Decentralised control of active distribution grids using optimisation and machine learning techniques

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(joint work with Stavros Karagiannopoulos and Gabriela Hug, ETH Zurich)

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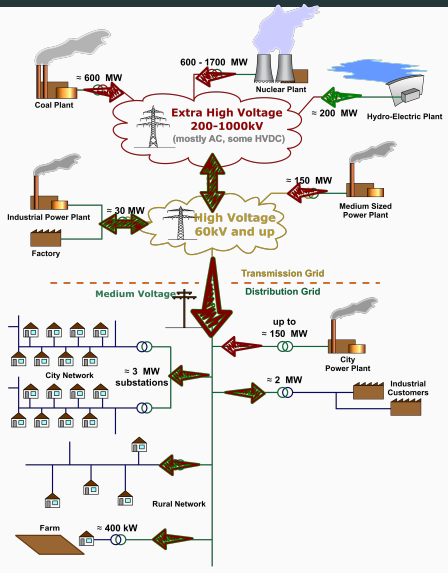
Motivation

Transformation of power systems

New developments in distribution grids



Transformation of power systems

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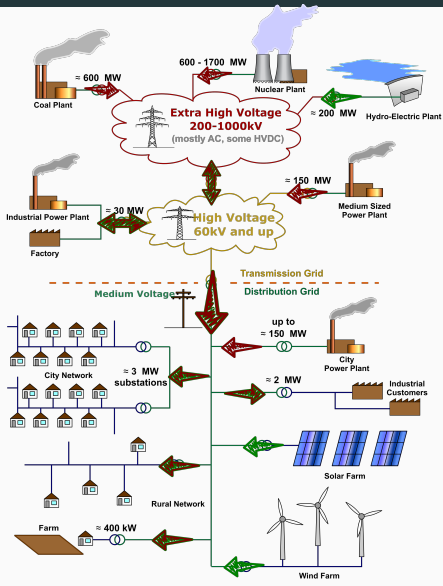

Transformation of power systems

New developments in distribution grids

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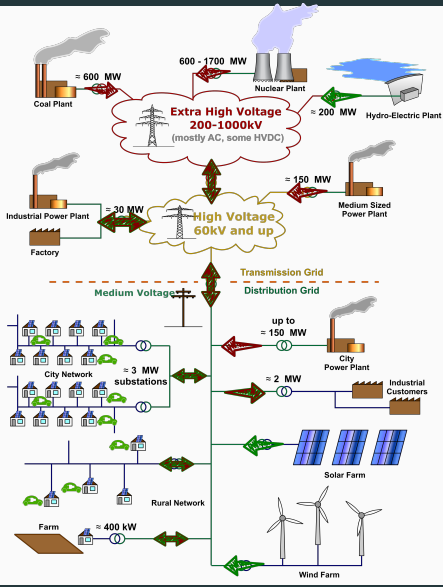
- Introduction of small distributed generators and energy storage systems
- Electrification of transportation (plug-in hybrid, battery electric, etc.)



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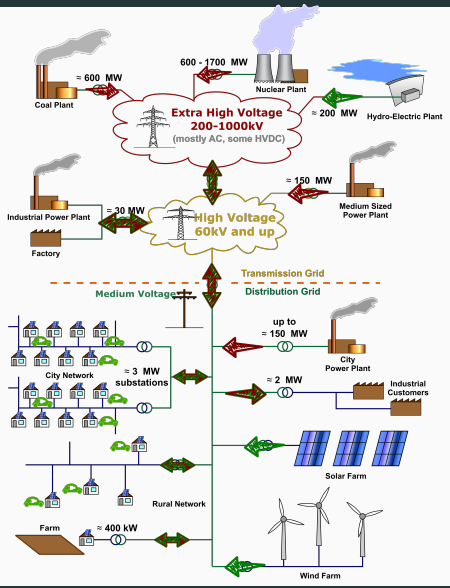
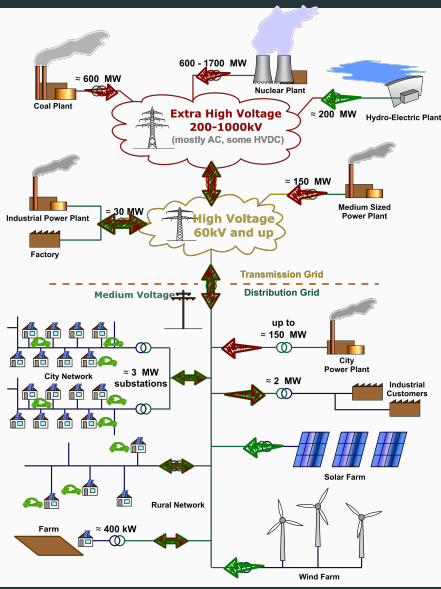
- Electrification of transportation (plug-in hybrid, battery electric, etc.)
- Demand response schemes (reaction to price signals, emergency load reduction, peak shaving, etc.)



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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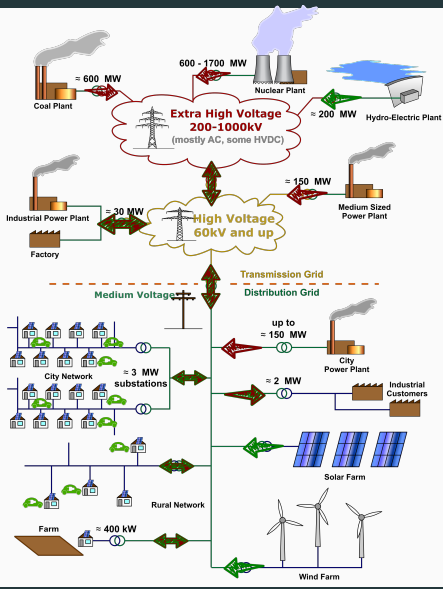

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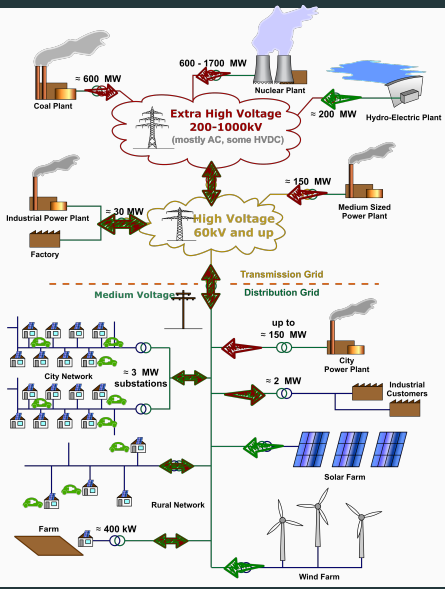

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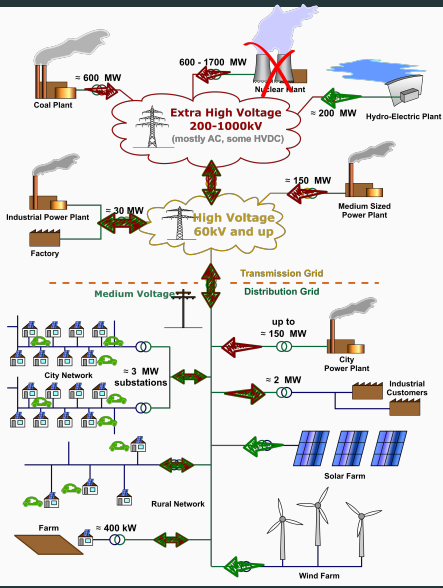
- **Decommission of conventional units.** *Loss of traditional "dispatchable" generation and control.*



Real-time operation

Distribution grid control approaches

Real-time operation

Distribution grid control approaches

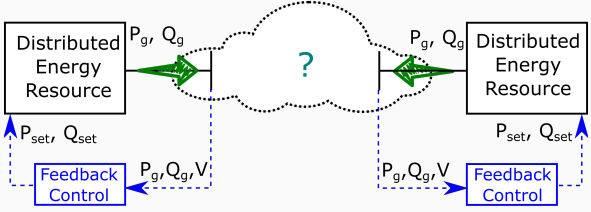
Local

Only local measurements and decisions

No communication

Lower cost and more robust

"One size fits all"



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Distributed
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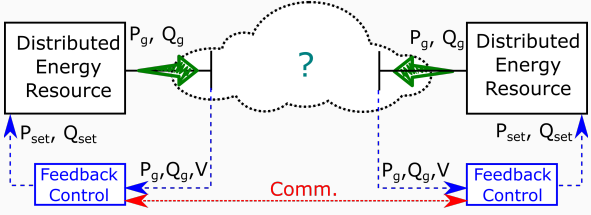

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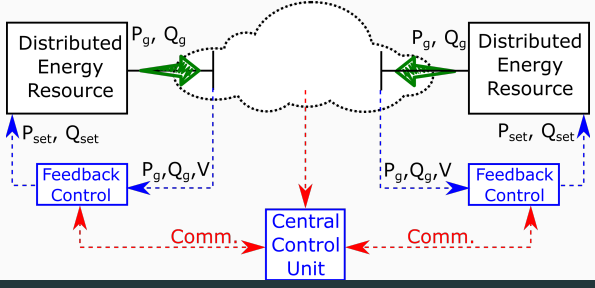
Centralised
Full monitoring and communication
Centralised decision
Better performance but higher cost
More security risks



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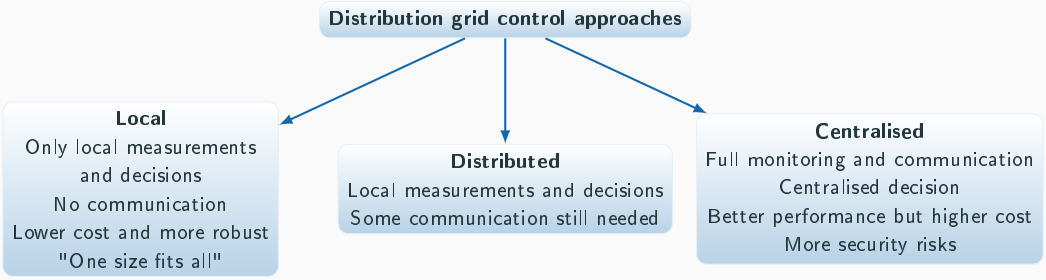

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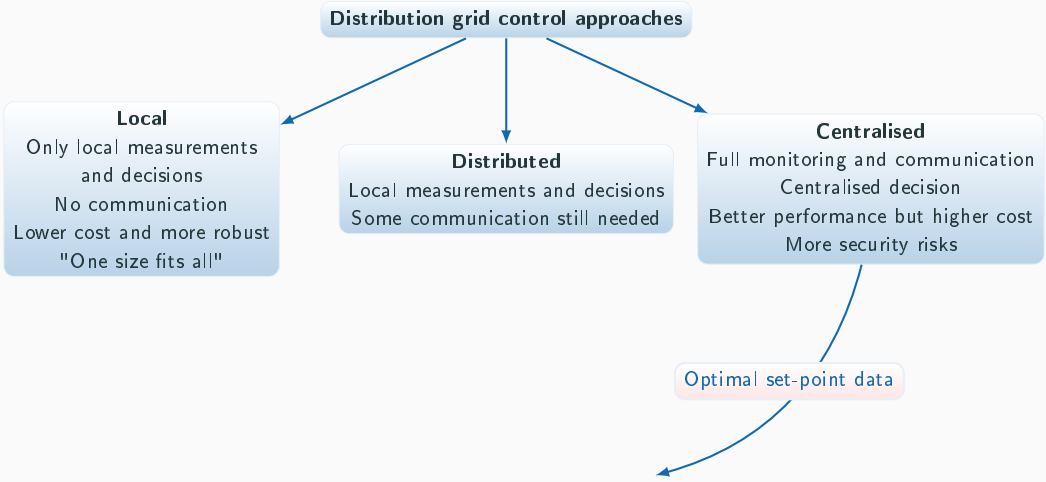

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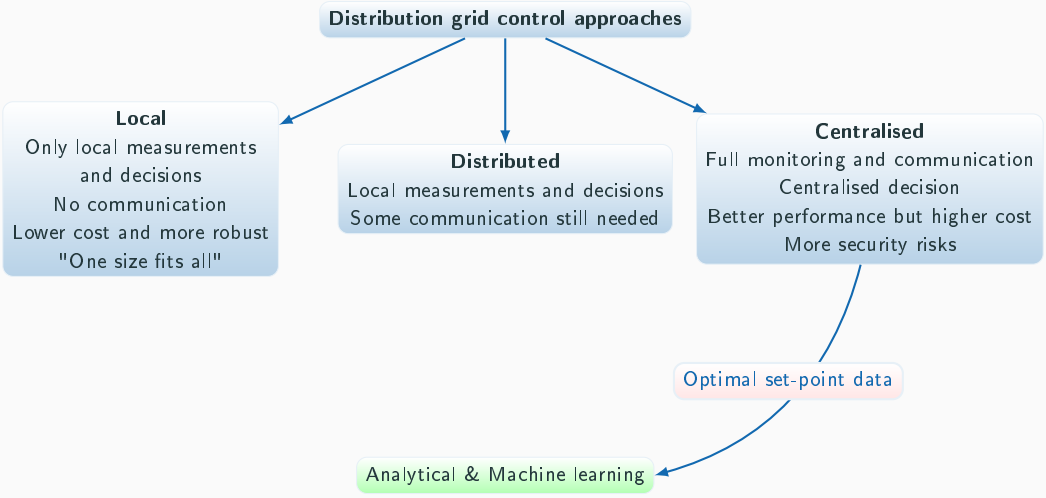

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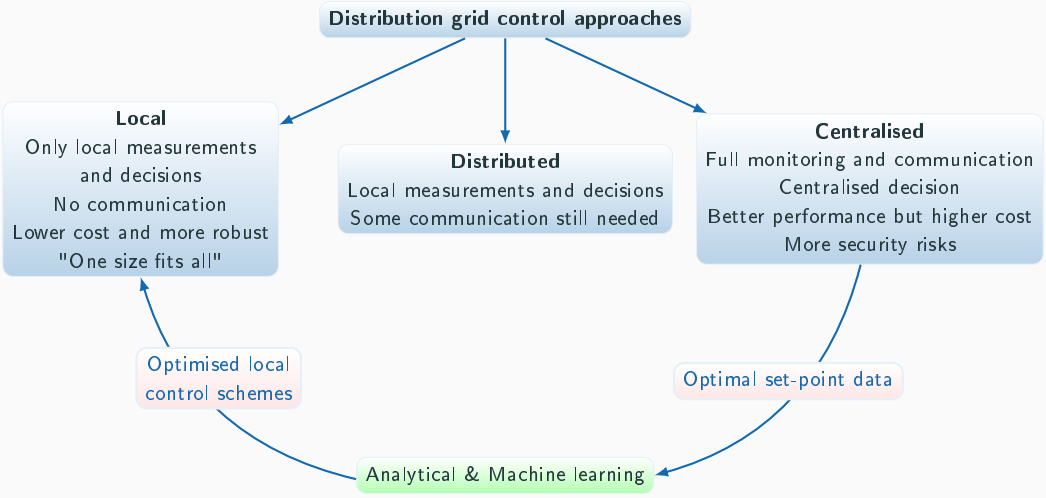


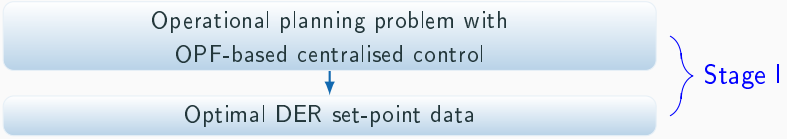
Optimised local control

Methodology overview

Operational planning problem with
OPF-based centralised control

Stage I

Methodology overview



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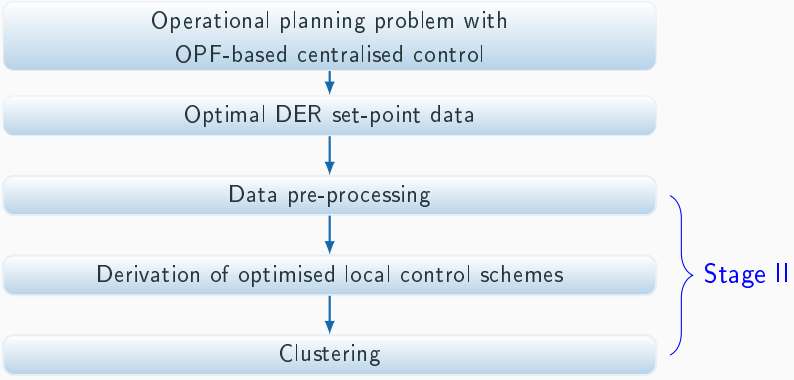

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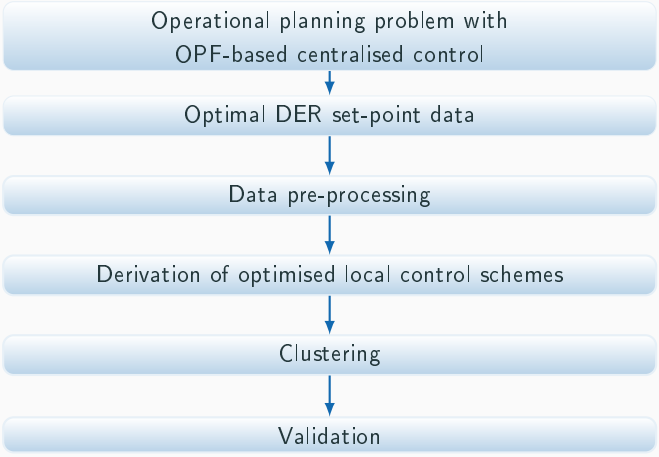

Stage III

Operational planning problem with centralised control

Multi-period OPF problem formulation

$$\min_{\boldsymbol{u}} \sum_{t} (c_{op}^{T}\boldsymbol{u} + c_{el}^{T} losses)\Delta t$$

$\boldsymbol{u}$:

- Active power curtailment (APC)
- Reactive power control (RPC)
- Battery Energy Storage Systems (BESS)
- Controllable loads (CLs)

Operational planning problem with centralised control

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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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AC power-flow constraints

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Operational planning problem with centralised control

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    - Iterative procedure
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    - Weakly meshed treatment

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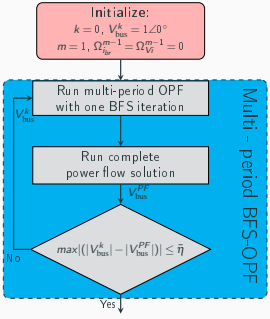
  - **Backward/Forward Sweep (BFS) power flow (Fortenbacher et al. 2016)**
    - Iterative procedure
    - Exploit the radial grid structure
    - Weakly meshed treatment
- **Use a single BFS iteration for the OPF problem**

Operational planning problem with centralised control



Operational planning problem with centralised control

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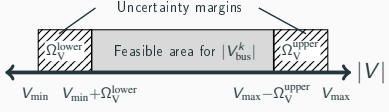
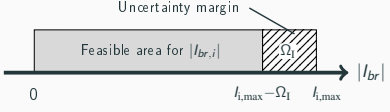




Operational planning problem with centralised control

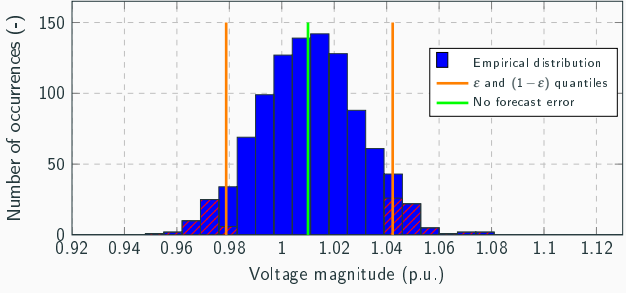
Uncertainty margins evaluation

- Analytical approach $\rightarrow$ Need to know the probability distribution

Operational planning problem with centralised control

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



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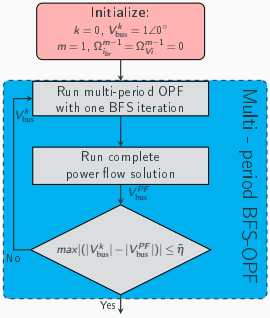

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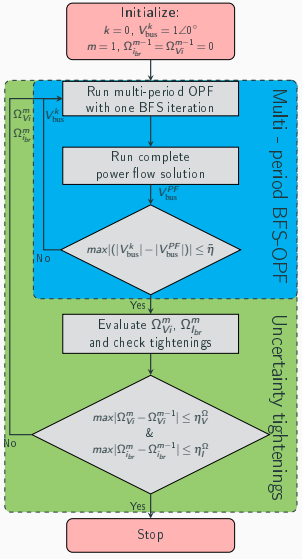
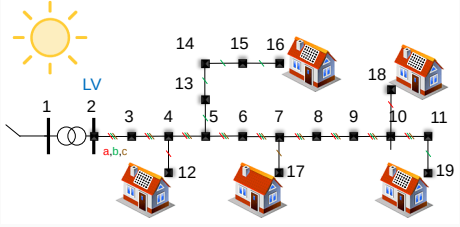


Test system



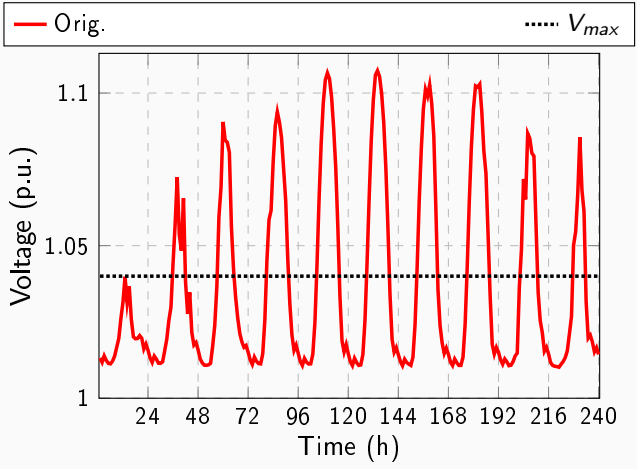
Control actions

- Active Power Curtailment (APC)
- Reactive Power Control (RPC)
- Battery Energy Storage System (BESS)
- Controllable load (CL)

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% *p.u.*
  - Current: up to 1 *p.u.*

Some results



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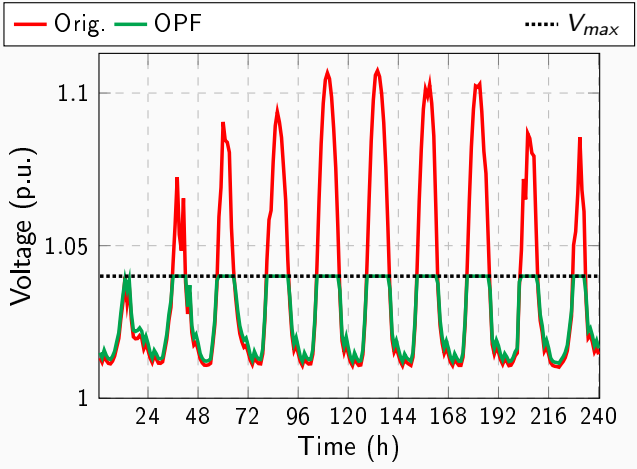

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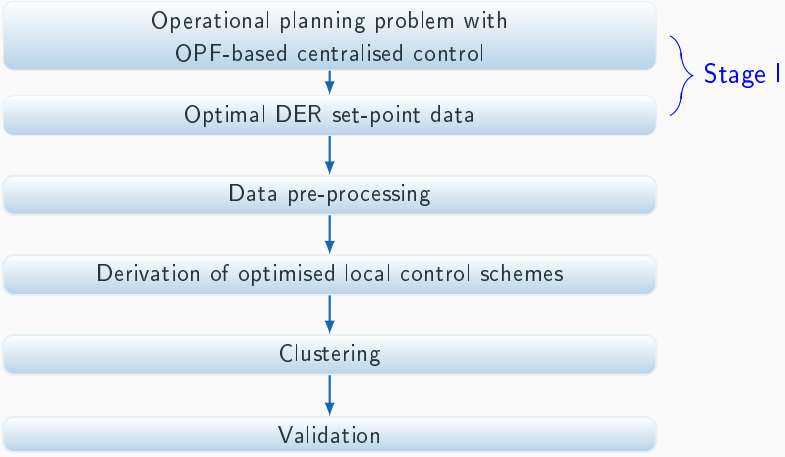

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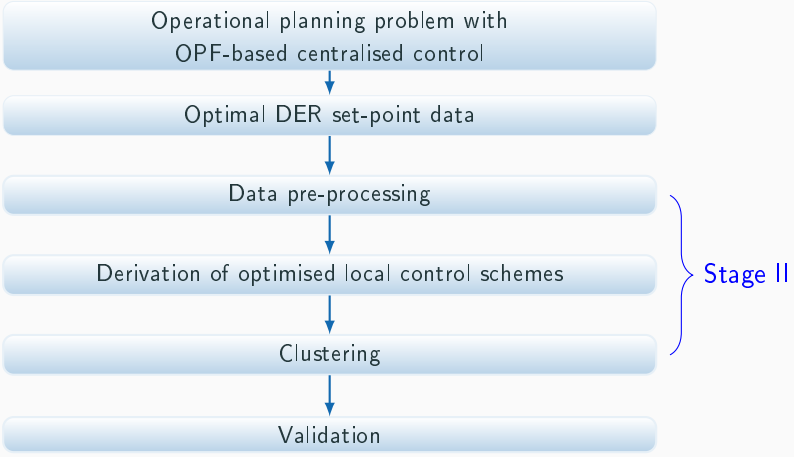

Local control schemes

Existing local control schemes

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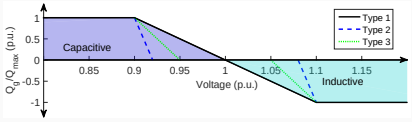

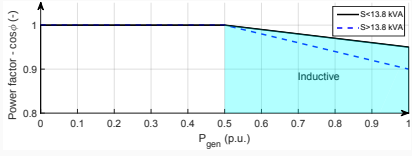

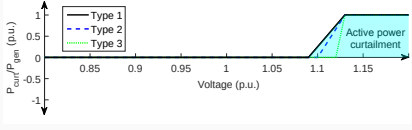

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  - Piece-wise (segmented) linear fitting
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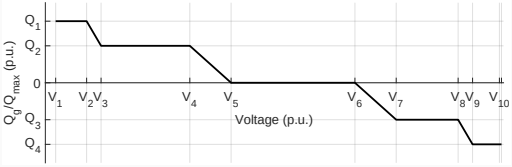
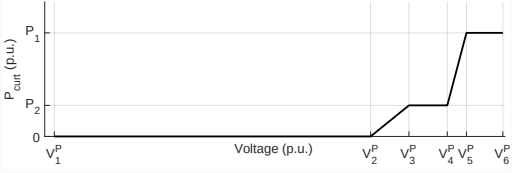
Optimised local control schemes

Piece-wise (segmented) linear fitting

- Simple and efficient (R, sklearn, MATLAB, etc.)
- Challenges
  - Breakpoint selection
  - Impose monotonicity and slope constraints





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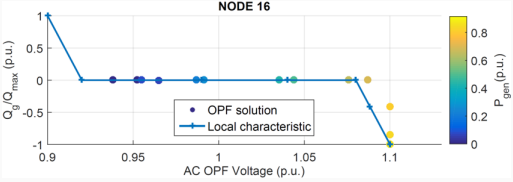

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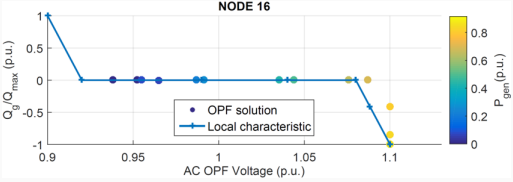
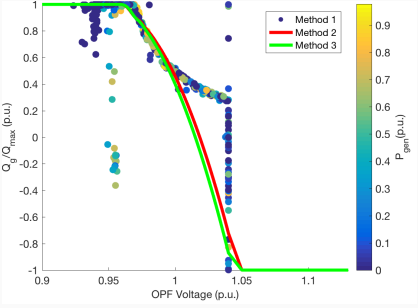


Optimised local control schemes

Support Vector Regression

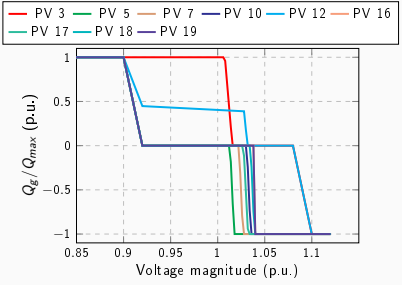
- Start from OPF-generated set-points (training data)
- Pre-process data (e.g., PV data during night)
- Non-linear SVR
  - Implicit mapping via kernels (Linear, Polynomial, Gaussian)
  - 5-fold cross-validation
  - Impose monotonicity and slope constraints



Optimised local control schemes

Unique characteristic curve per DER

- Implementation challenges
  - Need to program a different curve for each agent
  - Large number of inverter-based DERs



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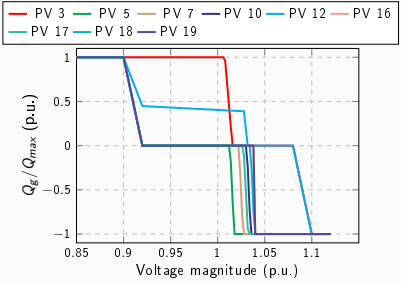
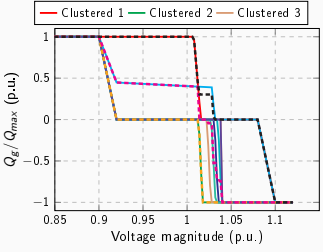
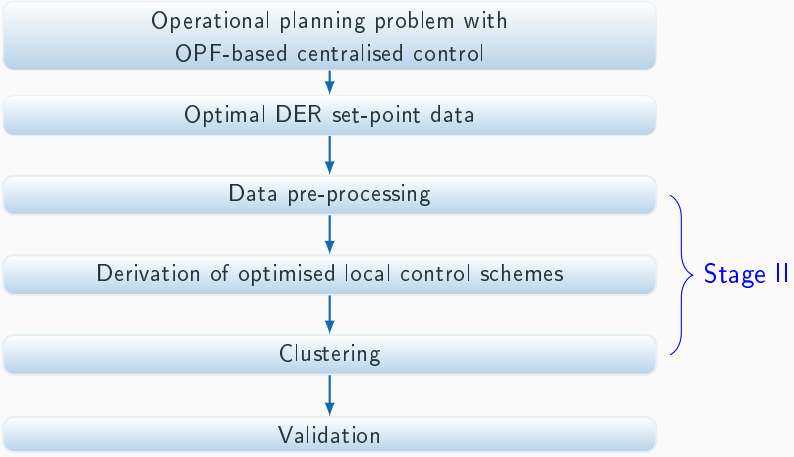


Clustering of the curves

- For each voltage value, use k-means algorithm to the n individual curves (use the centroids of the n_{cl} clusters to form the final clustered curves)
- Assign DERs to clustered curves based on "distance"



Methodology overview



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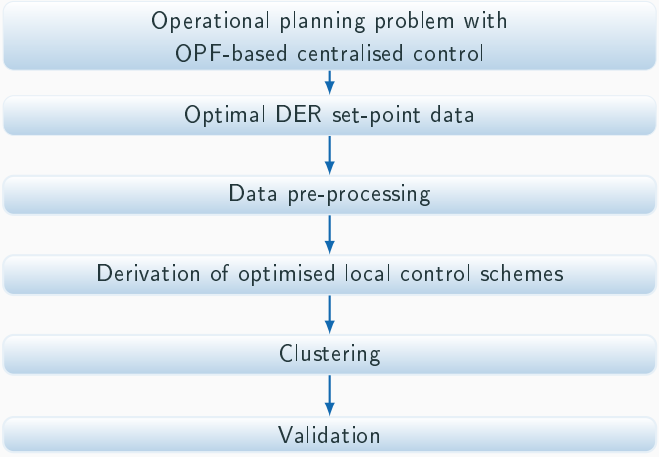
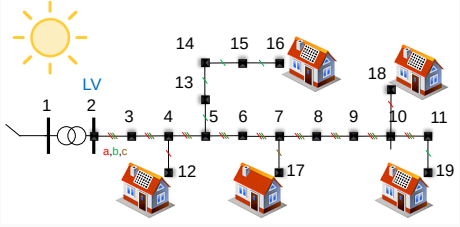


Stage III

Test system



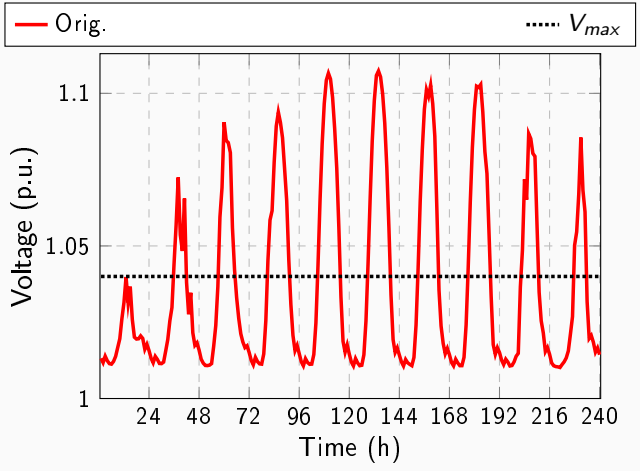
Control actions

- Active Power Curtailment (APC)
- Reactive Power Control (RPC)
- Battery Energy Storage System (BESS)
- Controllable load (CL)

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% *p.u.*
  - Current: up to 1 *p.u.*

Some results



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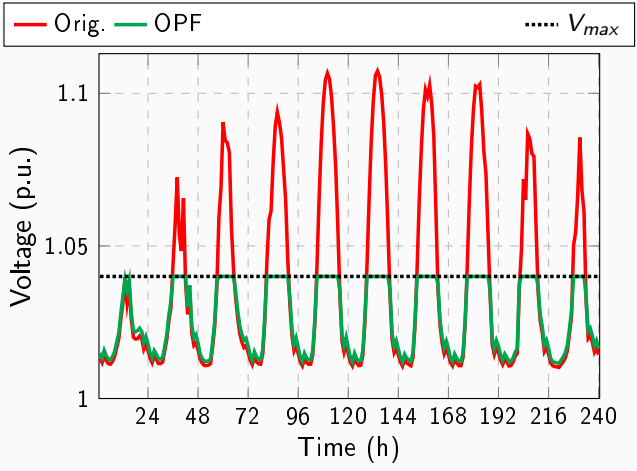

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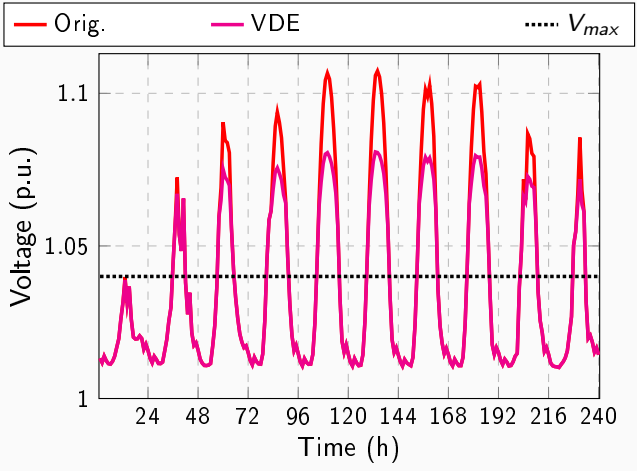

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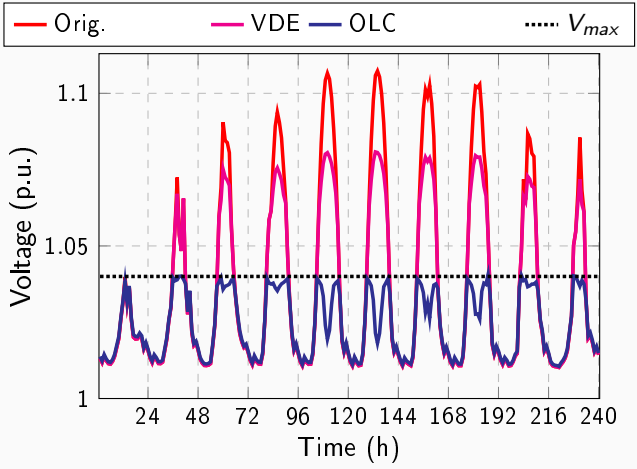

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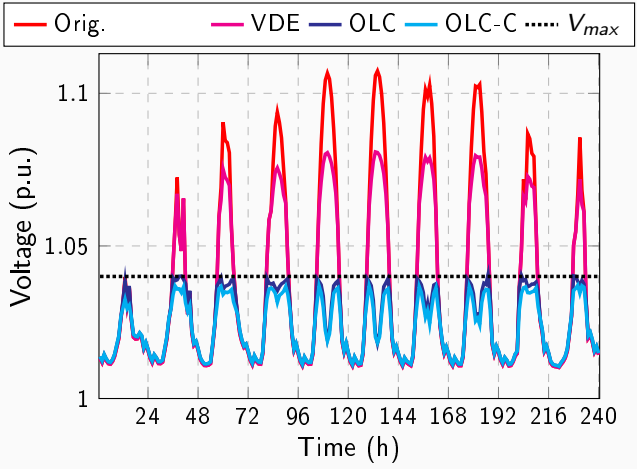

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Future steps

- Investigate different ML techniques and extend to multiple local "features"
- Experimental validation (EMPA, Zurich)


Questions?