Data-driven decentralised control design in distribution networks

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

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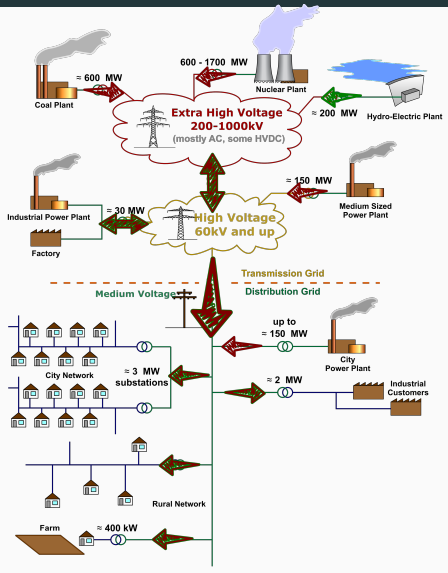
Motivation

Transformation of power systems

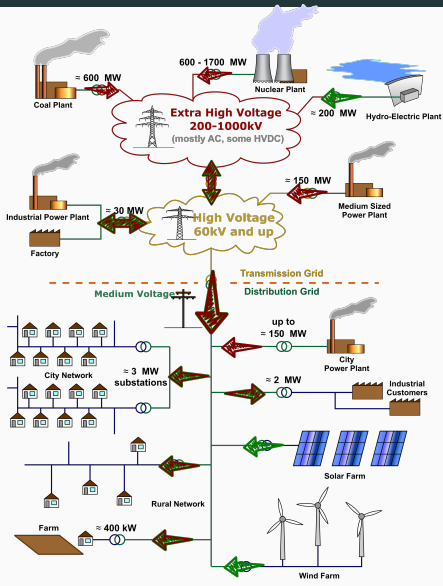
New developments in distribution grids



Transformation of power systems

New developments in distribution grids

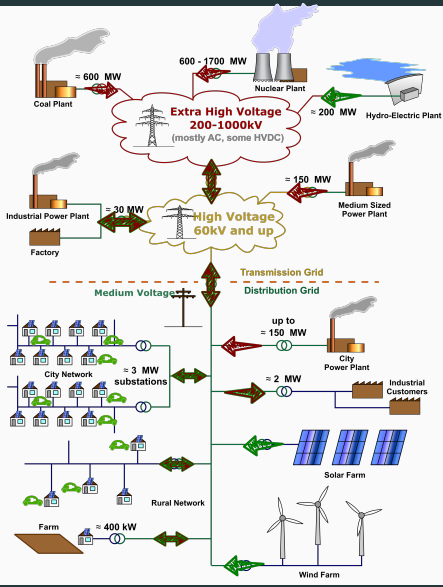
- Introduction of large distributed generators (renewable energy sources, etc.)



Transformation of power systems

New developments in distribution grids

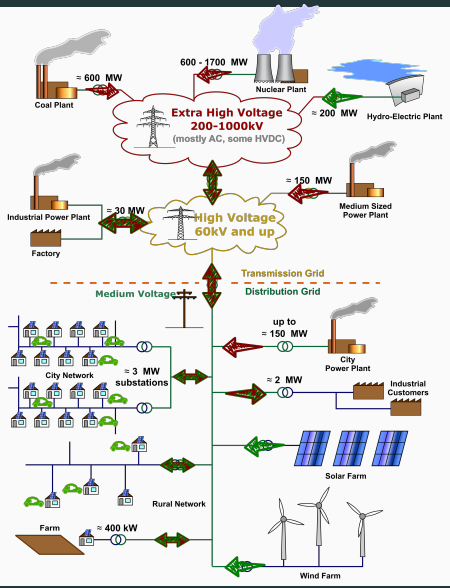
- Introduction of large distributed generators (renewable energy sources, etc.)
- Introduction of small distributed generators and energy storage systems
- Electrification of transportation (plug-in hybrid, battery electric, etc.)



Transformation of power systems

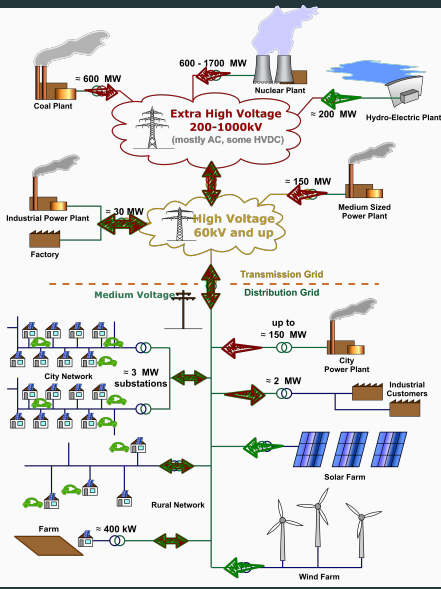
New developments in distribution grids

- 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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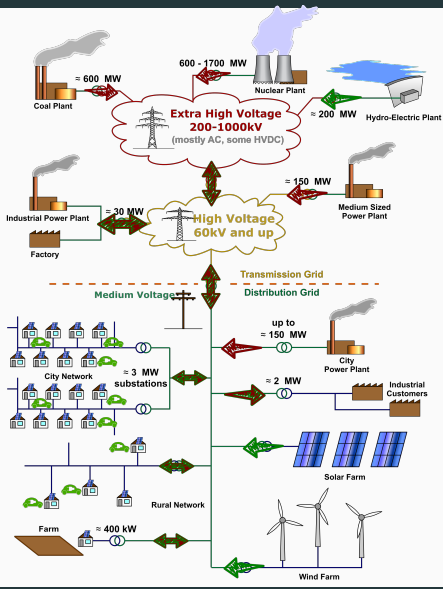

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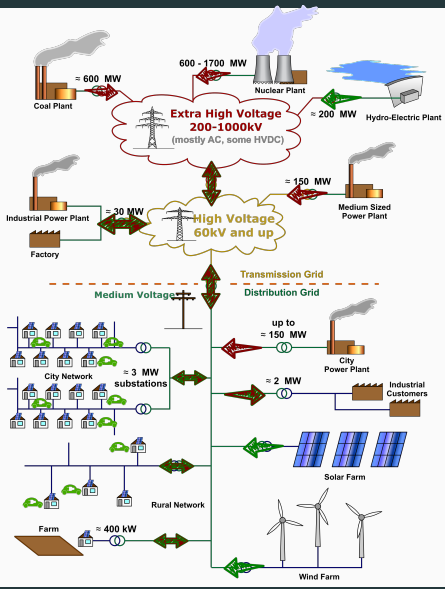

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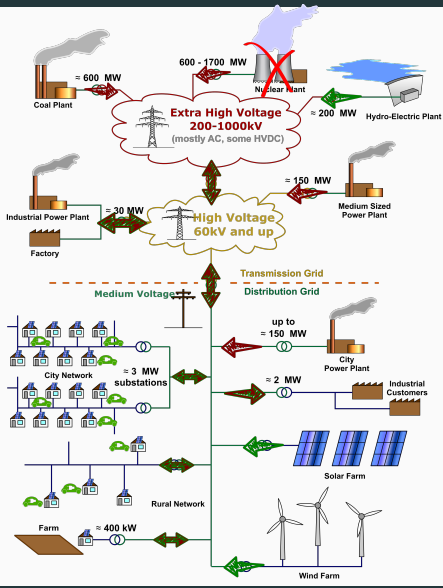
- **Decommission of conventional units.** *Loss of traditional "dispatchable" generation and control.*



Real-time operation

Distribution grid control approaches

Real-time operation

Distribution grid control approaches

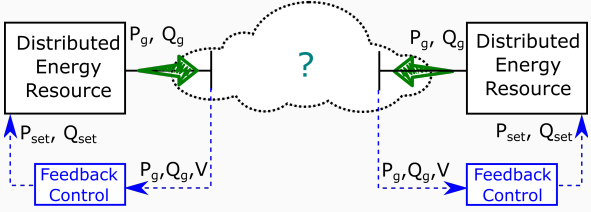
Local

Only local measurements and decisions

No communication

Lower cost and more robust

"One size fits all"



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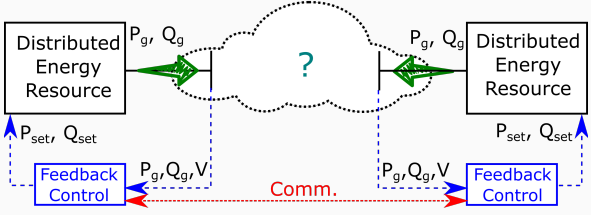

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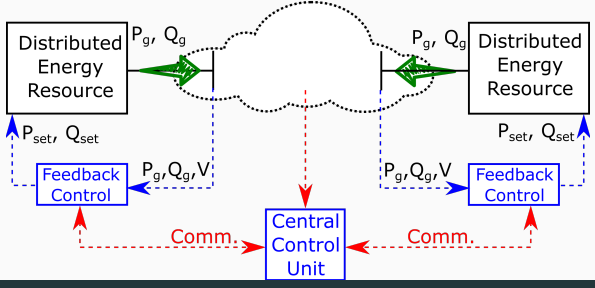
Centralised
Full monitoring and communication
Centralised decision
Better performance but higher cost
More security risks



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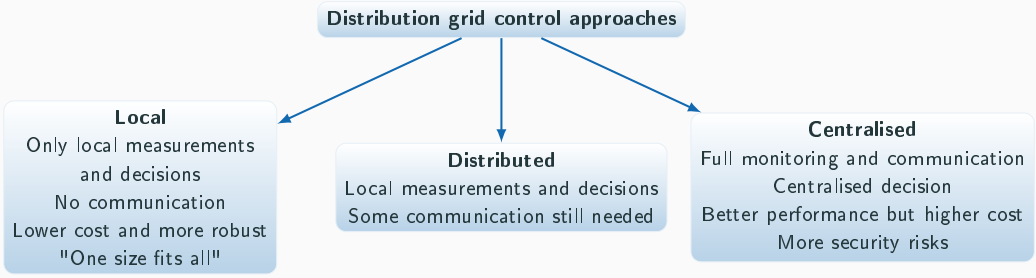

Can we derive a local control scheme that is trained to mimic the optimal behavior?

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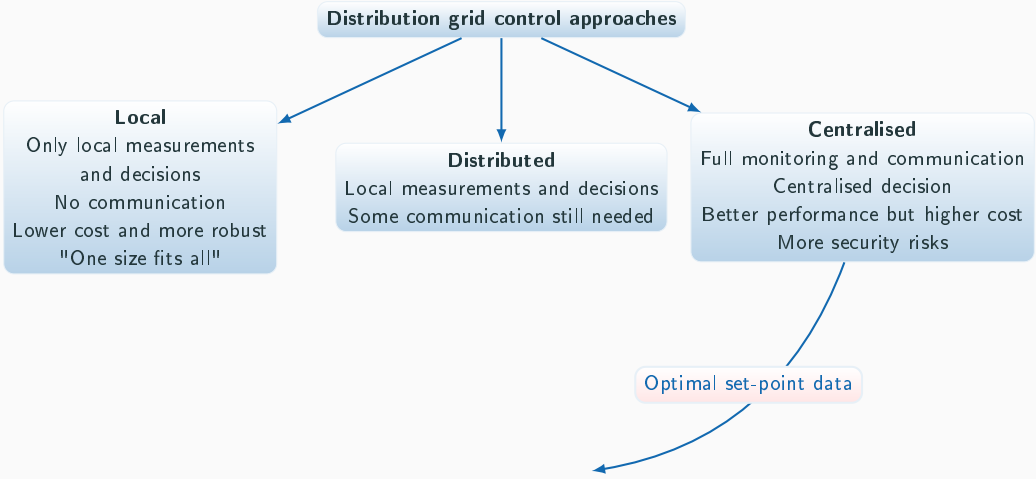

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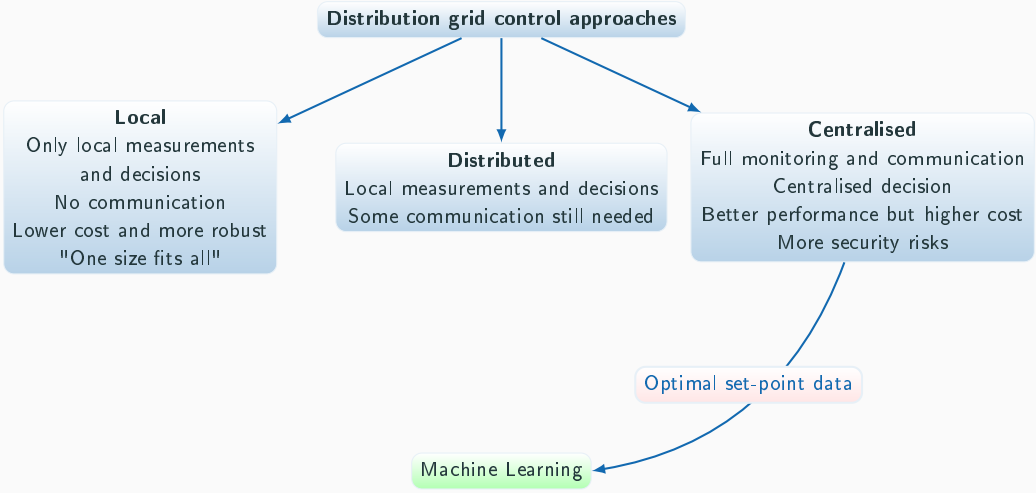

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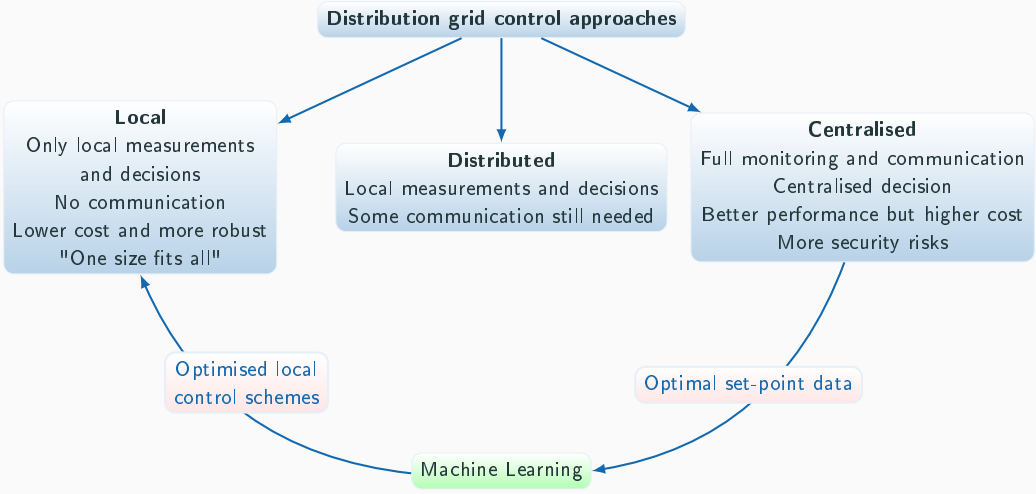
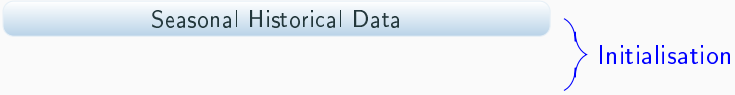


Optimised local control

Methodology overview



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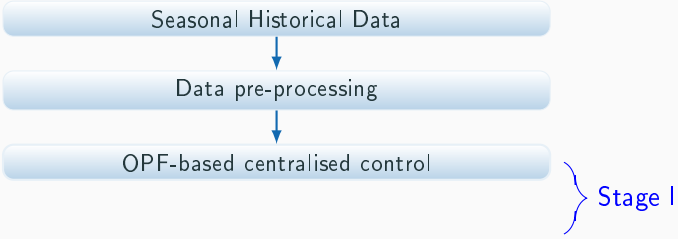

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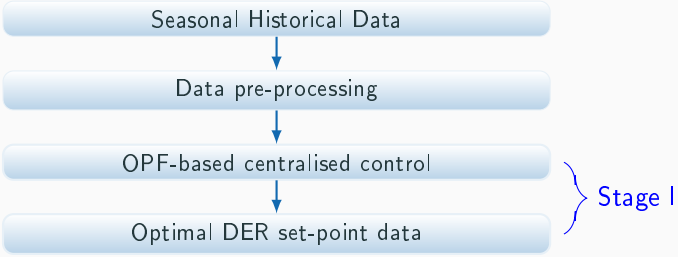

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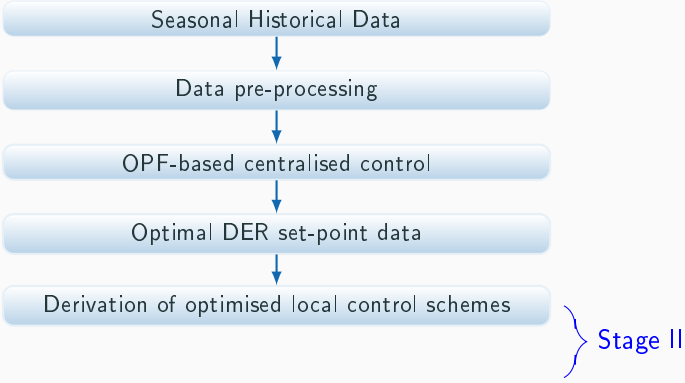

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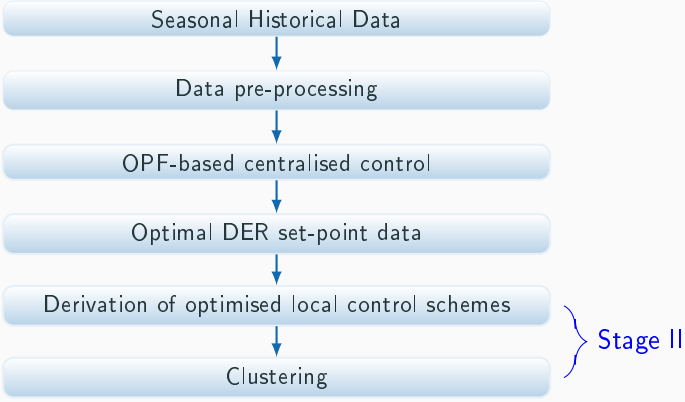

Methodology overview

Stage III

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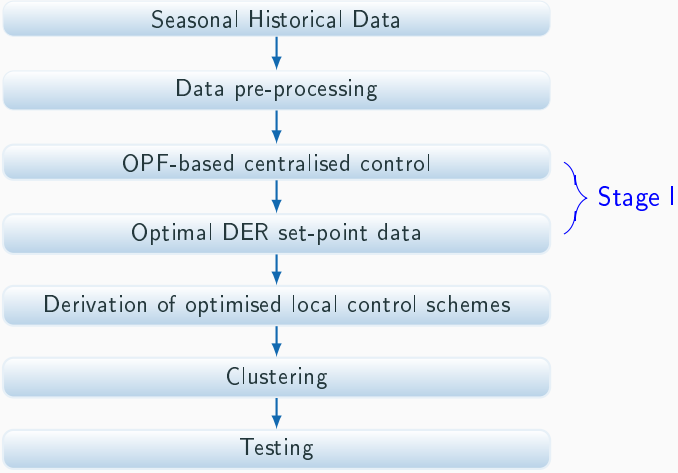

Operational planning problem with centralised control

Multi-period OPF problem formulation

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

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- Active power curtailment (APC)
- Reactive power control (RPC)
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Subject to:

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

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Operational planning problem with centralised control

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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, Molzaln & Hiskens 2015, Lavaei & Low 2012, Paudyaly et al. 2011)
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  - **Backward/Forward Sweep (BFS) power flow (Fortenbacher et al. 2016)**
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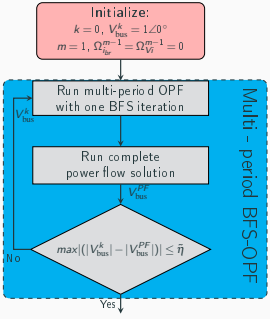
- **Use a single BFS iteration for the OPF problem**

Operational planning problem with centralised control



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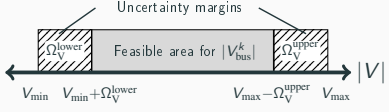

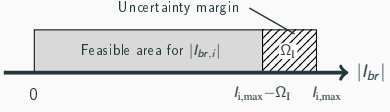

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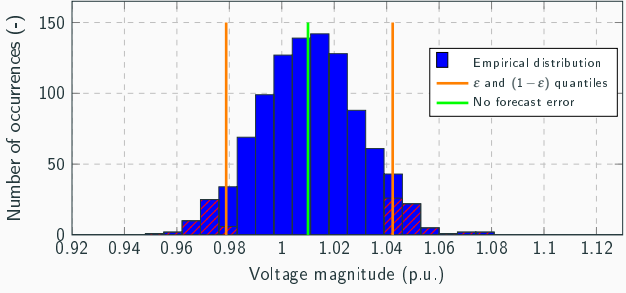
Uncertainty margins evaluation

- 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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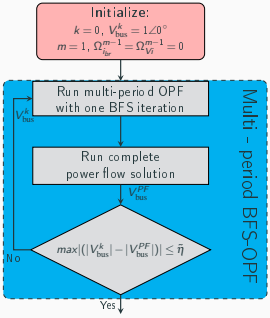

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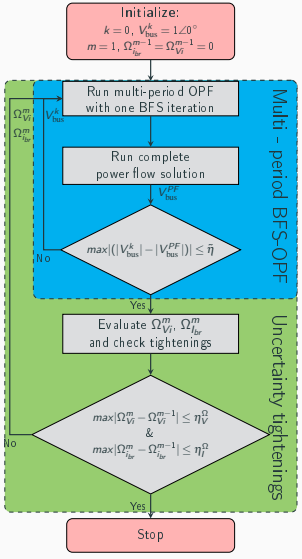
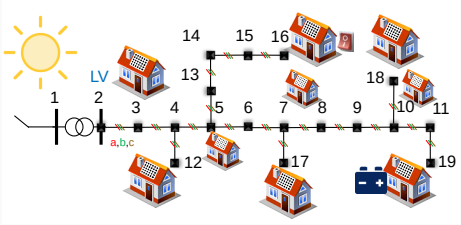


Test system



Control actions

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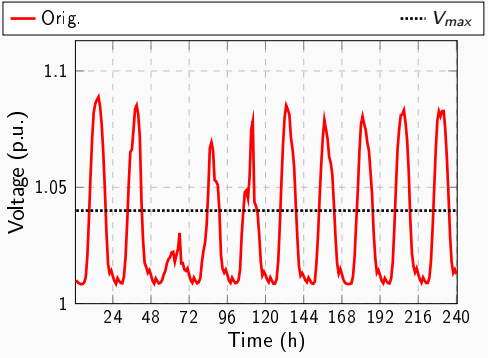
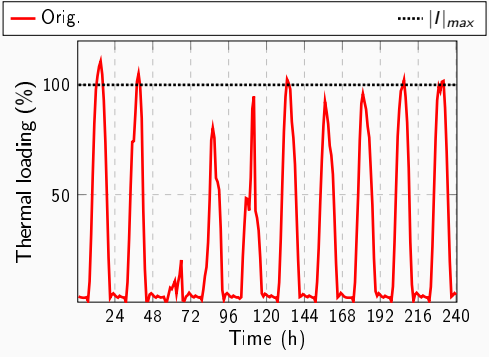
Network description

- 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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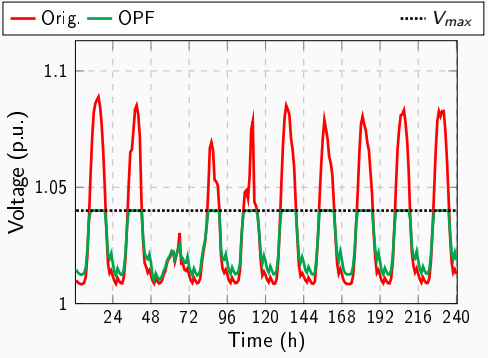

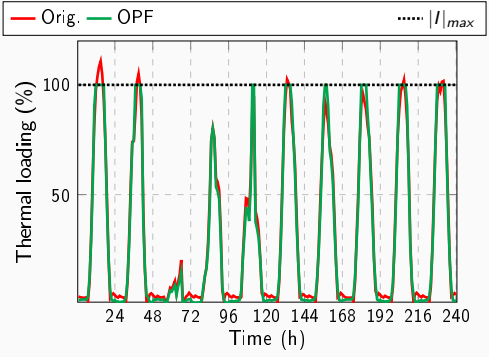

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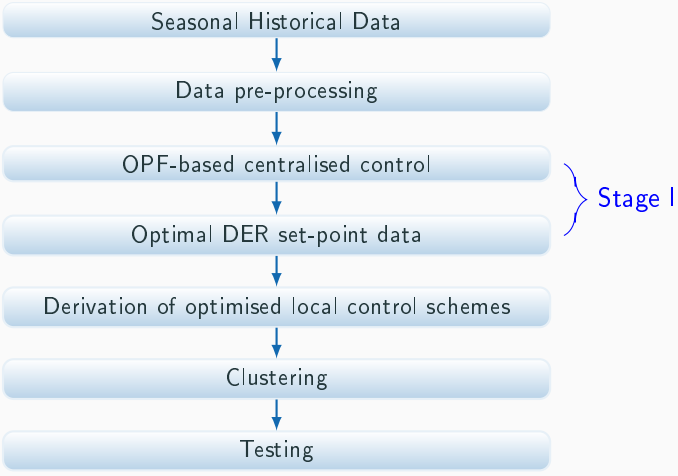

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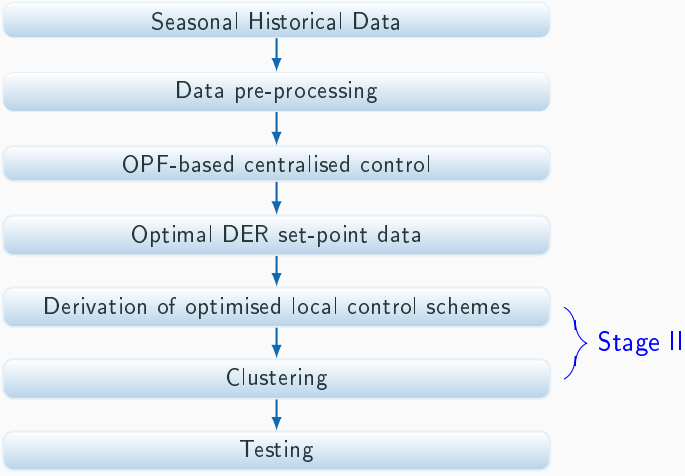

Optimised local control schemes

Selection of local input

- Local load (active and reactive), local generation (active), net load, power factor, local voltage magnitude, ...

Ability to better "map" OPF setpoints?

- Single feature
- Multiple features or a combination

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"Closed"-loop

- Output of the controller has an impact on the local measurements and influences the controller's input through a feedback term
- Can perform well even when the real-time conditions are "far" from the training dataset

Optimised local control schemes

Existing local control schemes

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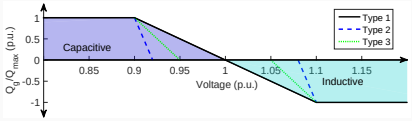

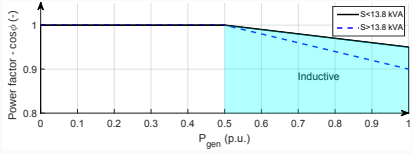

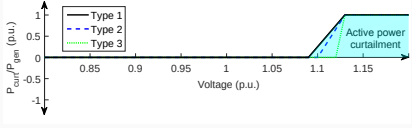

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- Customised local control scheme for each unit based on data from the previous stage

Optimised local control schemes

Existing local control schemes

- Usually all DERs 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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- Customised local control scheme for each unit based on data from the previous stage

1. Use predictive modelling techniques to derive controllers from data
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   - Support Vector Regression (SVR)
2. Use classification techniques for discrete controls
   - Support Vector Machine (SVM)

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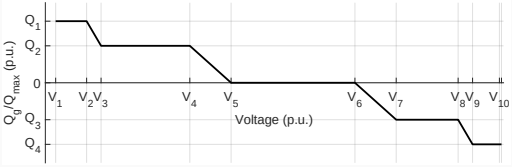
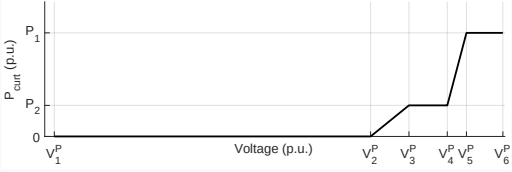
Piece-wise (segmented) linear fitting

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





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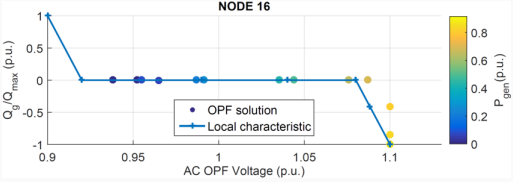

Optimised local control schemes

Piece-wise (segmented) linear fitting

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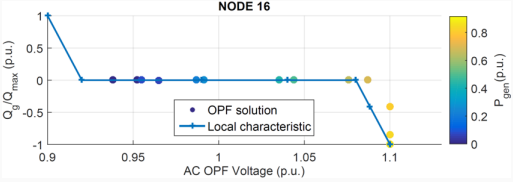
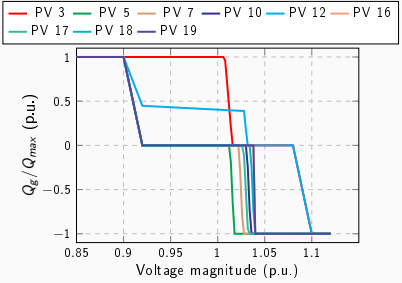
- Sensitivity to outliers
- Prone to overfitting



Optimised local control schemes

Unique characteristic curve per DG

- Need to program a different curve for each agent
- Large number of inverter-based DGs



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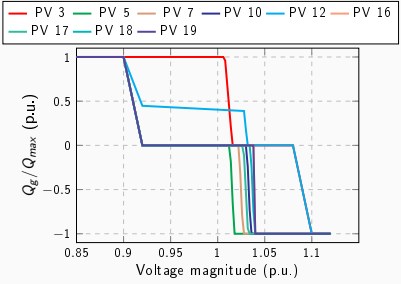
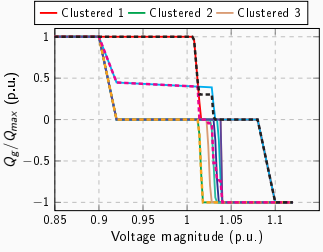


Clustering of the curves

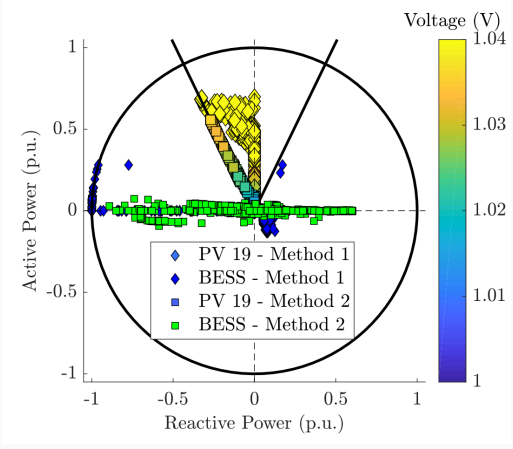
- For each voltage value, use k-means algorithm to the n individual curves (use the centroids of the n_{cl} clusters to form the final clustered curves)
- Assign DGs to clustered curves based on "distance"



Optimised local control schemes

Support Vector Regression for BESS

- Simple and efficient (R, sklearn, MATLAB, etc.)
- Impose monotonicity and slope constraints (e.g., monotone kernel regression methods)
- Implicit mapping via kernels (Linear, Polynomial, Gaussian)



Optimised local control schemes

Support Vector Machines as classifier for controllable loads

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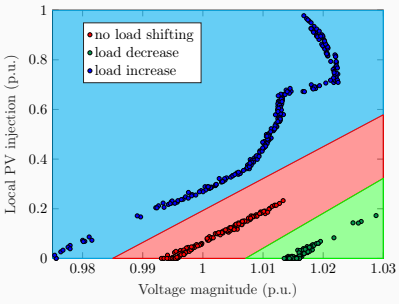
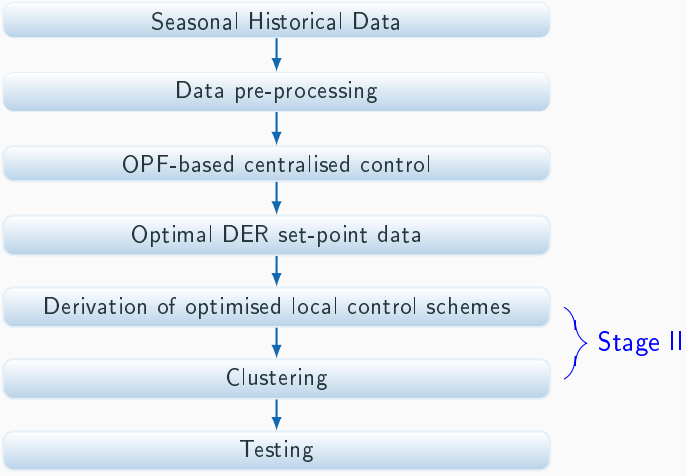


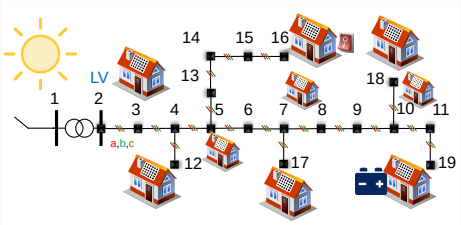
Methodology overview



Methodology overview

Stage III

Test system



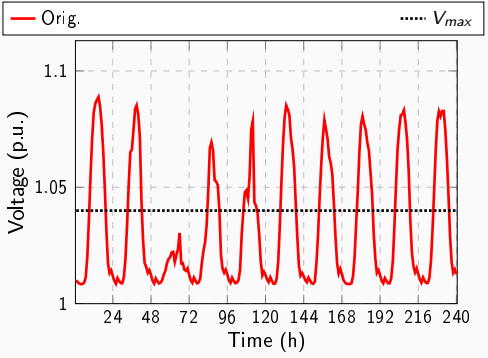
Control actions

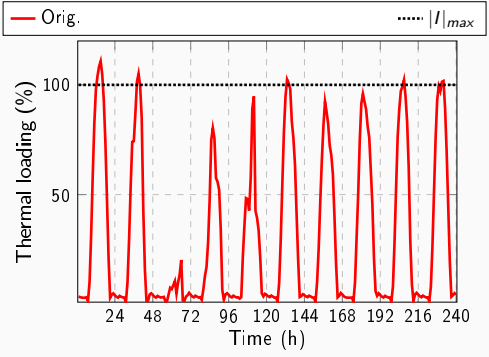
- Active Power Curtailment (APC)
- Reactive Power Control (RPC)
- Battery Energy Storage System (BESS)
- Controllable load (CL)
- On Load Tap Changers (OLTC)

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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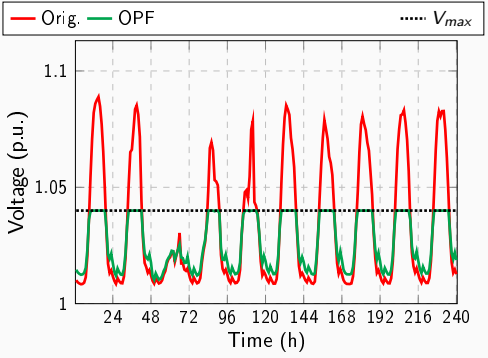

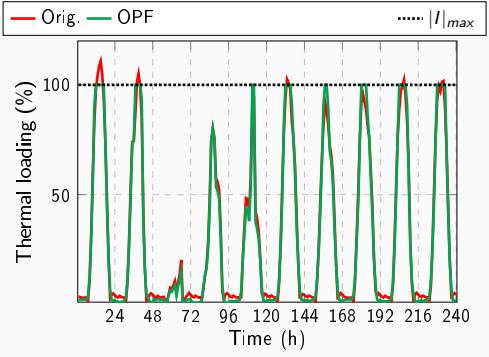

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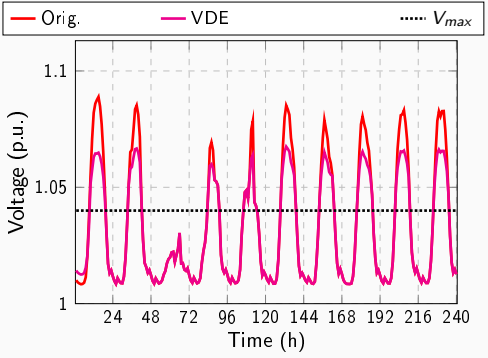

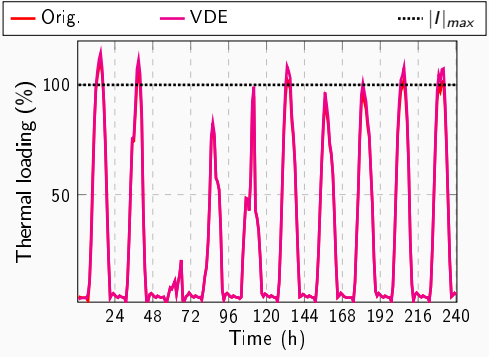

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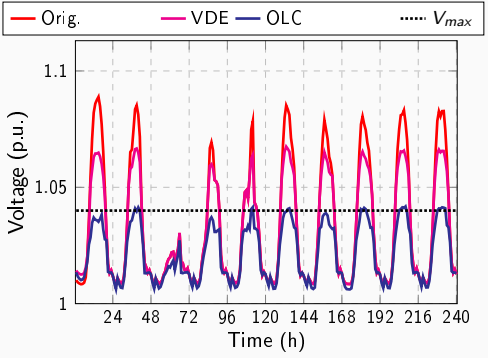

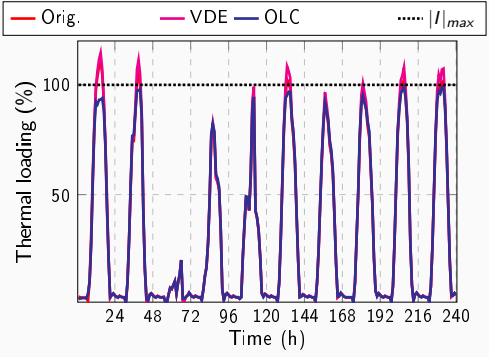

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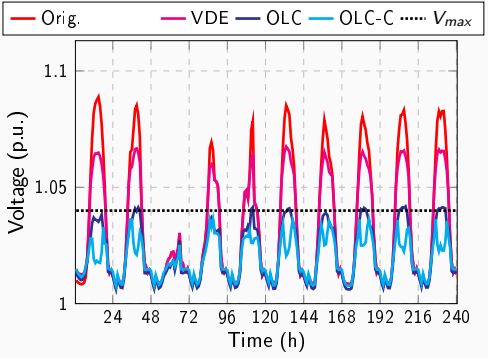
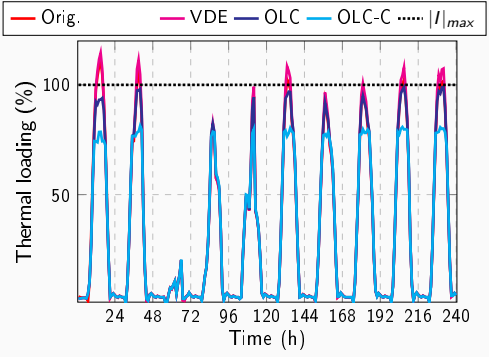
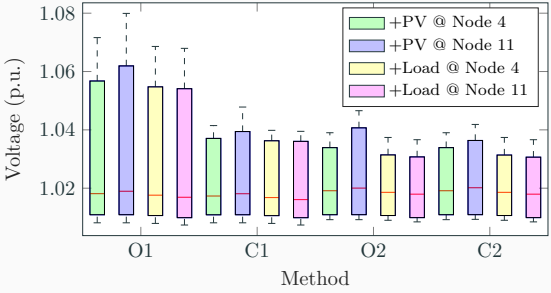




How will the schemes operate in 'unseen' conditions?

Open (O) vs. Closed (C) loop

- **O1**: VDE rule based on P_{PV}
- **C1**: Characteristic curves based on V
- **O2**: Regression based on P_L, Q_L, P_{PV}, Q_{max}
- **C2**: Regression based on V, P_L, Q_L, P_{PV}, Q_{max}



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Data-driven optimised local controllers can bridge the gap

Future steps

- Investigate different ML techniques to capture more complex behaviour
- Extend to multiple local "features" and historical "features"
- Experimental validation (NTUA Greece HIL testing)


Questions?