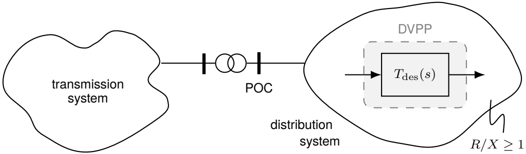

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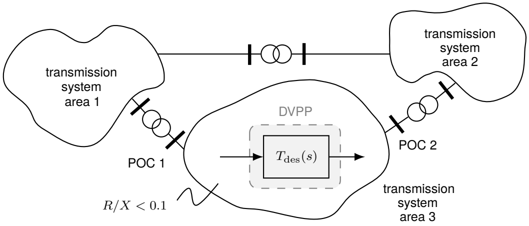

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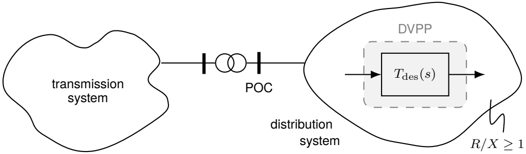

$\rightarrow$ rotational powers to decouple power flow equations

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

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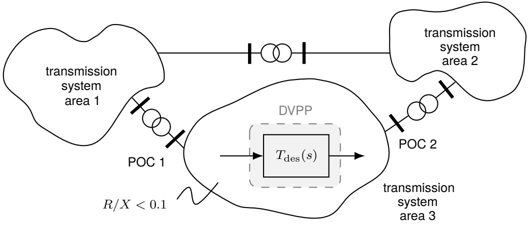

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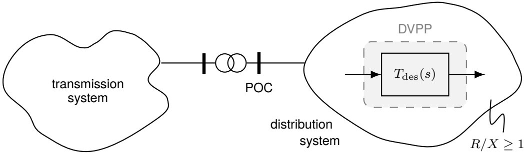

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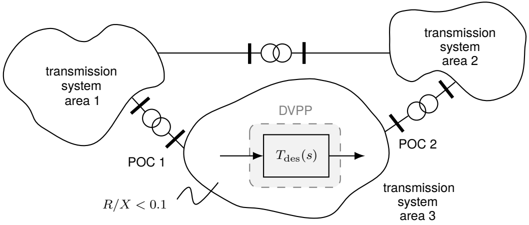

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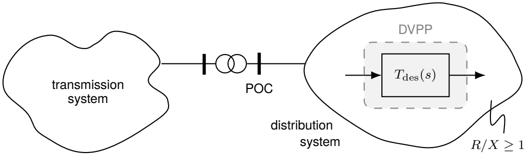

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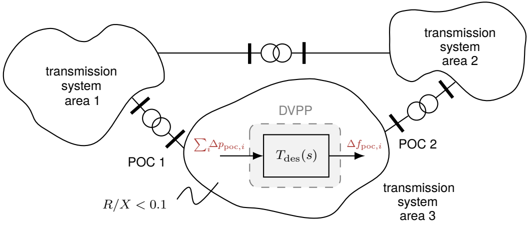

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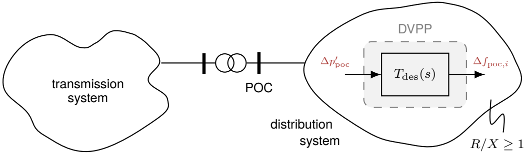

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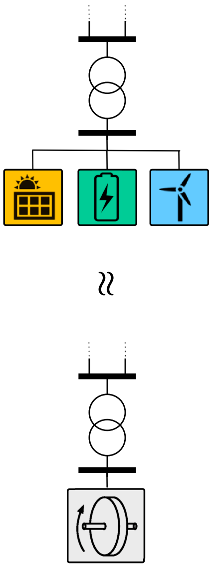
solution: consider global p-f (*or* p'-f) DVPP control at the POCs & use independent local q-v (*or* q'-v) controllers

Outline

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



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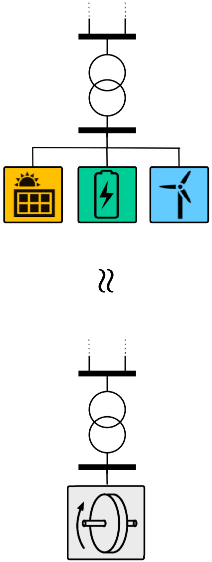

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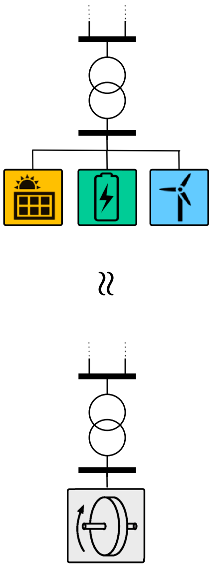
extensions & ongoing research

- 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



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