

Data-driven decentralised control design in Active Distribution Networks

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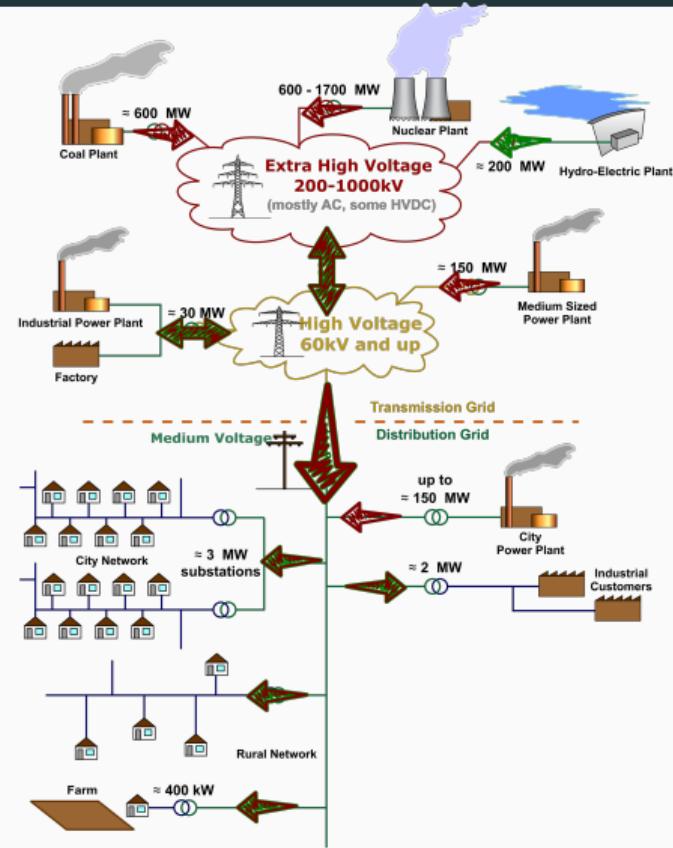
(joint work with S. Karagiannopoulos and G. Hug, ETH Zurich)



Motivation

Transformation of power systems

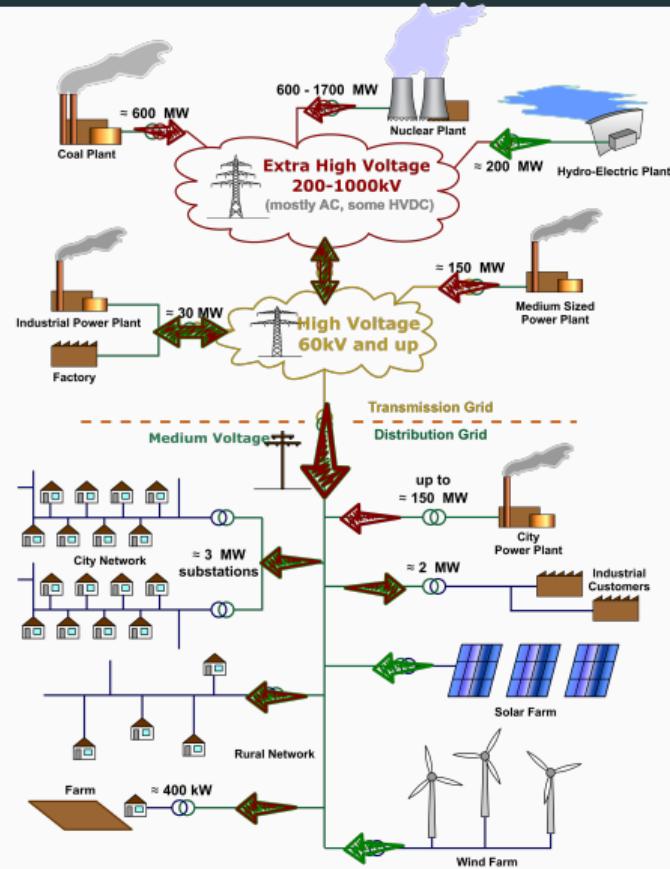
New developments in distribution grids



Transformation of power systems

New developments in distribution grids

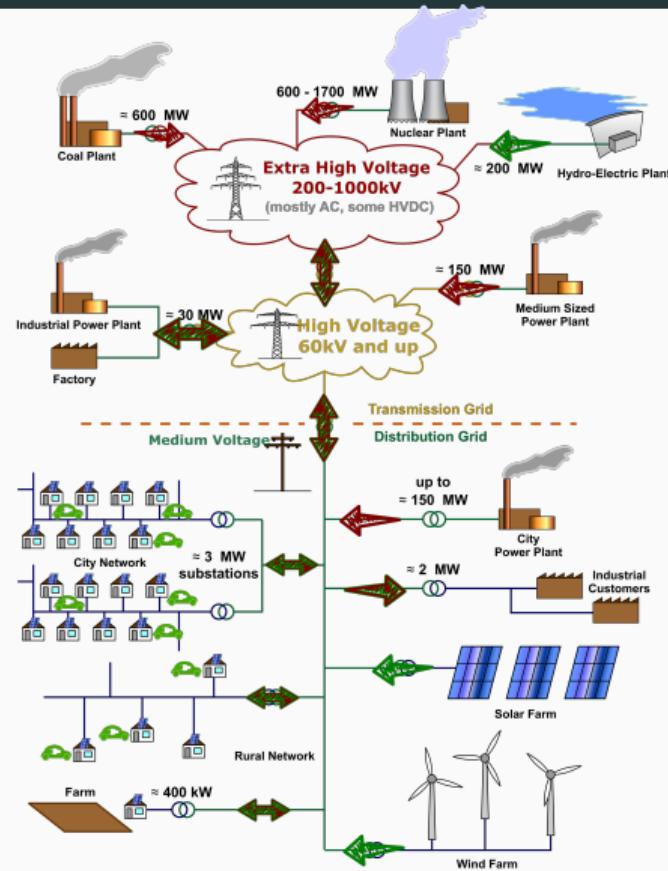
- Introduction of large distributed generators
(renewable energy sources, etc.)



Transformation of power systems

New developments in distribution grids

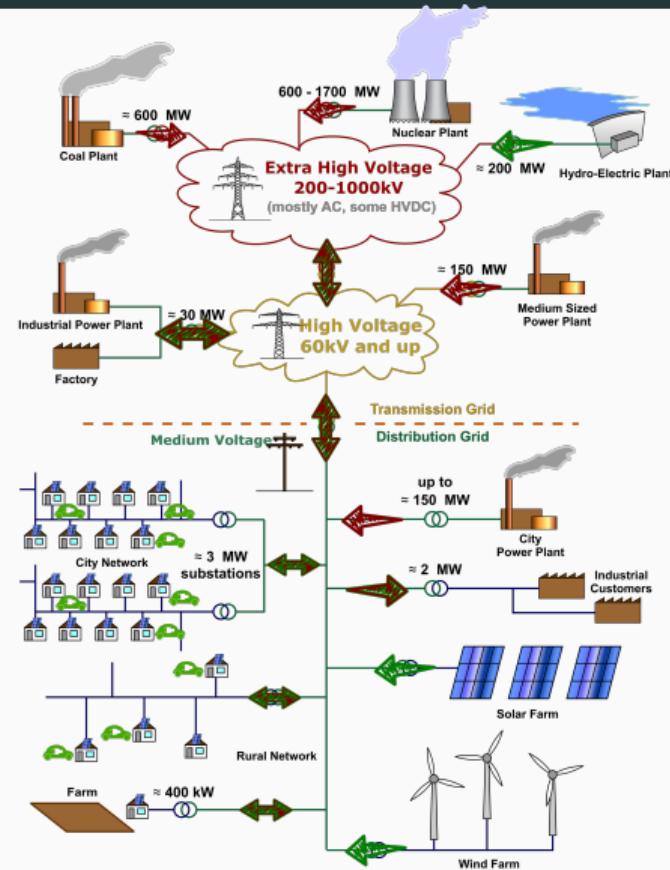
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- Introduction of small distributed generators and energy storage systems
- Electrification of transportation (plug-in hybrid, battery electric, etc.)



Transformation of power systems

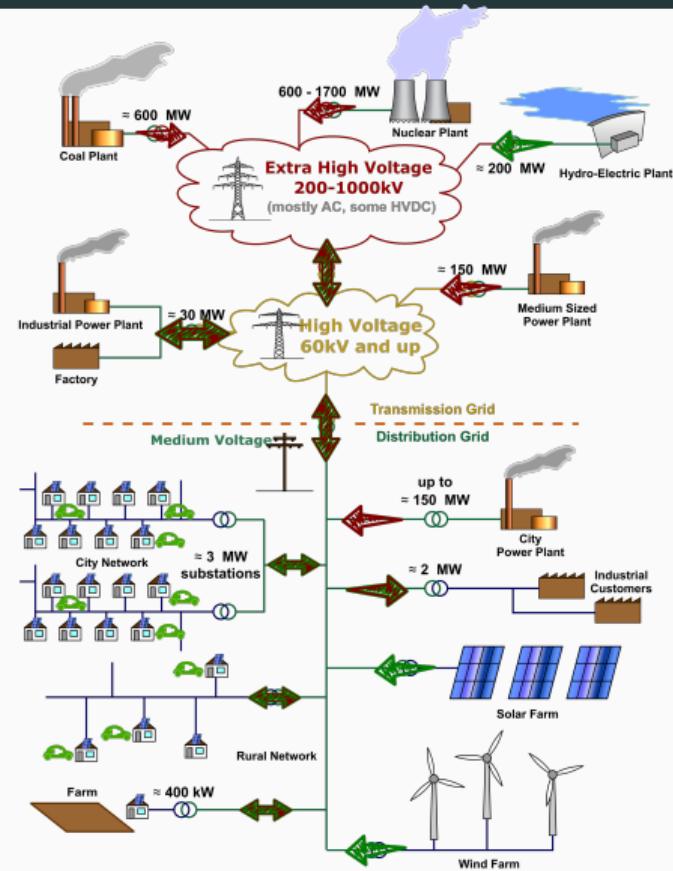
New developments in distribution grids

- Introduction of large distributed generators (renewable energy sources, etc.)
- Introduction of small distributed generators and energy storage systems
- Electrification of transportation (plug-in hybrid, battery electric, etc.)
- Demand response schemes (reaction to price signals, emergency load reduction, peak shaving, etc.)



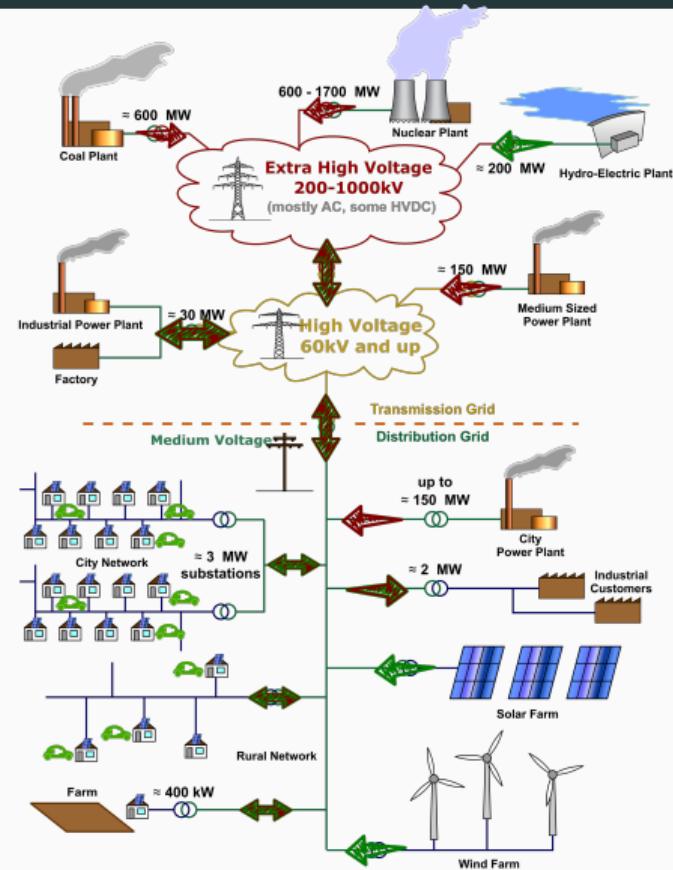
New challenges

- Operation of the distribution grids close or above the physical limits and hosting capacity. *Distribution grids were not designed to host generation.*



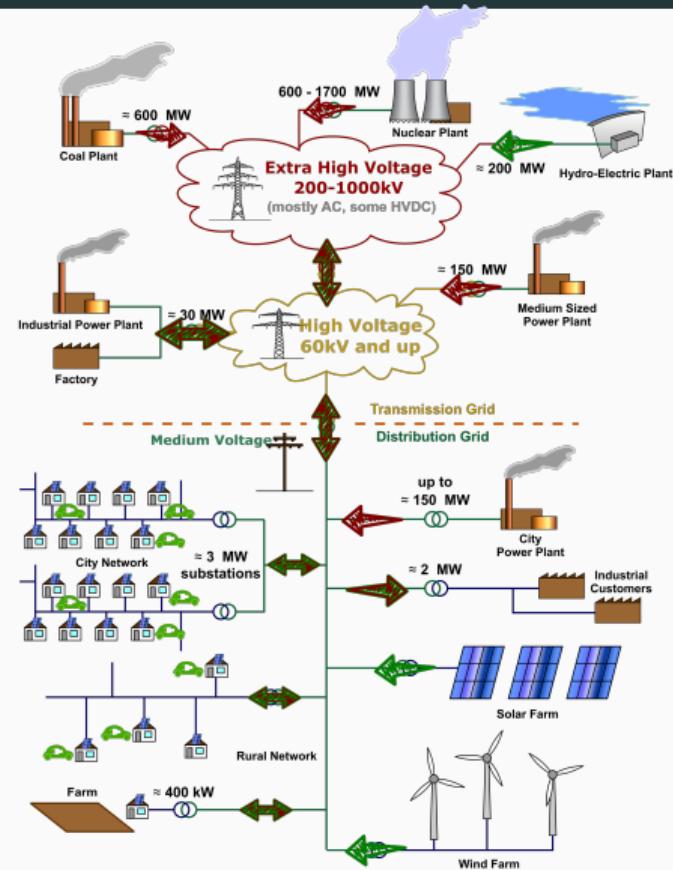
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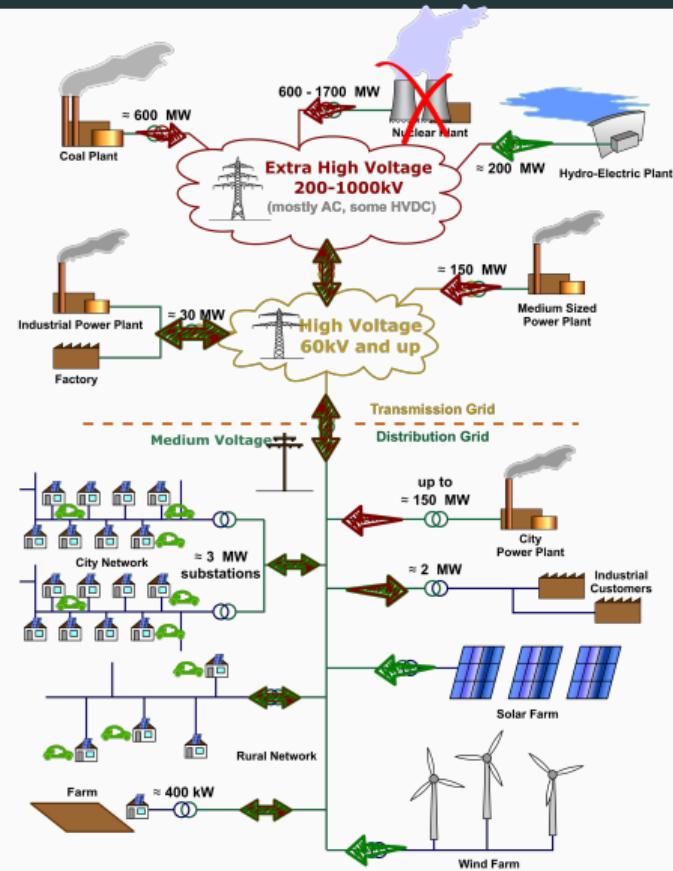
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- Increased uncertainty. *Intermittent generation, new consumption profiles and patterns, unknown consumer response.*



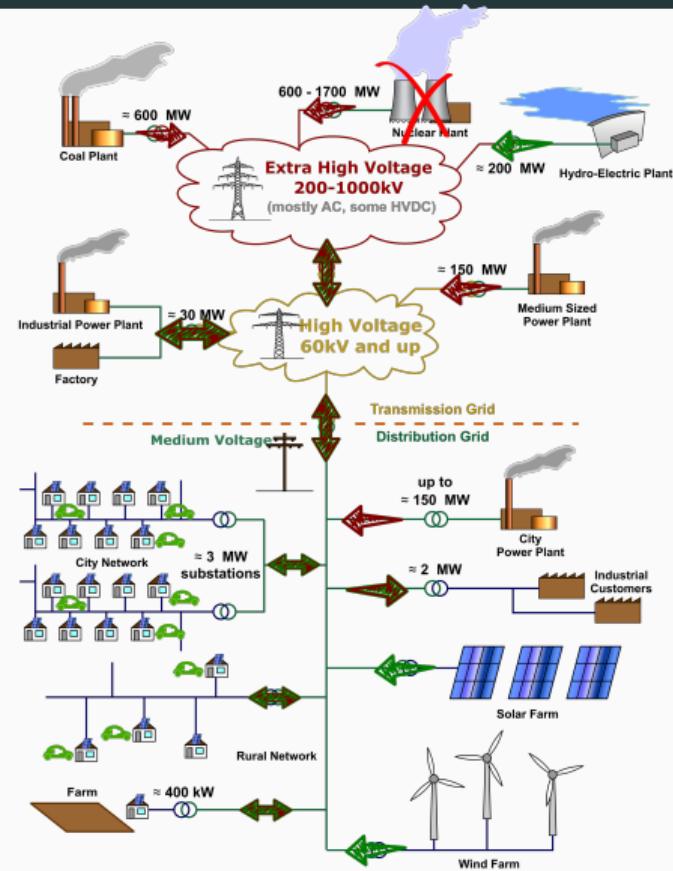
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- Bi-directional flows. *Most of system protections and operation practices were not designed for this.*
- Increased uncertainty. *Intermittent generation, new consumption profiles and patterns, unknown consumer response.*
- Decommission of conventional units. *Loss of traditional "dispatchable" generation and control.*



New challenges

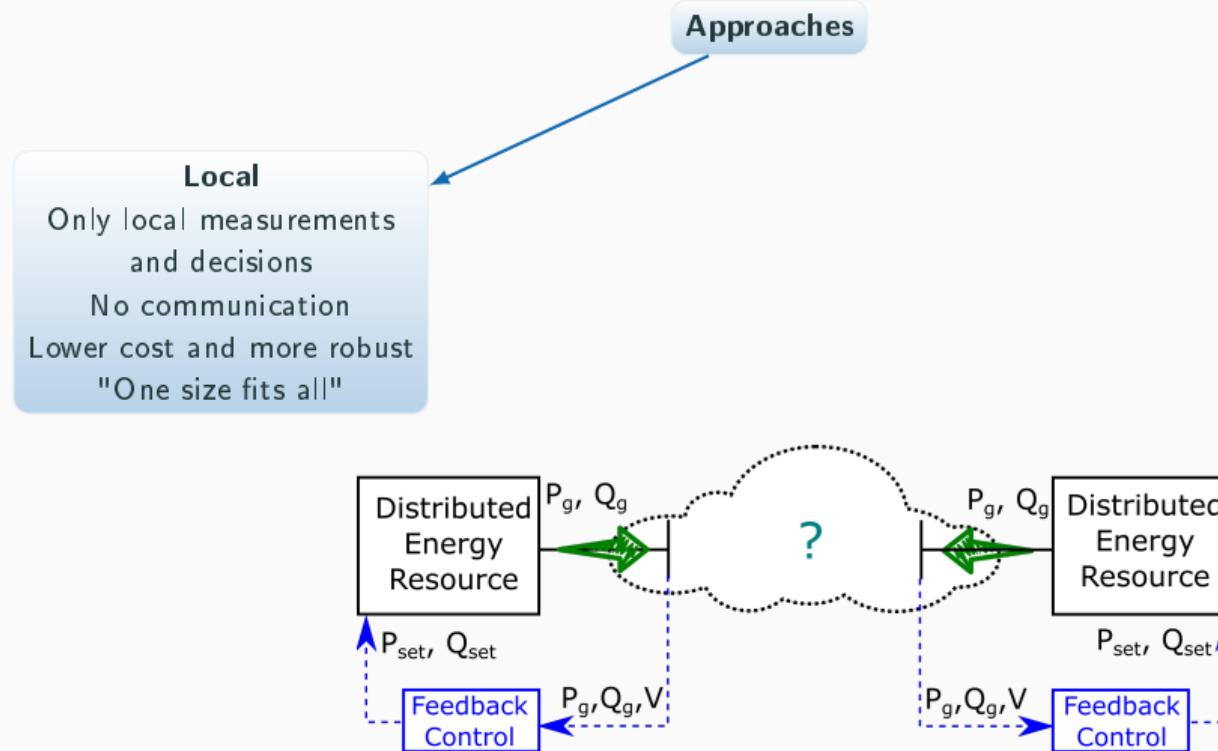
Need for Active Distribution Networks with
real-time control



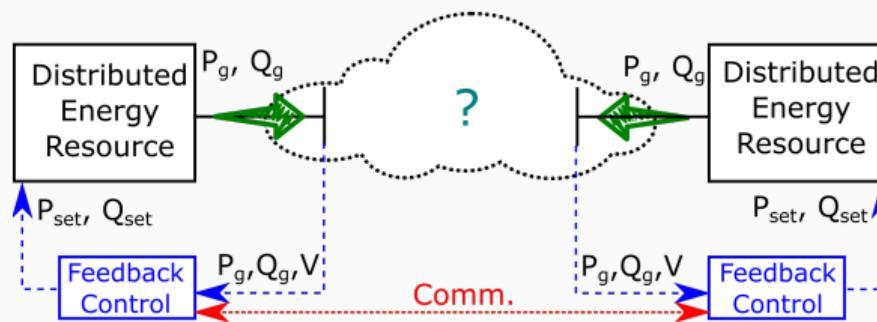
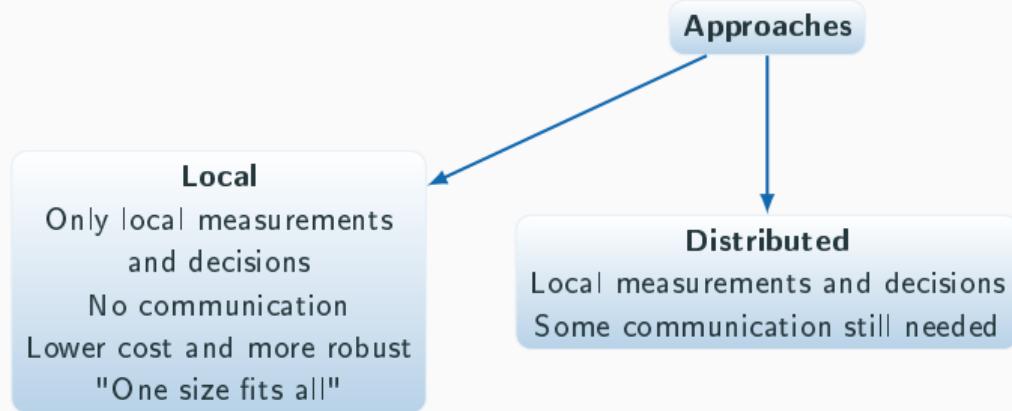
Real-time operation of distribution grids

Approaches

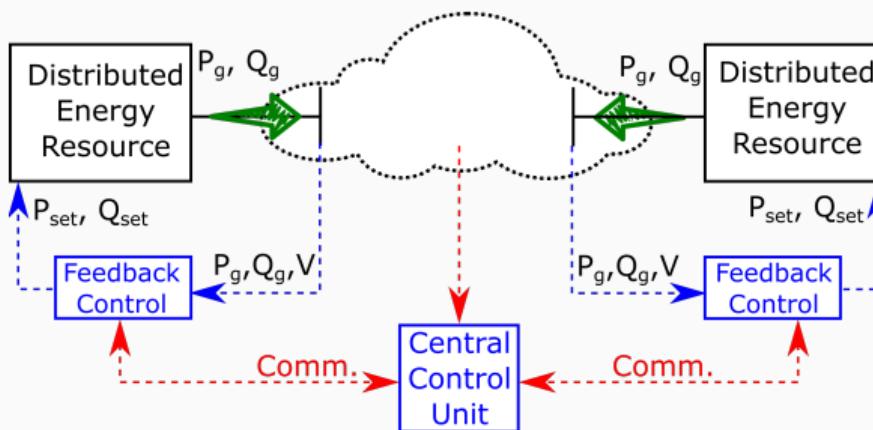
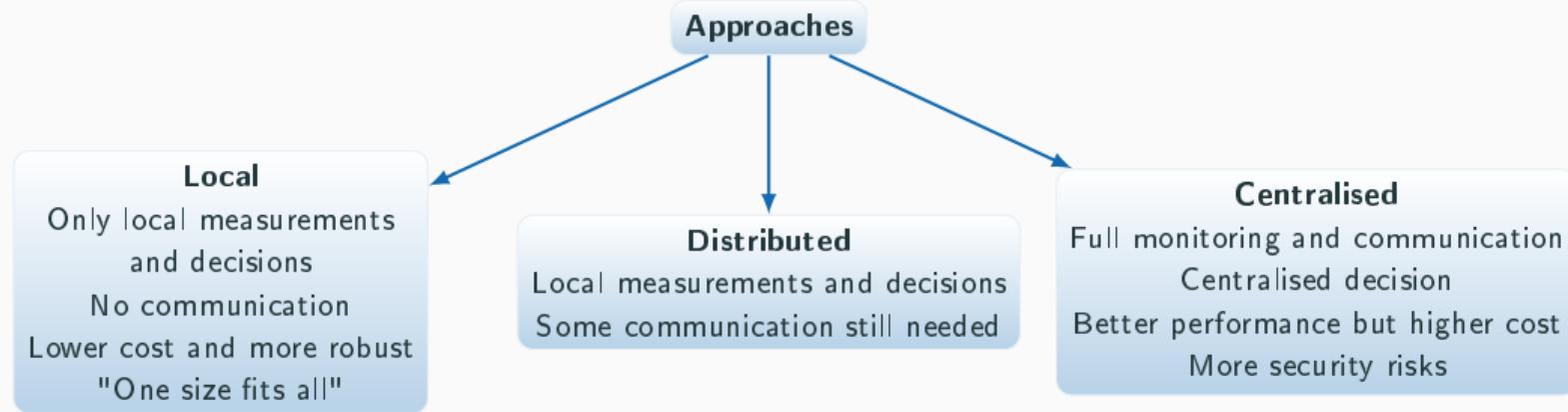
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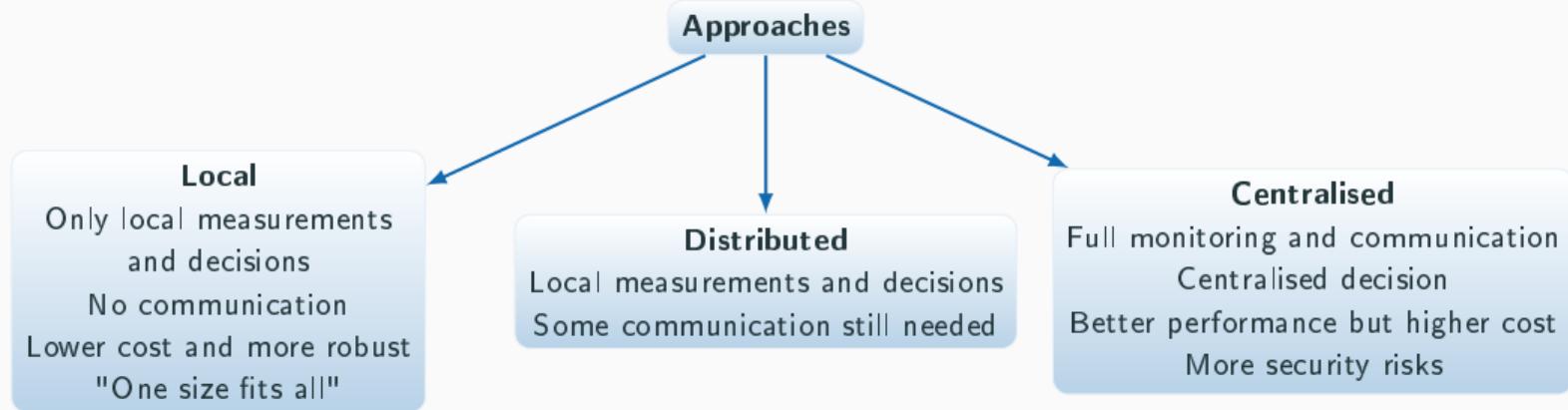
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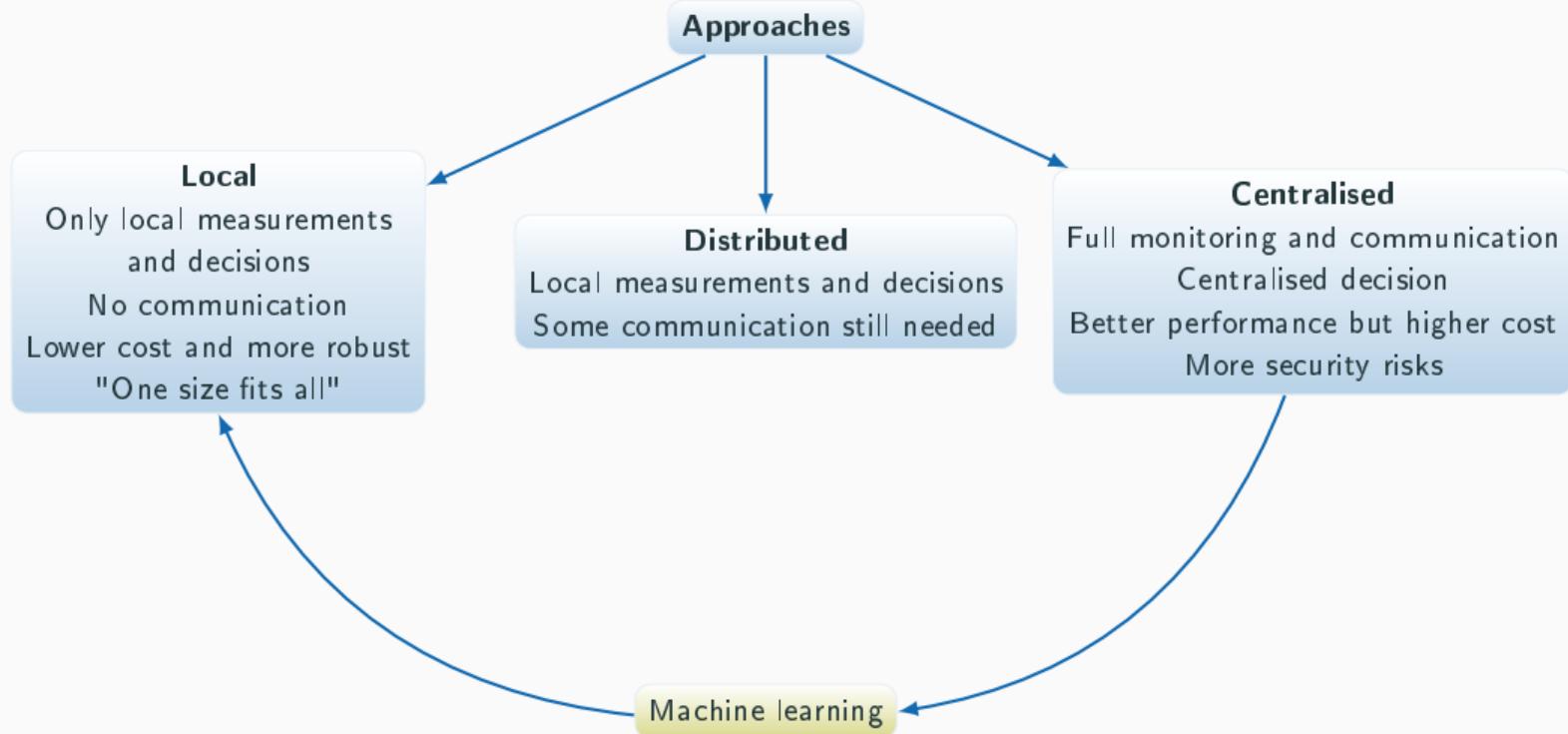


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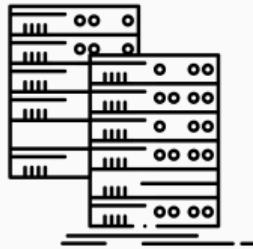
Can we design local controls that can mimic the optimal behavior?

Real-time operation of distribution grids



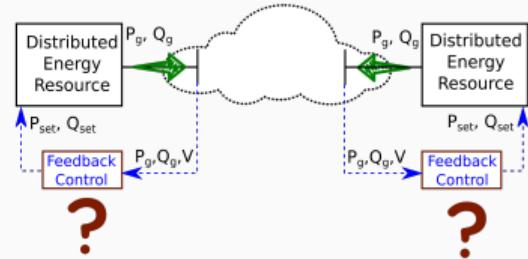
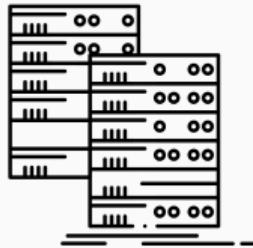
Data-driven local control design

Historical timeseries data



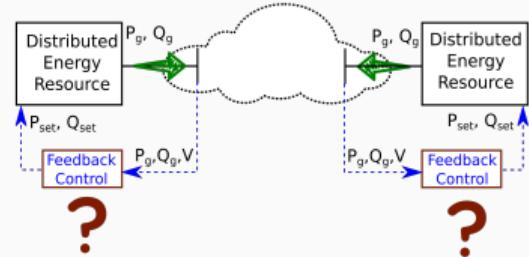
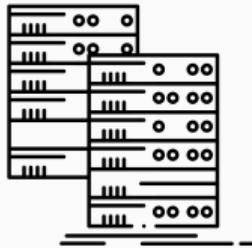
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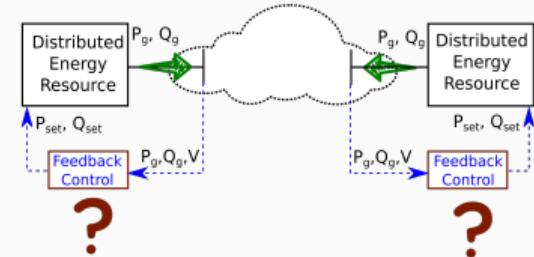
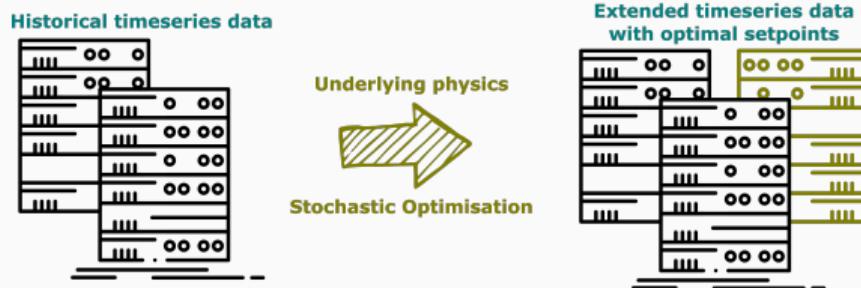
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Two-stage process

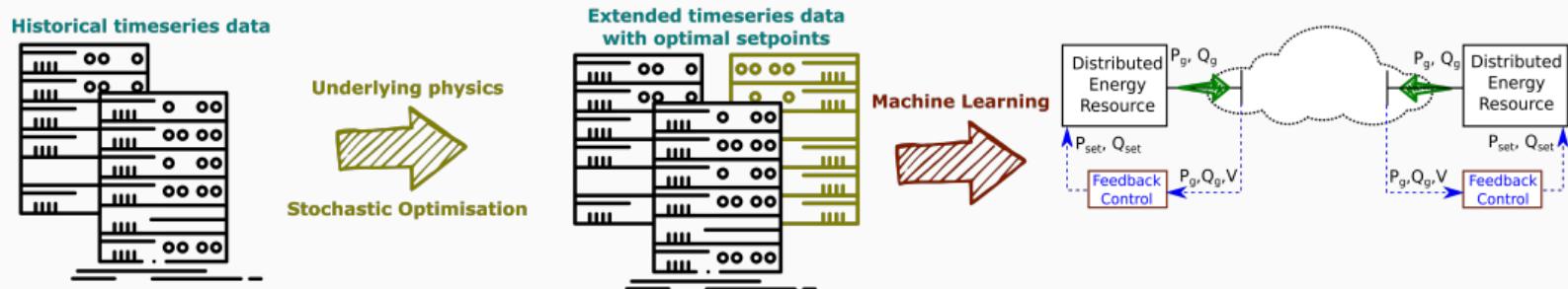
Data-driven local control design



Two-stage process

- **Step 1:** Process historical data and extend with optimal setpoints

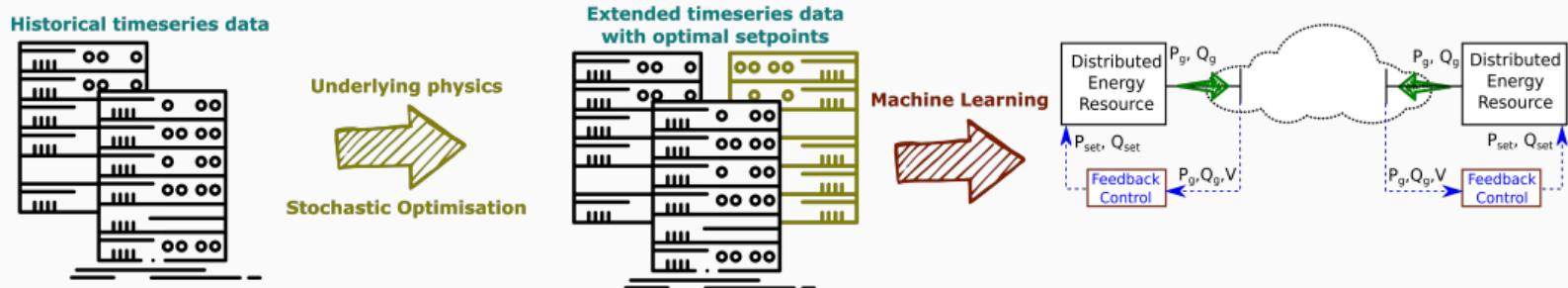
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Two-stage process

- **Step 1:** Process historical data and extend with optimal setpoints
- **Step 2:** Use ML on the extended dataset to design local controls

Data-driven local control design



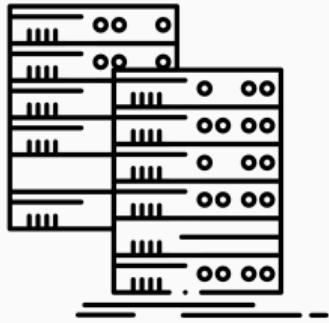
Two-stage process

- **Step 1:** Process historical data and extend with optimal setpoints
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- Testing and validation

Data-driven local control design

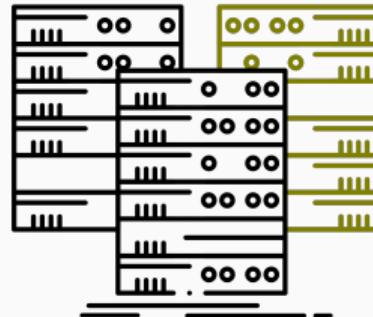
Extending historical data with optimal setpoints

Historical timeseries data



Underlying physics
Stochastic Optimisation

Extended timeseries data
with optimal setpoints



Multi-period OPF problem formulation

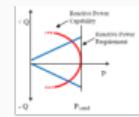
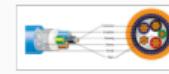
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Multi-period OPF problem formulation

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Controls (\boldsymbol{u}):

- Active power curtailment (APC)
- Reactive power control (RPC)
- Battery Energy Storage Systems (BESS)
- Controllable loads (CLs)
- On-Load Tap Changers (OLTC)



OPF-based data processing

Multi-period OPF problem formulation

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Subject to:

- AC power-flow constraints
- Voltage limits
- Thermal loading limits
- DER limits
- Balancing constraints
- Controllable load constraints
- BESS dynamics

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OPF-based data processing

AC power-flow constraints

- Non-convex and non-linear

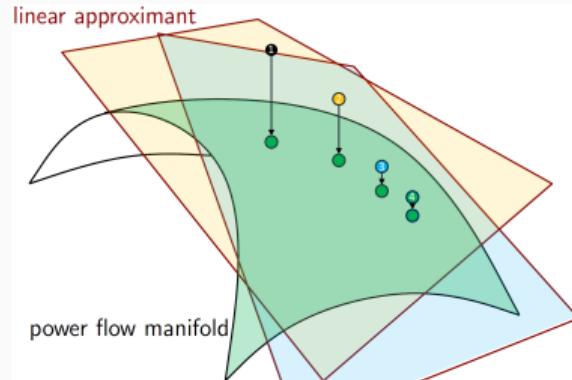
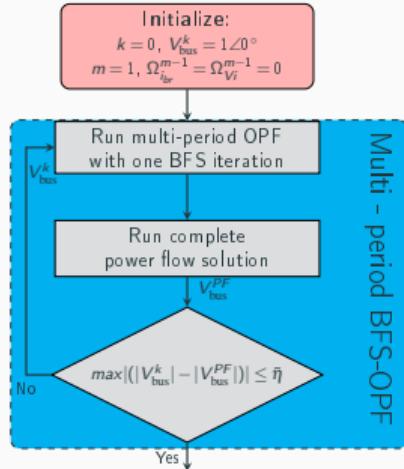
AC power-flow constraints

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 - Linear approximations of the AC power flows, heuristics, convex relaxations (Venzke et al 2018, Shchetinin & Hug 2017, Capitanescu & Bilibin 2016, Sankur et al. 2016, Bolognani & Dörfler 2015, Dall' Anese et al. 2015, Molzahn & Hiskens 2015, Lavaei & Low 2012, Paudyal et al. 2011)
 - Backward/Forward Sweep (BFS) power flow (Fortsenbacher et al. 2016)
 - ▶ Iterative procedure
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 - ▶ Weakly meshed treatment

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 - **Backward/Forward Sweep (BFS) power flow (Fortenbacher et al. 2016)**
 - ▶ Iterative procedure
 - ▶ Exploit the radial grid structure
 - ▶ Weakly meshed treatment
- **Use a single BFS iteration for the OPF problem**

OPF-based data processing



Qualitative illustration of the iterative BFS-OPF scheme

Tackling Uncertainty

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OPF-based data processing

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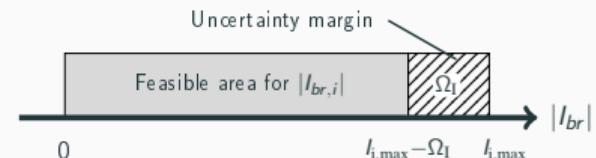
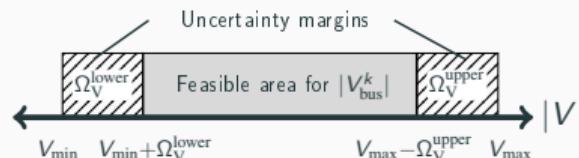
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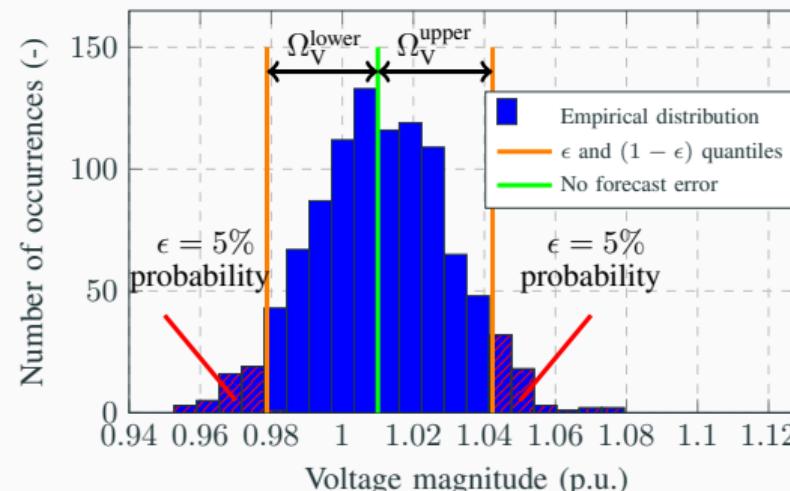


Uncertainty margins evaluation

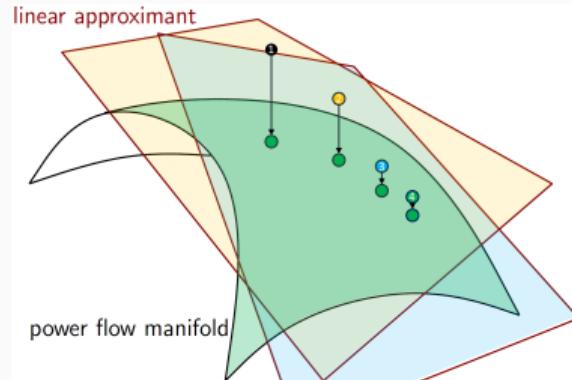
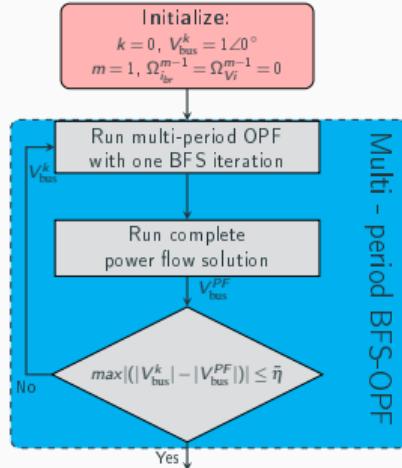
- Analytical approach → Need to know the probability distribution

Uncertainty margins evaluation

- Analytical approach → Need to know the probability distribution
- Monte Carlo simulation using historical data from forecast errors
 - No assumptions about the uncertainty distribution
- Quantile ϵ calculation

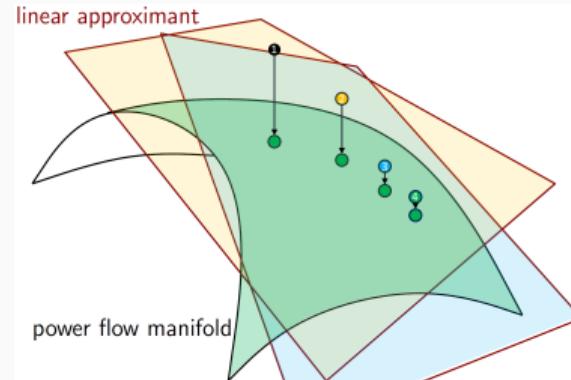
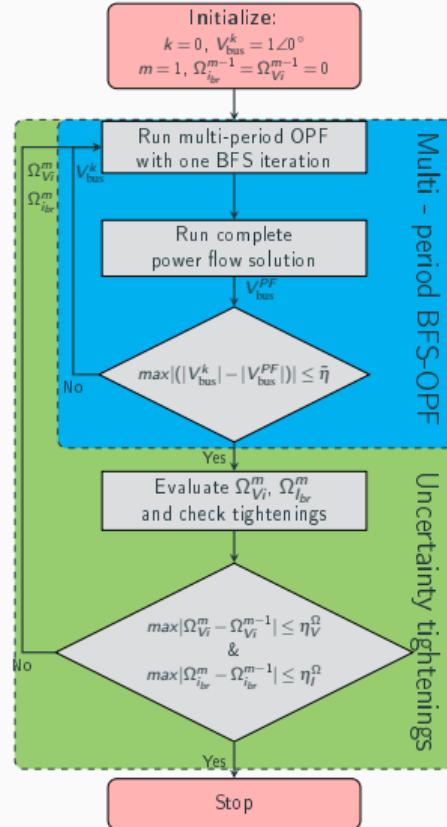


OPF-based data processing

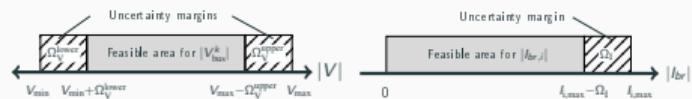


Qualitative illustration of the iterative BFS-OPF scheme

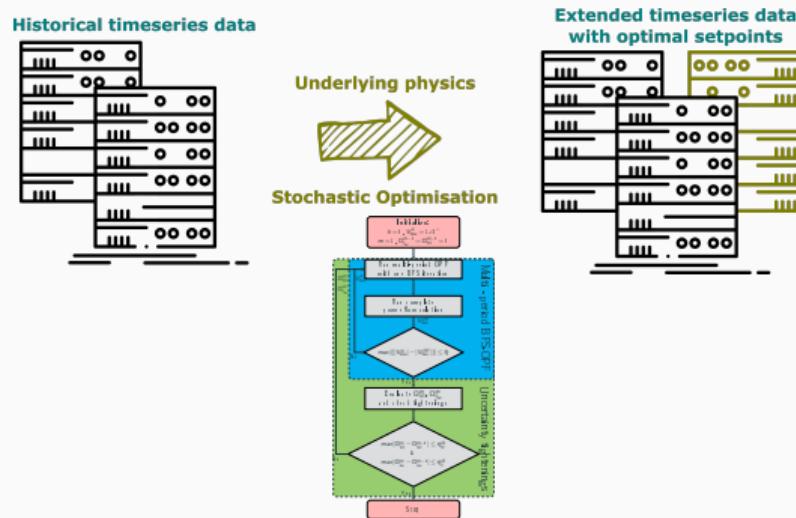
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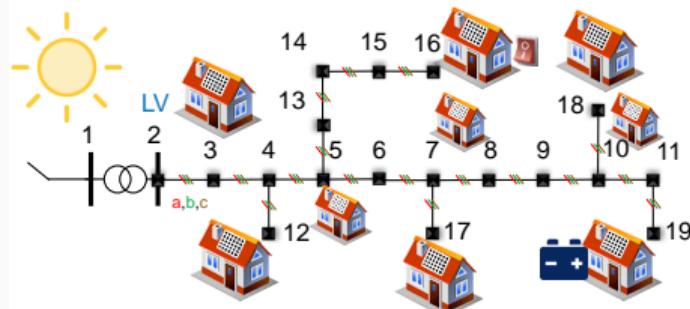
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Extending historical data with optimal setpoints



Test system



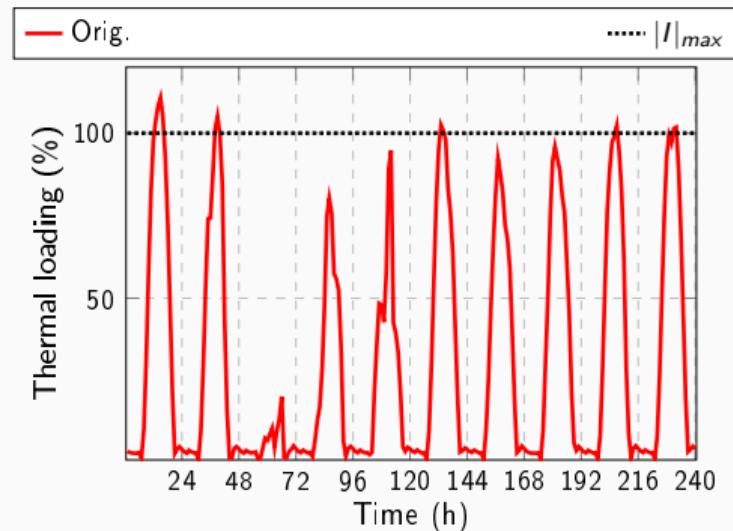
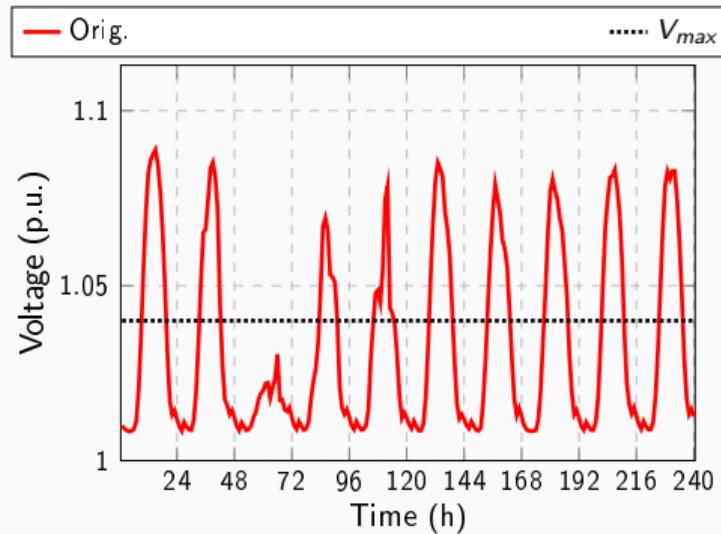
Control actions

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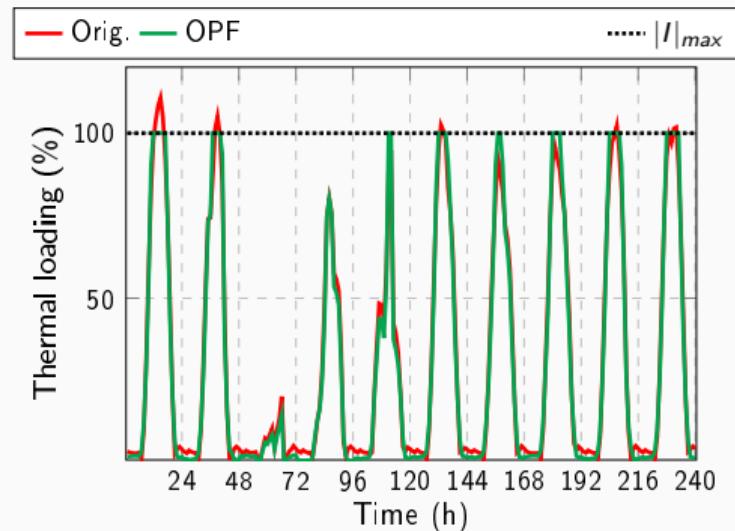
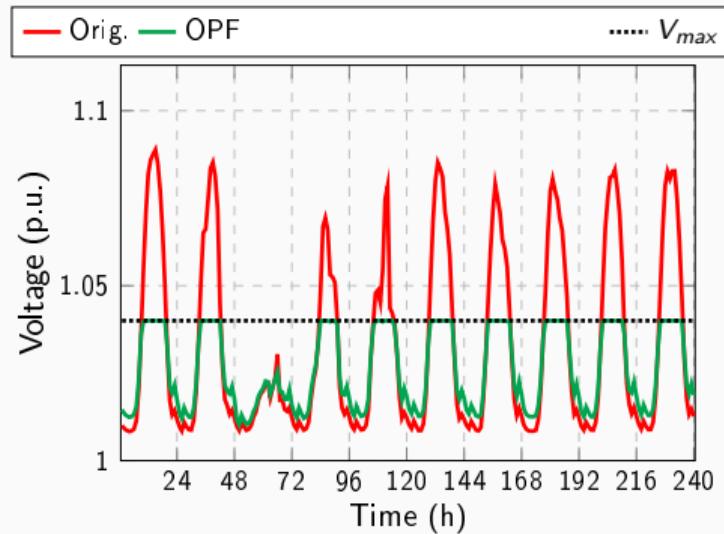
Network description

- Based on European CIGRE LV grid
- Normalized profiles
 - PV & forecasts: Real data from Zurich
 - Load: Typical profiles based on CIGRE
- Summer day simulations
 - High solar radiation
- Acceptable limits:
 - Voltage: $\pm 4\%$
 - Current: up to 1 p.u.
 - VUF: up to 2%

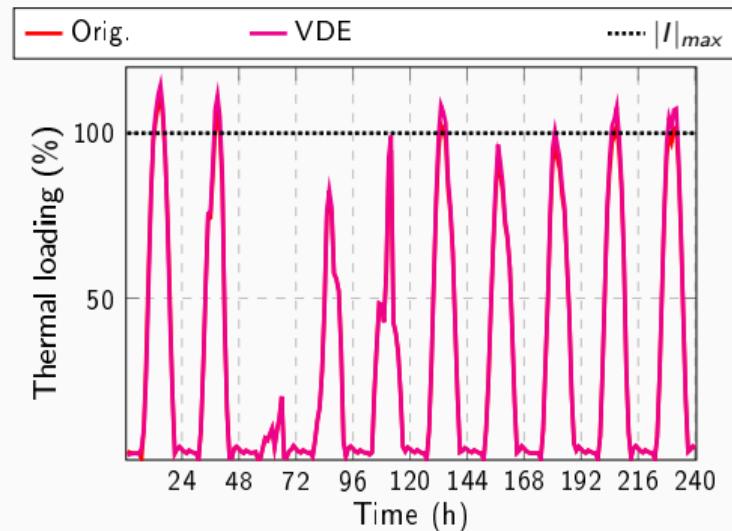
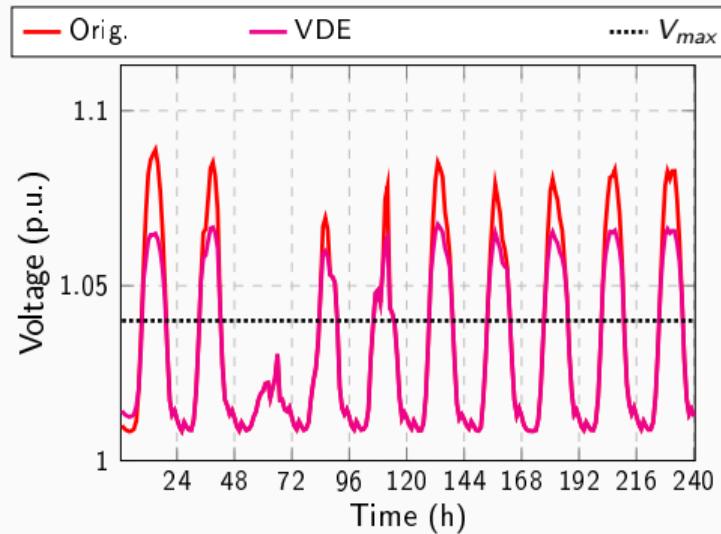
Some results



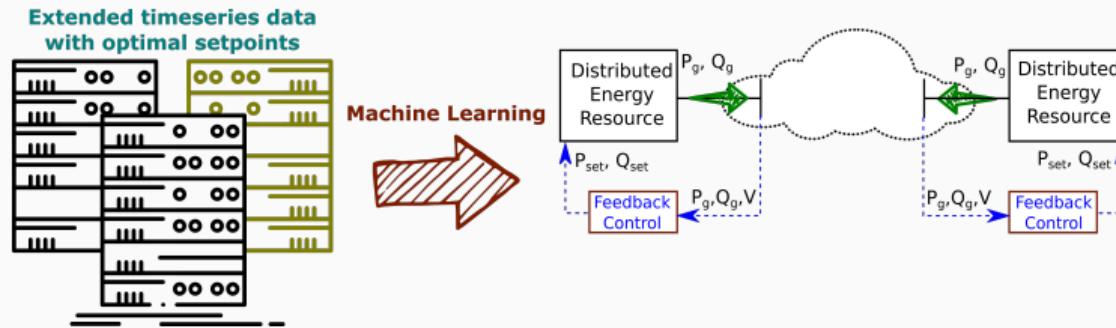
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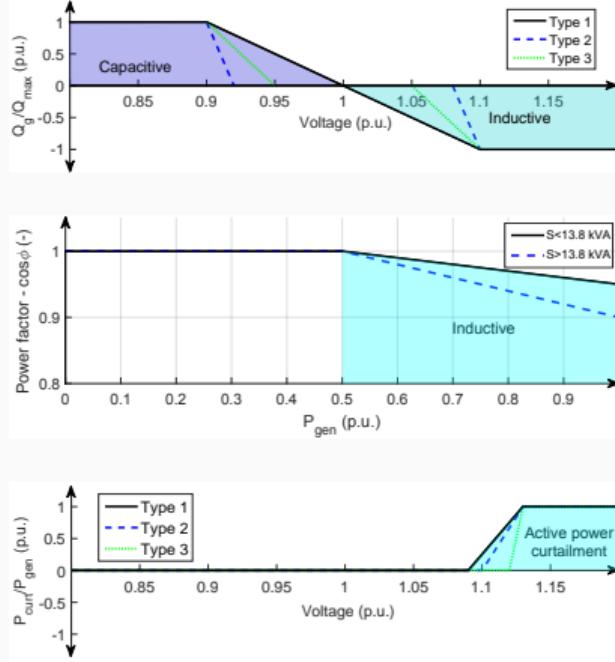
Optimised local control schemes



Optimised local control schemes

Existing local control schemes

- Usually all distributed generators of same type and similar size have the same curve
- Several types, usually: $Q = f(V)$, $\cos\phi = f(P)$, $P_{curt} = f(V)$
- "Open" loop or "closed" loop



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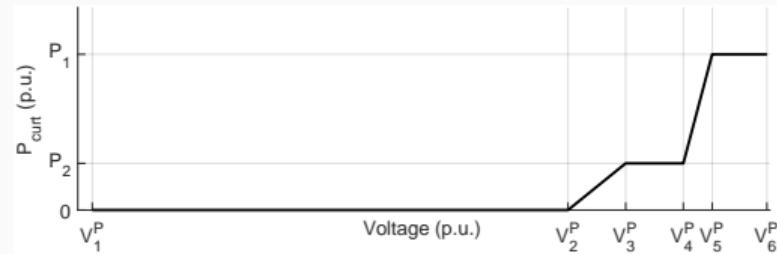
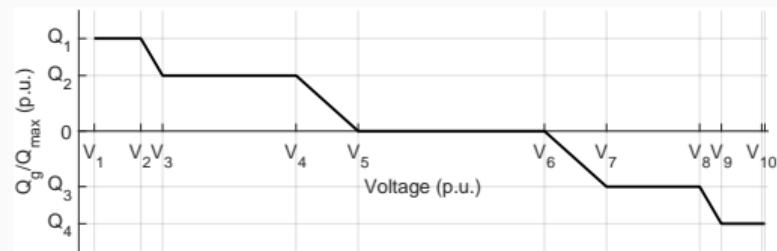
Optimised local control schemes

- Data-driven local controls based on processed data from the previous step
- Candidate DERs
 - Distributed Generators (DGs)
 - Battery Energy Storage Systems (BESS)
 - Controlable Loads (CLs)

Optimised local control schemes

DGs: Piece-wise (segmented) linear fitting

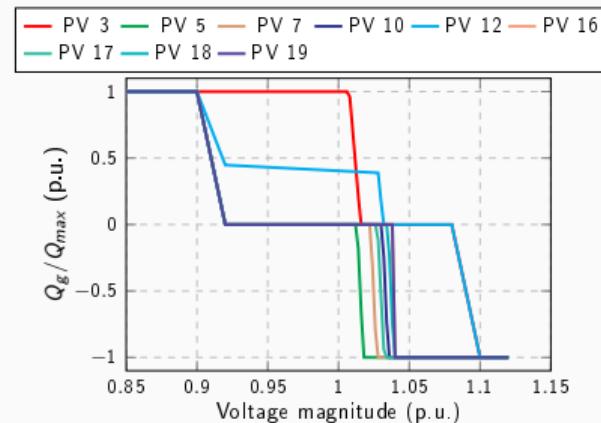
- Simple and efficient (R, sklearn, MATLAB, etc.)
 - Breakpoint selection
 - Nonlinear least squares regression
- Modified to impose stability-related monotonicity and slope constraints



Optimised local control schemes

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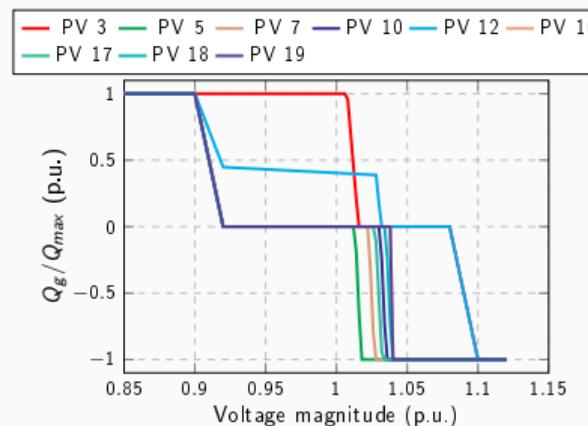
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Optimised local control schemes

Unique characteristic curve per DG

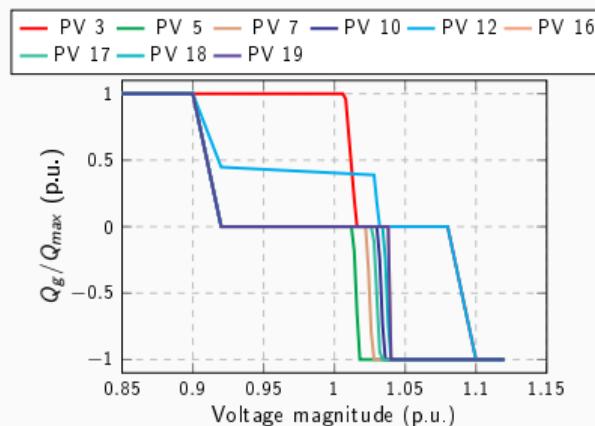
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- Large number of inverter-based DGs



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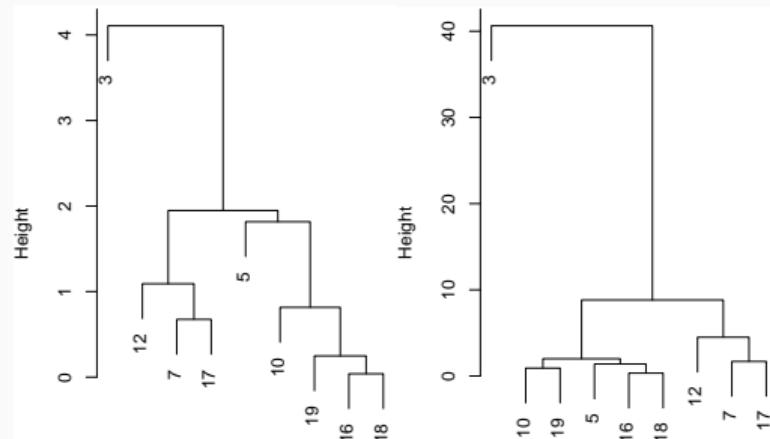
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Clustering of the curves

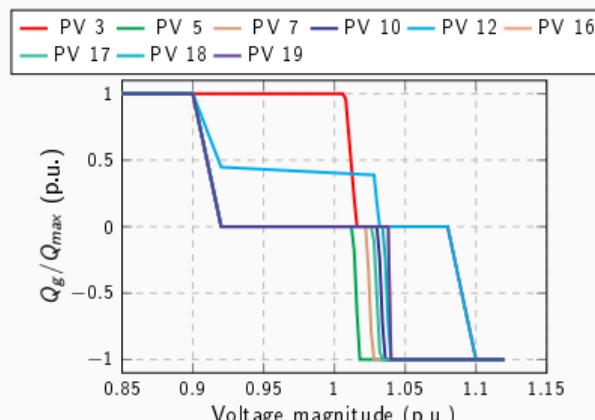
- Assign DGs to clustered curves based on “distance” with hierarchical clustering



Optimised local control schemes

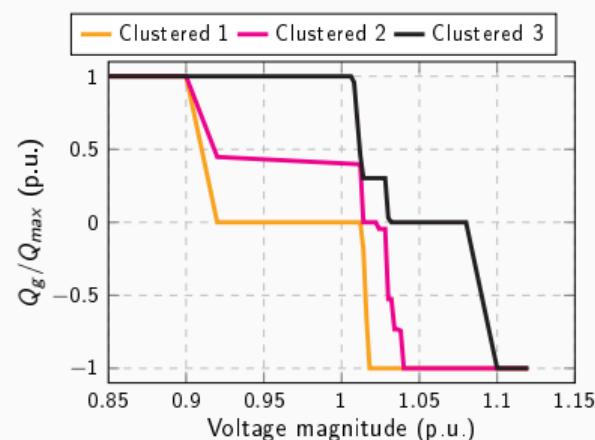
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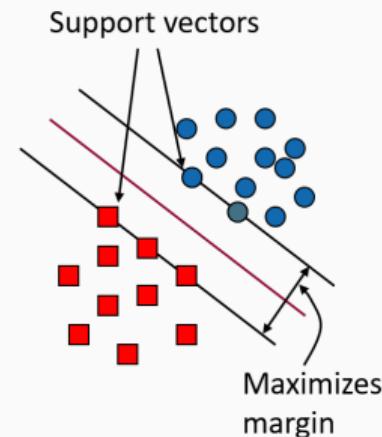
Clustering of the curves

- Assign DGs to clustered curves based on “distance” with hierarchical clustering



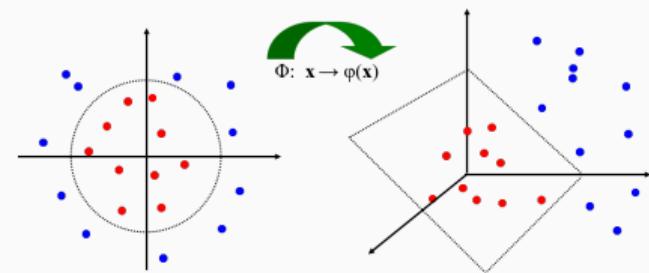
BESS: Support Vector Machine (regression)

- Maximize the margin around the separating hyperplane
- Simple and efficient (R, sklearn, MATLAB, etc.)
 - quadratic programming problem



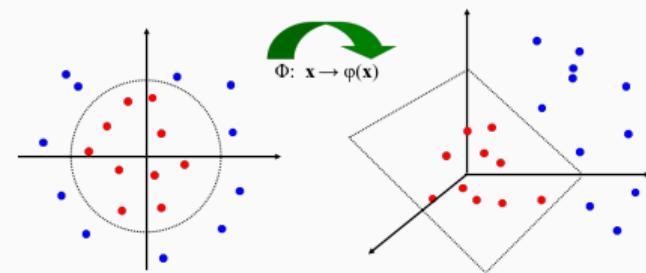
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- Modified to impose stability-related impose monotonicity and slope constraints (e.g., monotone kernel regression methods)



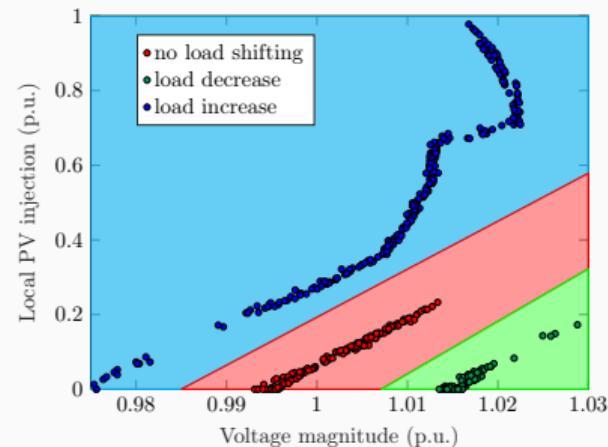
CLs: Support Vector Machines (classification)

- Easy to implement (Python, MATLAB)
- Apply SVM with different kernel functions using the following features:
 - Voltage
 - Active power consumption
 - Reactive power consumption
 - Active PV power injection

Optimised local control schemes

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Optimised local control schemes

Summary of methods

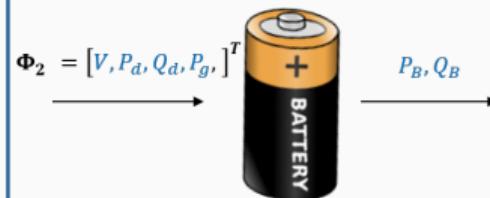
Distributed Generators

- Segmented regression with unknown breakpoints
- Monotonicity & slope constraints
- Volt/Var & Volt/Watt curves



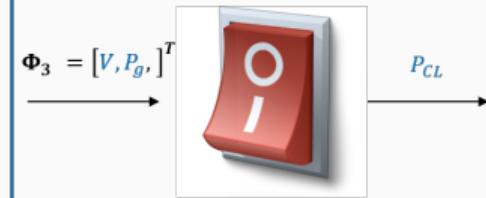
BESS

- Support Vector Machine (SVM) regression
 - Various kernel functions
 - Energy constraints

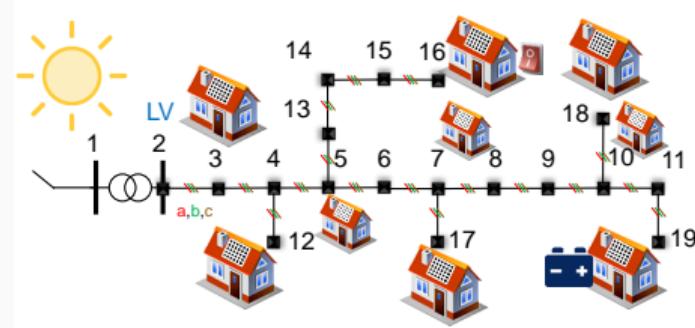


CLs

- Support Vector Machine (SVM) classification
 - Various kernel functions
 - 3 classes: load decrease, increase, or no shifting



Test system



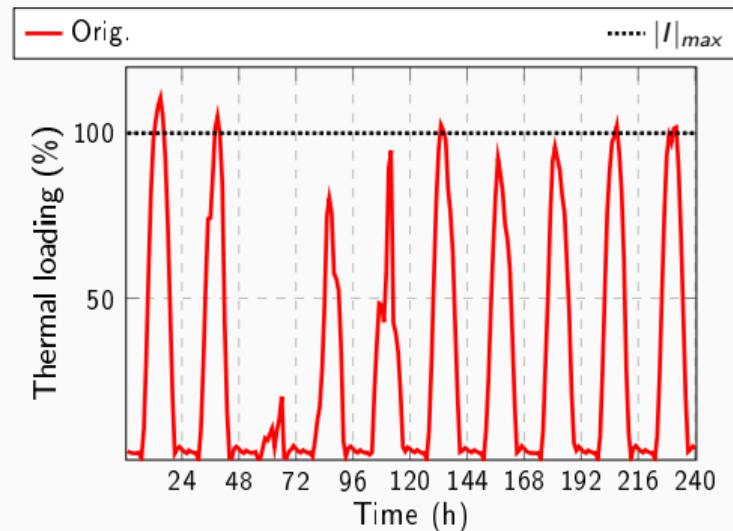
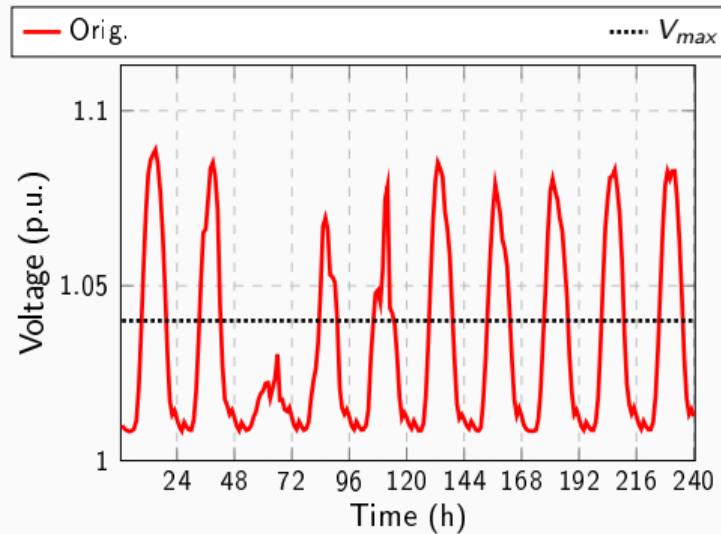
Control actions

- Active Power Curtailment (APC)
- Reactive Power Control (RPC)
- Battery Energy Storage System (BESS)
- Controllable load (CL)
- On Load Tap Changers (OLTC)

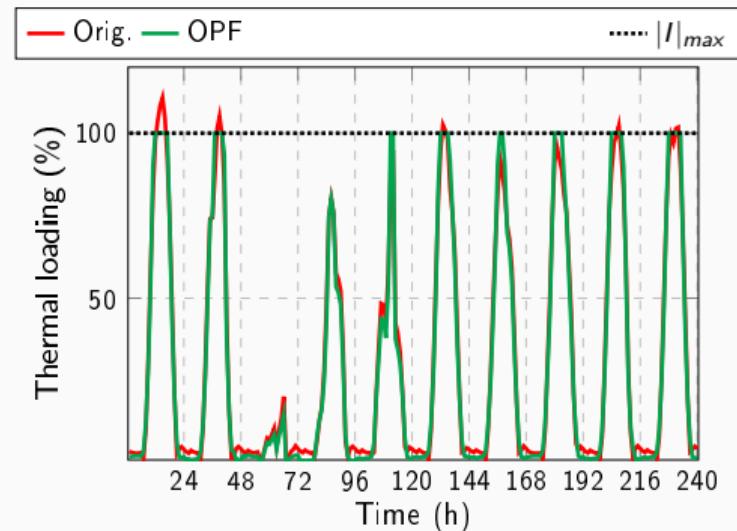
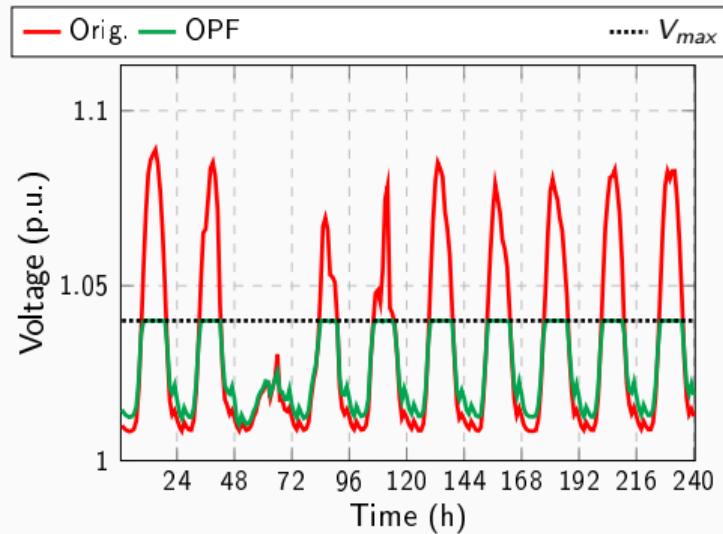
Network description

- Based on European CIGRE LV grid
- Normalized profiles
 - PV & forecasts: Real data from Zurich
 - Load: Typical profiles based on CIGRE
- Summer day simulations
 - High solar radiation
- Acceptable limits:
 - Voltage: $\pm 4\%$
 - Current: up to 1 p.u.
 - VUF: up to 2%

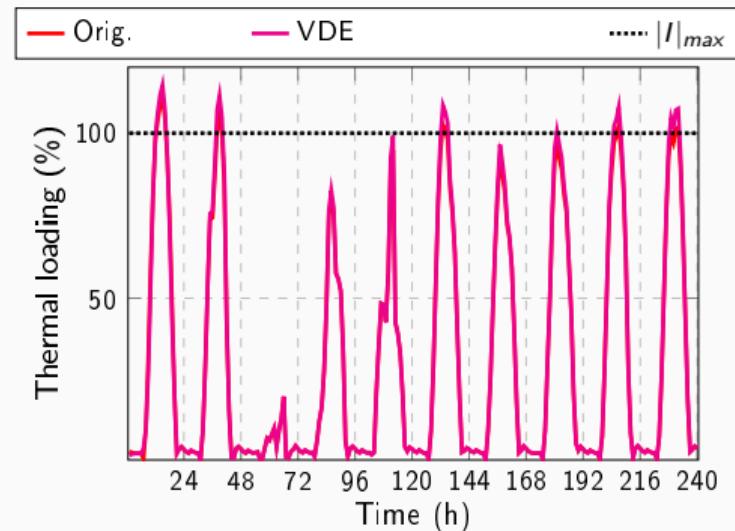
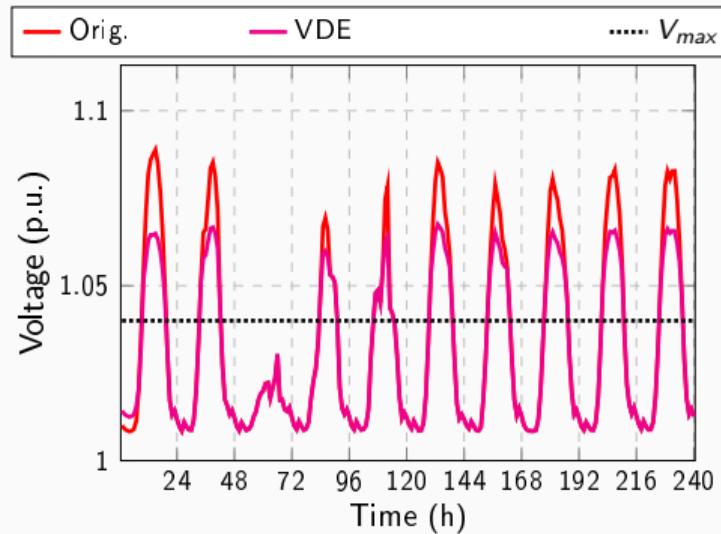
Some results



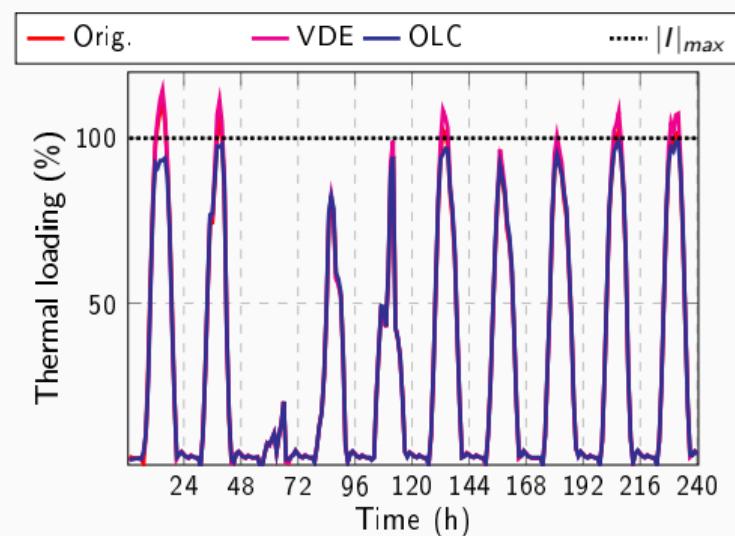
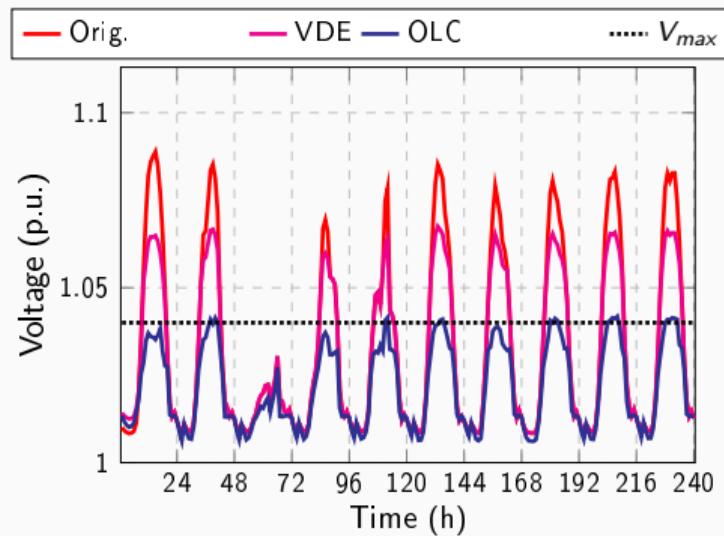
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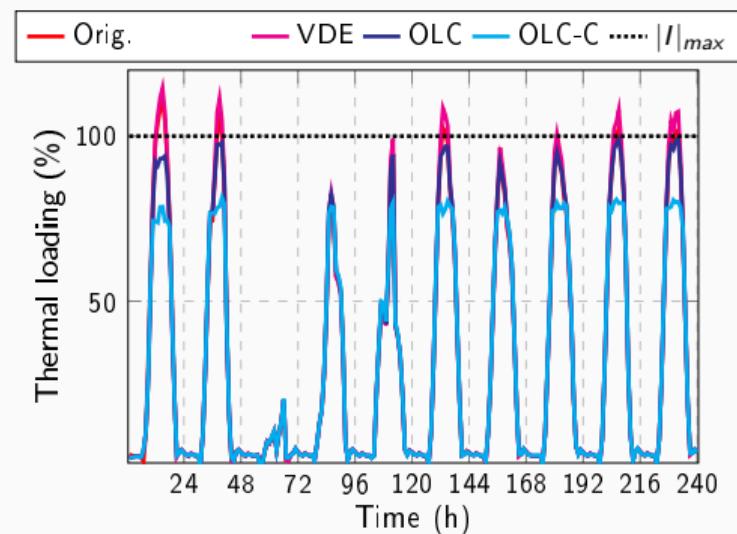
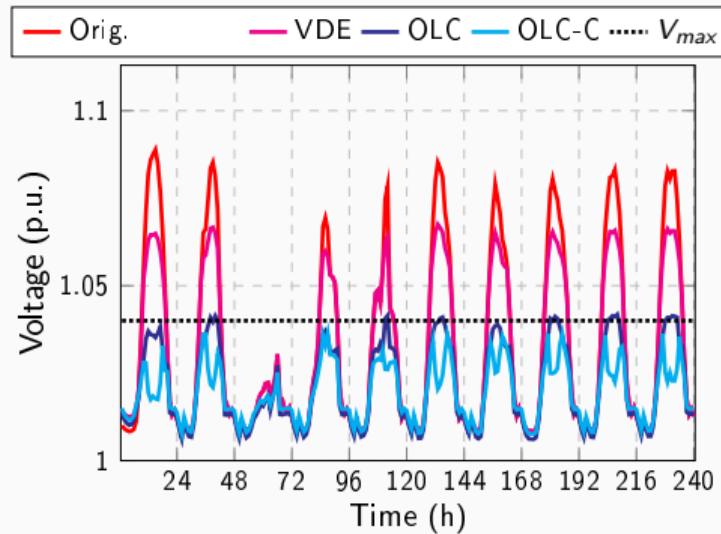
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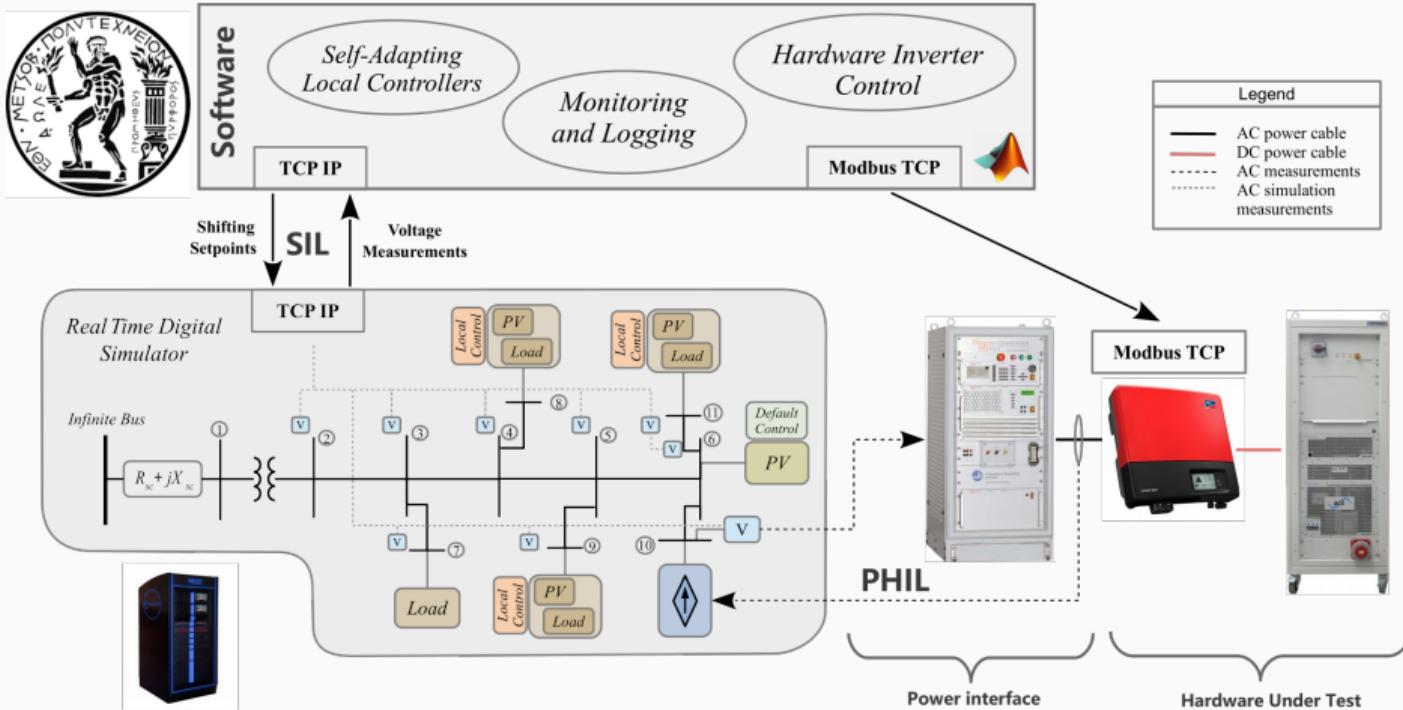
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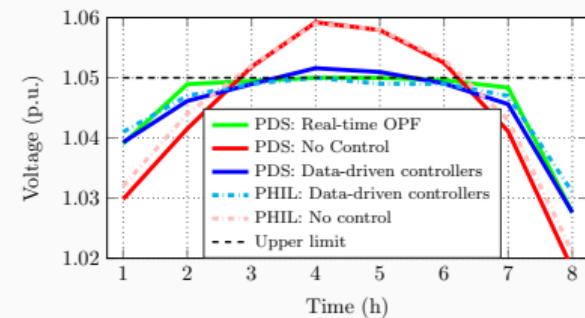
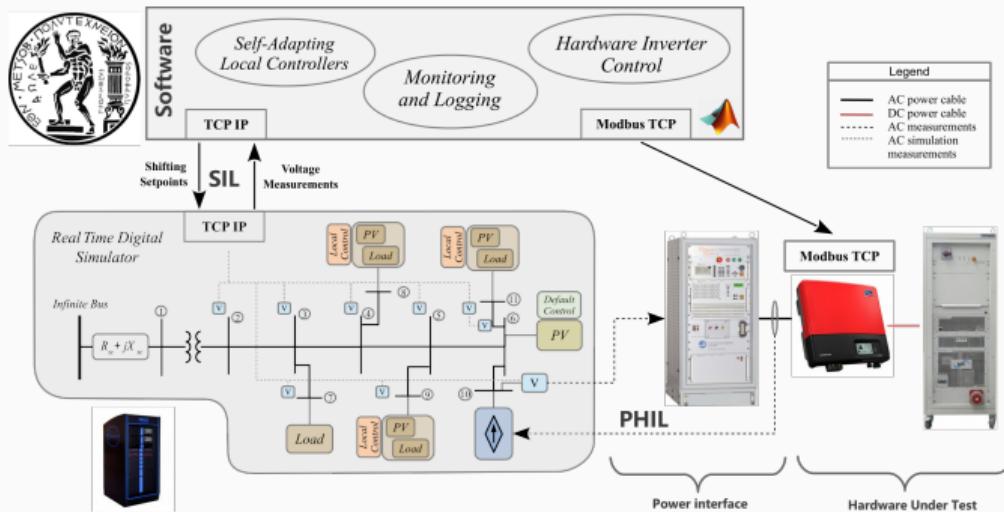
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How about a hardware validation?



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Concluding remarks

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Future steps

- Extend to different types of controls and embed grid-supporting services.
- Single-stage data-driven control design → distributionally robust optimisation?
- Self-adapting controls through online learning to handle changing conditions → (Deep)RL?

Questions?

