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

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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.
Real-time operation

Distribution grid control approaches

- **Local**
  - Only local measurements and decisions
  - No communication
  - Lower cost and more robust
  - "One size fits all"

- **Distributed**
  - Local measurements and decisions
  - Some communication still needed

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

Analytical & Machine learning

- Optimal set-point data
- Optimised local control schemes
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Optimised local control schemes

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Analytical & Machine learning
Optimised local control
Methodology overview

Operational planning problem with OPF-based centralised control

Stage I
Methodology overview

Operational planning problem with OPF-based centralised control

Optimal DER set-point data

Stage I

Stage II

Stage III
Methodology overview

Operational planning problem with OPF-based centralised control → Optimal DER set-point data → Data pre-processing → Derivation of optimised local control schemes → Clustering

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Operational planning problem with centralised control

Multi-period OPF problem formulation

$$\min_u \sum_t (c_{op}^T u + c_{el}^T \text{losses}) \Delta t$$

$u$:

- Active power curtailment (APC)
- Reactive power control (RPC)
- Battery Energy Storage Systems (BESS)
- Controllable loads (CLs)
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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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- Non-convex and non-linear
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AC power-flow constraints

- Non-convex and non-linear
  - Backward/Forward Sweep (BFS) power flow (Fortenbacher et al. 2016)
    ▶ Iterative procedure
    ▶ Exploit the radial grid structure
    ▶ Weakly meshed treatment
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AC power-flow constraints

- Non-convex and non-linear
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    - Iterative procedure
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    - Weakly meshed treatment

- Use a single BFS iteration for the OPF problem
Operational planning problem with centralised control

Initialize:
\[ k = 0, \ V_{\text{bus}}^0 = 1.0 \angle 0^\circ \]
\[ m = 1, \ \Omega_{m-1} = \Omega_{m-1}^0 = 0 \]

Run multi-period OPF with one BFS iteration

Run complete power flow solution

\[ \max(|V_{\text{bus}}| - |V_{PF_{\text{bus}}}|) \leq \tilde{\eta} \]

Evaluate \( \Omega_m V_i \), \( \Omega_m I_{br} \) and check tightenings

\[ \max(|\Omega_m V_i| - |\Omega_{m-1} V_i|) \leq \eta \Omega \]
\[ \max(|\Omega_m I_{br}| - |\Omega_{m-1} I_{br}|) \leq \eta \Omega \]

Stop

Yes

No

Multi-period BFS-OPF

Operational planning problem with centralised control

Tackling Uncertainty

• Branch current flows and voltages are functions of the power injections and are hence influenced by renewable generator & load power uncertainty
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Formulation of Chance Constraints

\[
\mathbb{P}\{|V_{bus,j,t}| \leq V_{\text{max}}\} \geq 1 - \varepsilon \\
\mathbb{P}\{|V_{bus,j,t}| \geq V_{\text{min}}\} \geq 1 - \varepsilon \\
\mathbb{P}\{|I_{br,i,t}| \leq I_{\text{i,max}}\} \geq 1 - \varepsilon
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**Reformulate into deterministic constraints through “tightenings”**

\[
V_{\text{min}} + \Omega_{V,j,t}^{\text{lower}} \leq \left| V_{bus,j,t} \right| \leq V_{\text{max}} - \Omega_{V,j,t}^{\text{upper}}
\]

\[
\left| I_{br,i,t} \right| \leq I_{i,max} - \Omega_{br,i}^{k}\]

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Operational planning problem with centralised control

Uncertainty margins evaluation

• Analytical approach → 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 $\varepsilon$ calculation

Operational planning problem with centralised control

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Stop

Yes

No

Multi-period BFS-OPF
Operational planning problem with centralised control

**Initialization:**
- \( k = 0, \ V_{bus}^k = 1 \angle 0^\circ \)
- \( m = 1, \ \Omega_{m-1}^{m-1} = \Omega_{m-1}^{m-2} = 0 \)

Run multi-period OPF with one BFS iteration

Run complete power flow solution

\[
\max |(|V_{bus}^k| - |V_{bus}^{PF}|)| \leq \tilde{\eta}
\]

Evaluate \( \Omega_m^{m}, \Omega_m^{m-1}, \Omega_m^{m-1} \) and check tightenings

\[
\max |\Omega_{m}^m - \Omega_{m-1}^{m-1}| \leq \eta^\Omega
\]
\[
\max |\Omega_{m-1}^{m-1} - \Omega_{m-2}^{m-2}| \leq \eta^\Omega
\]

Stop

**Multi-period BFS-OPF**

**Uncertainty tightenings**

Case Study
Introduction
POSITIVE SEQUENCE only

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

![Graph showing voltage (p.u.) over time (h)]

<table>
<thead>
<tr>
<th>Time (h)</th>
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</tr>
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<tbody>
<tr>
<td>24</td>
<td>1</td>
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<tr>
<td>48</td>
<td>1.05</td>
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<tr>
<td>72</td>
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- Orig.
- \( V_{max} \)
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<td>Orig.</td>
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</tr>
<tr>
<td>OPF</td>
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<td></td>
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The graph shows the voltage (p.u.) over time, with red representing Orig., green representing OPF, and a dotted line indicating $V_{max}$. The voltage fluctuates periodically, with peaks and troughs at specific time intervals.
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Stage I
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Local control schemes

Existing local control schemes

- Usually all DERs of same type and similar size have the same curve.
Local control schemes

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• Several types, usually: $Q = f(V)$, $\cos \phi = f(P)$, $P_{curt} = f(V)$
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Optimised local control schemes
- Customised local control scheme for each unit based on data from the previous stage
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- Simple and efficient (R, sklearn, MATLAB, etc.)
- Challenges
  - Breakpoint selection
  - Impose monotonicity and slope constraints
Optimised local control schemes

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- Challenges
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  - Sensitivity to outliers
  - Prone to overfitting
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
Optimised local control schemes

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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”
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- Orig.
- OPF
- $V_{max}$

The graph shows the voltage profile over time, with "Orig." and "OPF" indicating the original and optimal power flow, respectively.
## Some results

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Voltage (p.u.)

- **Orig.**
- **VDE**
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The diagram shows the voltage over time for different scenarios, including the original (Orig.), VDE, OLC, and OLC-C methods, with the maximum voltage level marked as $V_{max}$. The voltage values are indicated at specific time intervals.
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Legend:
- Orig.
- VDE
- OLC
- OLC-C
- $V_{max}$
Concluding remarks
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• Lack monitoring, communication, and control infrastructure
Concluding remarks

- Most of the new *Smart Grid-driven* developments are located in distribution grids
- Lack *monitoring*, *communication*, and *control* infrastructure
- **Centralised** controllers have great performance but high cost and robustness concerns
- **Local** controllers are robust and low cost but cannot cope with modern challenges

Future steps

- Investigate different ML techniques and extend to multiple local features
- Experimental validation (EMP A, Zurich)
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• Lack monitoring, communication, and control infrastructure
• Centralised controllers have great performance but high cost and robustness concerns
• Local controllers are robust and low cost but cannot cope with modern challenges

Data-driven optimised local controllers can bridge the gap
Concluding remarks

- Most of the new Smart Grid-driven developments are located in distribution grids
- Lack monitoring, communication, and control infrastructure
- Centralised controllers have great performance but high cost and robustness concerns
- Local controllers are robust and low cost but cannot cope with modern challenges

Data-driven optimised local controllers can bridge the gap

Future steps

- Investigate different ML techniques and extend to multiple local “features”
- Experimental validation (EMPA, Zurich)
Questions?