Data-driven Security Constrained OPF

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Center for Electric Power and Energy (CEE)

- **Established 15 August 2012** by merging two existing units (Lynbgy + Risø)
  - Among the strongest university centers in Europe with approx. 100 employees

- **Bachelor and Master programs:** Sustainable Energy Design, Electrical Engineering, Wind Energy, Sustainable Energy

- **Direct support from:** Energinet, Siemens, Ørsted (DONG Energy), Danfoss

  *DTU consistently ranks among the top 10 universities of the world in Energy Science and Engineering (Shanghai ranking, 2016, 2017, 2018)*
Research themes in line with today’s needs

**Digital Energy Solutions**
- New business models
- Data-driven solutions
- Digital solutions in grids
- System operation tools

**Interconnected Energy System**
- Multi energy carriers
- Smart energy in cities
- Markets and flexibility
- HVAC/HVDC grids

**Optimised Electric Energy Technologies**
- Novel equipment concepts
- Electric vehicle integration
- Prosumer solutions
- Cost-effective wind power
Towards a fully controllable system

Enhancing Stability

Market design

Advanced computational methods

Data-driven approaches

Convex approximations for chance-constrained OPF

Convex relaxations and recovery of the global optimum

Data-driven and HVDC Control Methods to Enhance Power System Security

MultiDC
Robust Control for Near-Zero Inertia Systems

MultiDC
Market Integration of HVDC

Data-driven security and optimization of AC and HVDC Grids
Data-Driven Security Constrained OPF

work with:
Lejla Halilbasic, Florian Thams, Andreas Venzke
The feasible space of power system operations

- Nonlinear and nonconvex AC power flow equations
- Component limits
The feasible space of power system operations

- Nonlinear and nonconvex AC power flow equations
- Component limits
  + Stability limits
The feasible space of power system operations

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- Other security criteria (e.g., N-1)
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- Component limits
  + Stability limits
  + Other security criteria (e.g., N-1)
  + Uncertainty $\xi$ in nodal power injections
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The feasible space of power system operations

- Nonlinear and nonconvex AC power flow equations
- Component limits
  - Stability limits
  - Other security criteria (e.g., N-1)
- Uncertainty $\xi$ in nodal power injections
Operational Challenges

- Identifying the boundary of the feasible operating region
- Incorporating the boundary in an optimization framework
- Finding the true optimal solution & maintaining computational efficiency
How to encode **feasible operating region** for electricity markets?

Security considerations live in AC space, but market is based on DC approximations!
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Traditionally, TSOs define Net-Transfer Capacities
How to encode **feasible operating region** for electricity markets?

Security considerations live in AC space, but market is based on DC approximations!

Traditionally, TSOs define **Net-Transfer Capacities**

![Diagram](image-url)
Better but reality of power system operations is nonconvex!

Improvements with Flow-Based Market Coupling but still convex!
What we work on

- **Data** to approximate boundary of N-1 secure and small-signal stable space

- **Mixed Integer Convex Programming** to integrate N-1 & stable space in optimization framework

- **Relaxations and approximations of chance-constrained AC-OPF** to account for uncertainty
We need data!

• We need data that accurately capture the whole security region
  – so that we can successfully use machine learning approaches for classification

• Historical data are insufficient
  – They contain very limited number of abnormal situations

• We need to generate simulation data

• Assessing the stability of 100’000s of operating points is an extremely demanding task
Efficient Database Generation

- Modular and highly efficient algorithm

- Can accommodate numerous definitions of power system security (e.g. N-1, N-k, small-signal stability, voltage stability, transient stability, or a combination of them)

- 10-20 times faster than existing state-of-the-art approaches

- Our use case: N-1 security + small-signal stability

- Generated Database for NESTA 162-bus system online available!
  
  https://osf.io/5nax8/  (~300,000 points)

Efficient Database Generation: Convex Relaxations and Directed Walks

- Convex relaxations to discard large infeasible regions
  - Certificate: if a point is infeasible for the semidefinite relaxation, it is infeasible for the original problem

1. Sample the search space:
   e.g. from \( P_{g,\text{min}} \) to \( P_{g,\text{max}} \) for all Gens

2. **If** a sample is infeasible:
   Find minimum radius of a (hyper)sphere around that point, that intersects with the feasible space of the semidefinite relaxation

3. Discard all points inside the hypersphere

- Convex optimization! And drastically reducing search space!
Efficient Database Generation: Convex Relaxations and Directed Walks

- “Directed walks”: steepest-descent based algorithm to explore the remaining search space, focusing on the area around the security boundary
  1. Variable step-size
  2. Parallel computation
  3. Steepest descent: sensitivity of damping ratio (small-signal stability)
  4. Exhaustive search of the space around security boundary
  5. Full N-1 contingency check
## Results

<table>
<thead>
<tr>
<th>Points close to the security boundary (within distance ( \gamma ))</th>
<th>IEEE 14-bus</th>
<th>NESTA 162-bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brute Force</td>
<td>100% of points in <strong>556.0 min</strong></td>
<td><em>intractable</em></td>
</tr>
<tr>
<td>Importance Sampling</td>
<td>100% of points in <strong>37.0 min</strong></td>
<td><strong>901 points</strong> in 35.7 hours</td>
</tr>
<tr>
<td>Proposed Method</td>
<td>100% of points in <strong>3.8 min</strong></td>
<td><strong>183’295 points</strong> in 37.1 hours</td>
</tr>
</tbody>
</table>

- Further benefits for the decision tree:
  - Higher accuracy
  - Better classification quality (Matthews correlation coefficient)

- Generated Database for NESTA 162-bus system online available! [https://osf.io/5nax8/](https://osf.io/5nax8/)
Data-driven security-constrained OPF

Offline security assessment

Database of stable and unstable OPs \( \{P, Q, V, \theta, \zeta\} \)

Decision Tree

Diagram showing stable and unstable regions in \( x^u \) and \( x_1 \) space.
Data-driven security-constrained OPF

Offline security assessment

Database of stable and unstable OPs \(\{P, Q, V, \theta, \zeta\}\) → Decision Tree

Partitioning the secure operating region
Data-driven security-constrained OPF

Offline security assessment

Database of stable and unstable OPs \{P,Q,V,\theta,\zeta\} \rightarrow \text{Decision Tree}

Partitioning the secure operating region
Data-driven security-constrained OPF

Database of stable and unstable OPs \( \{P, Q, V, \theta, \zeta\} \)

Decision Tree

Offline security assessment

Partitioning the secure operating region
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Database of stable and unstable OPs \{P, Q, V, θ, ζ\}

Decision Tree

Optimization

Integer Programming to incorporate partitions (DT)

- DC-OPF (MILP)
- AC-OPF (MINLP)
- Relaxation (MIQCP, MISOCP)
We gain \( \sim 22\% \) of the feasible space using data and Mixed Integer Programming.
MIP + convex AC-OPF approximation finds better solutions than nonconvex problem!

Optimum located at boundary of considered security region
Works also for DC-OPF (MILP): Market dispatch is N-1 secure and stable

Eliminate redispatching costs

- Redispatching costs: over 400 Million Euros in a year, just for Germany

- Data-driven SC-OPF for markets: DC-OPF becomes MILP
  - But, MILP is already included in market software (e.g. Euphemia, for block offers, etc.)
  - Efficient MILP solvers already existing
Works also for DC-OPF (MILP):
Market dispatch is N-1 secure and stable

Eliminate redispatching costs
### OPF under uncertainty

#### Approximations and relaxations of chance-constrained AC-OPF

<table>
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<tr>
<th>Semidefinite programming</th>
<th>Second-order cone programming</th>
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<tbody>
<tr>
<td>• Global optimality</td>
<td>• Ex-post feasibility recovery</td>
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<tr>
<td></td>
<td>• Computational efficiency</td>
</tr>
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<td></td>
<td>• Better approximations of confidence region</td>
</tr>
</tbody>
</table>

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OPF under uncertainty

Approximations and relaxations of chance-constrained AC-OPF

Second-order cone programming

\[
(I) \quad \tilde{y} = y + \frac{\partial y}{\partial \xi} \xi = Y\xi
\]

\[
\mathbb{P} \left( (P_l + Y_l^P \xi)^2 + (Q_l + Y_l^Q \xi)^2 \leq (S_l)^2 \right) \geq 1 - \epsilon
\]

(II)*

1. \( \mathbb{P} \left( |P_l + Y_l^P \xi| \leq k_l^P \right) \geq 1 - \beta_l \epsilon \\
2. \( \mathbb{P} \left( |Q_l + Y_l^Q \xi| \leq k_l^Q \right) \geq 1 - (1 - \beta_l) \epsilon \\
3. \( (k_l^P)^2 + (k_l^Q)^2 \leq (S_l)^2 \\

\beta_l \in (0,1) ensures \( \mathbb{P}((1) \cup (2)) \geq 1 - \epsilon \\

Convex AC-OPF approximation + separation of quadratic chance constraint finds better solutions than nonconvex problem!

Lower-cost region, where nonconvex CC-AC-OPF is more expensive!

Boundary of confidence region
Conclusions

• Framework for the tractable reformulation of security and uncertainty considerations, which ...  

... can be included in any optimization problem ...

... and leverages data analytics and convex relaxations & approximations to make larger regions of the feasible space accessible, while remaining computationally efficient
Interested in a PhD?

- Open position

- Topic: **Data-driven Security and Optimization for AC and HVDC Grids**

- Contact: [spchatz@elektro.dtu.dk](mailto:spchatz@elektro.dtu.dk)

- Deadline: December 15, 2018
Thank you!

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References:


