Data-driven Security Constrained OPF

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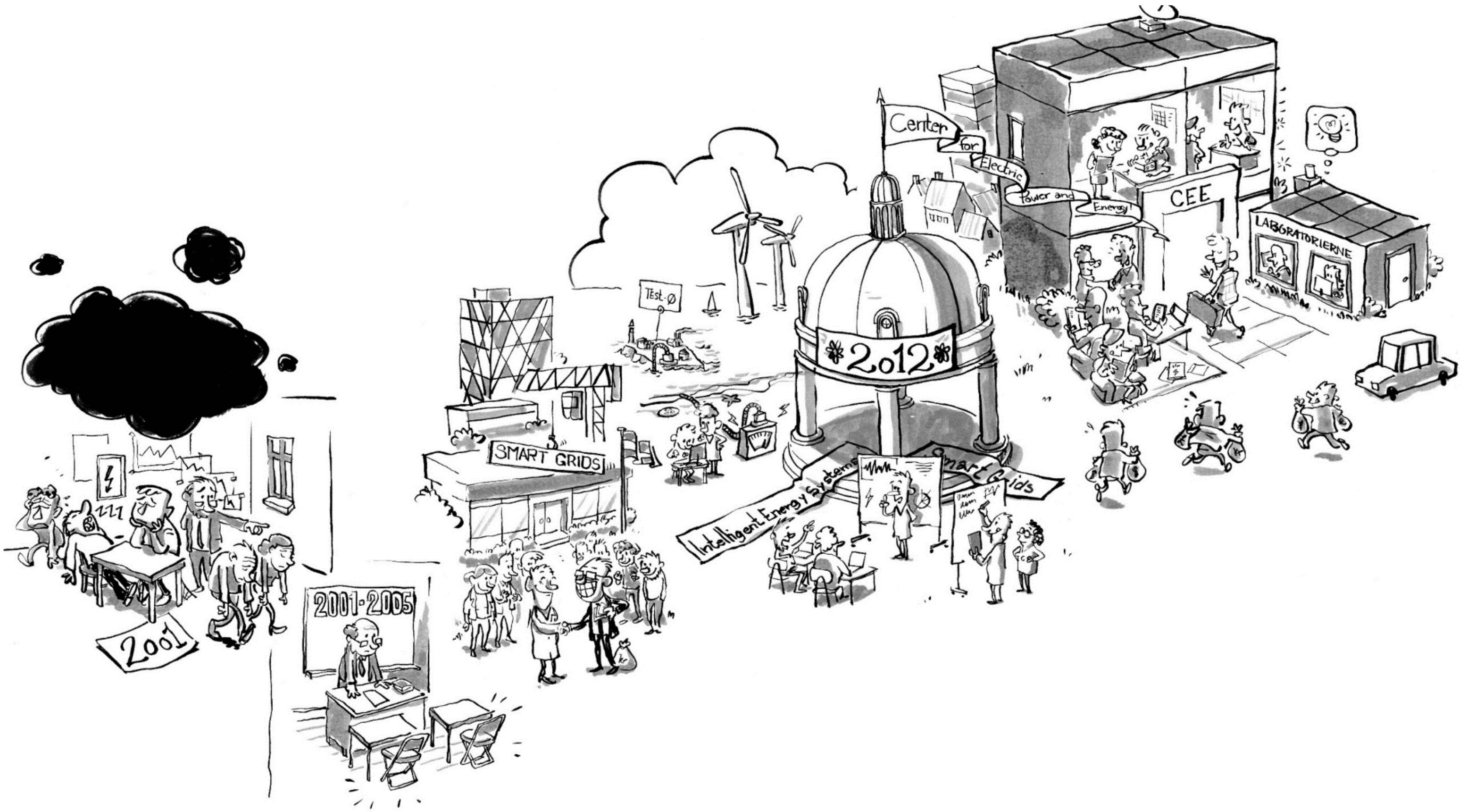
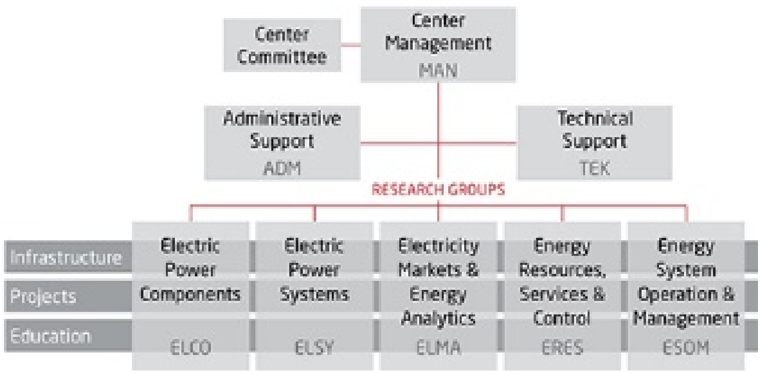


Center for Electric Power and Energy (CEE)

- **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

multiDC

Robust Control for Near-Zero Inertia Systems

Market design

multiDC

Market Integration of HVDC

Data-driven approaches

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

multiDC

Data-driven security and optimization of AC and HVDC Grids

?

Advanced computational methods

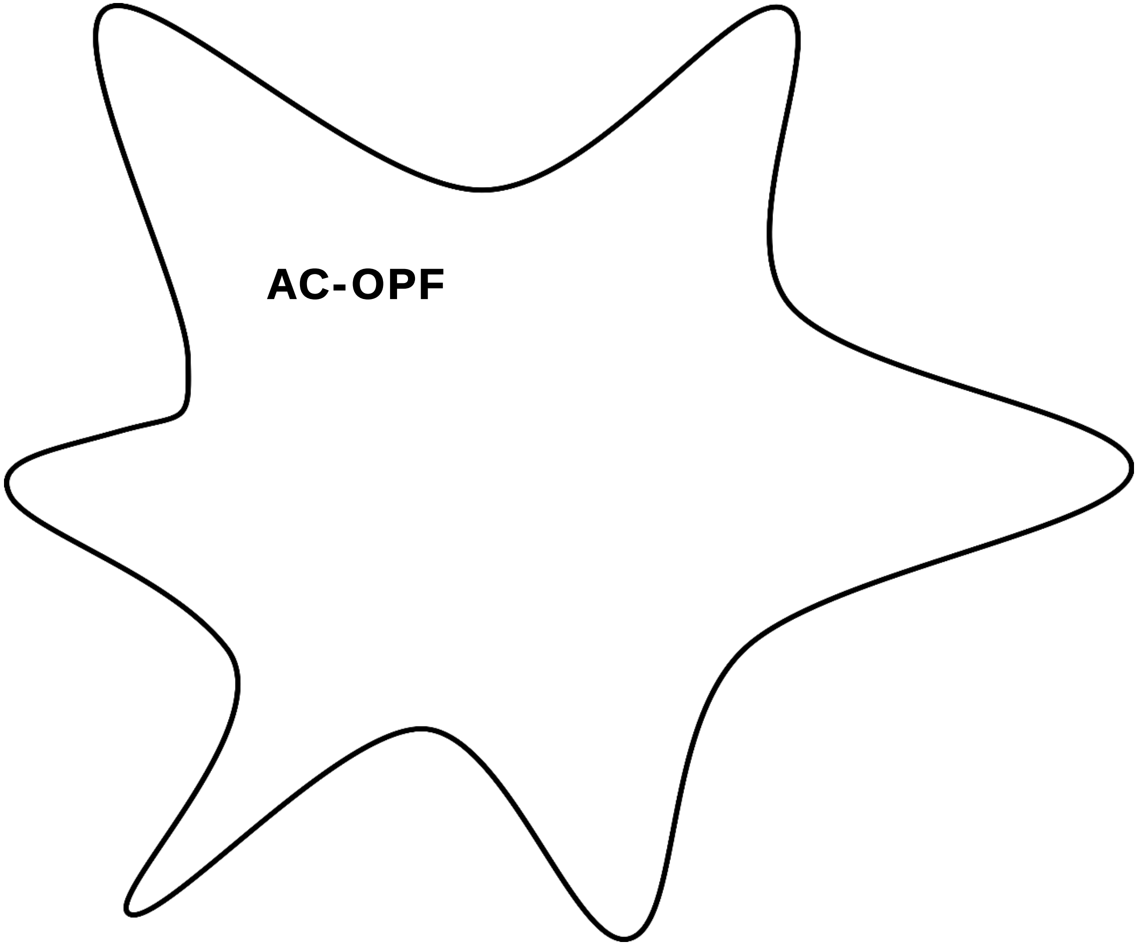
Convex approximations for chance-constrained OPF

Convex relaxations and recovery of the global optimum

Data-Driven
Security Constrained OPF

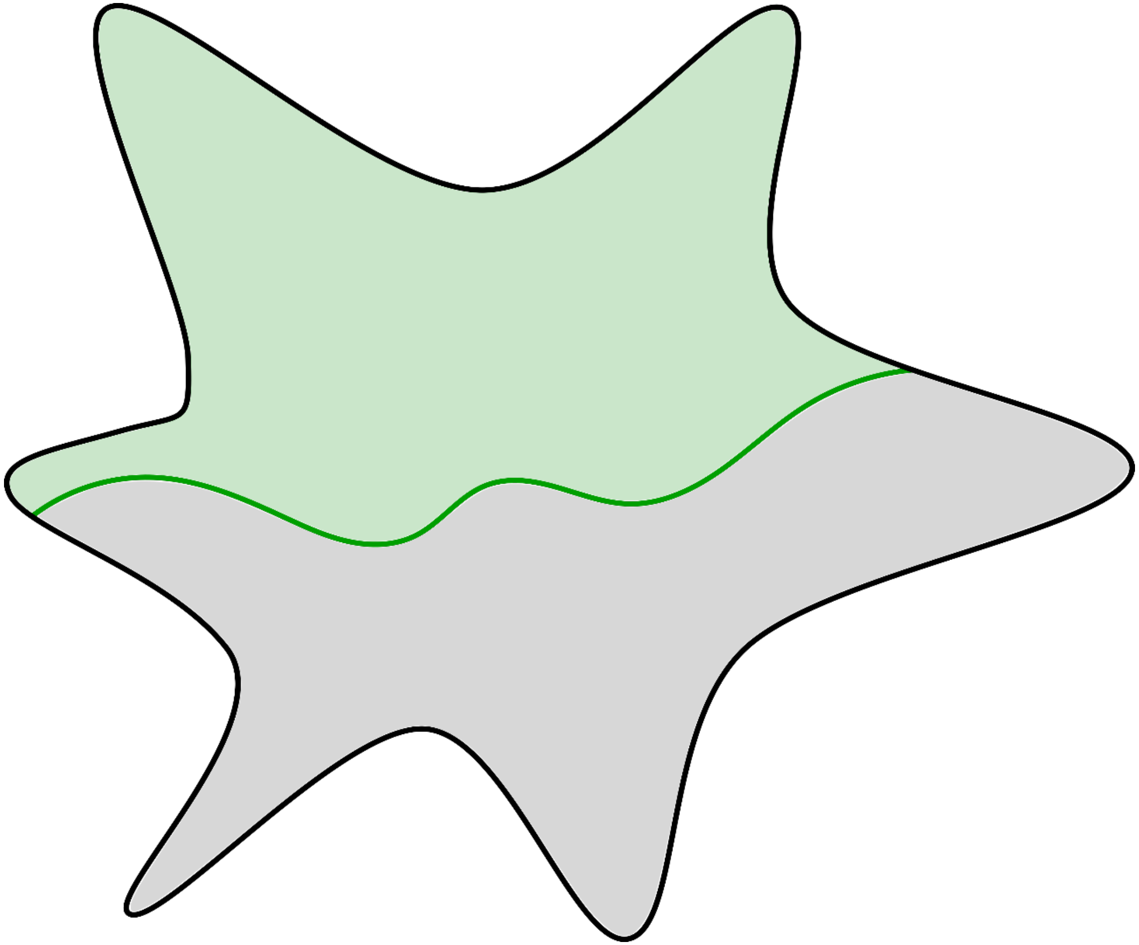
work with:
Lejla Halilbasic, Florian Thams, Andreas Venzke

The feasible space of power system operations



- Nonlinear and nonconvex AC power flow equations
- Component limits

The feasible space of power system operations



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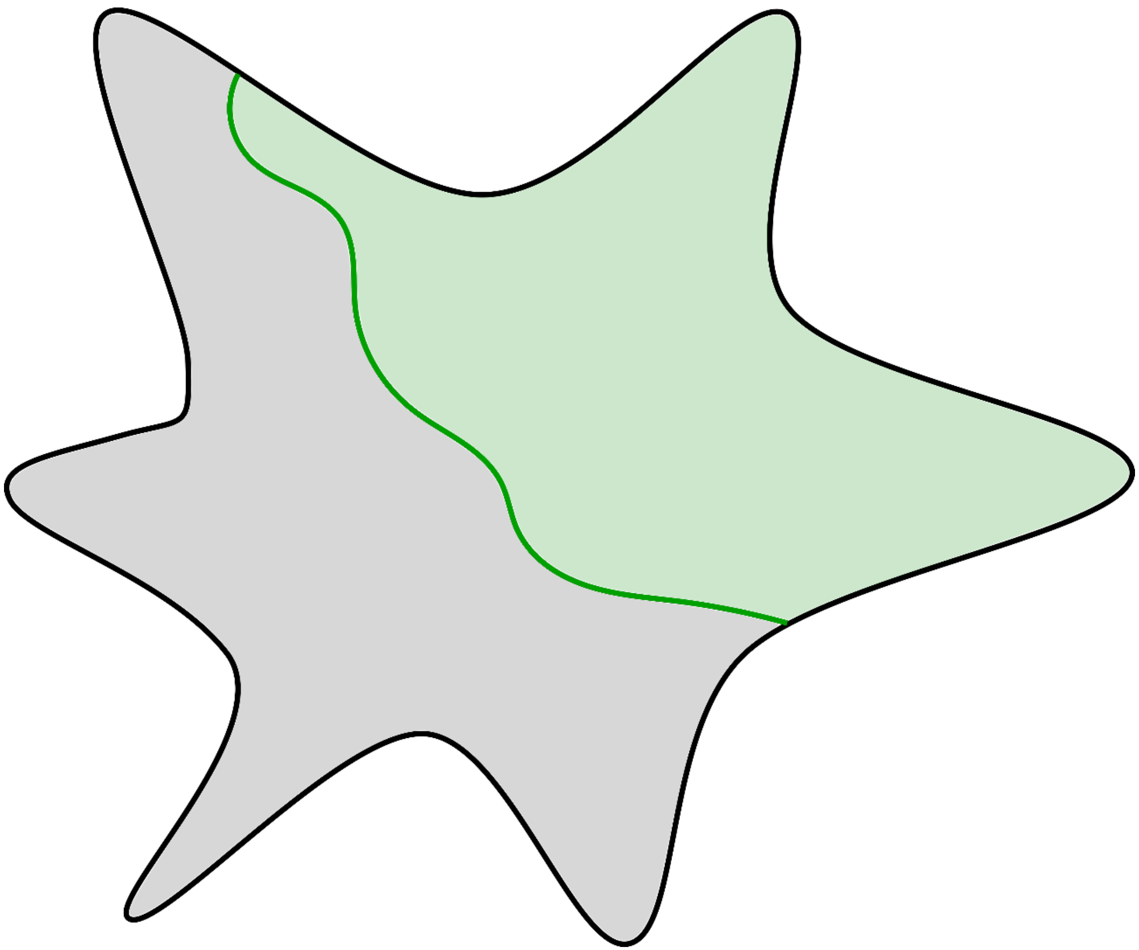

- Nonlinear and nonconvex AC power flow equations
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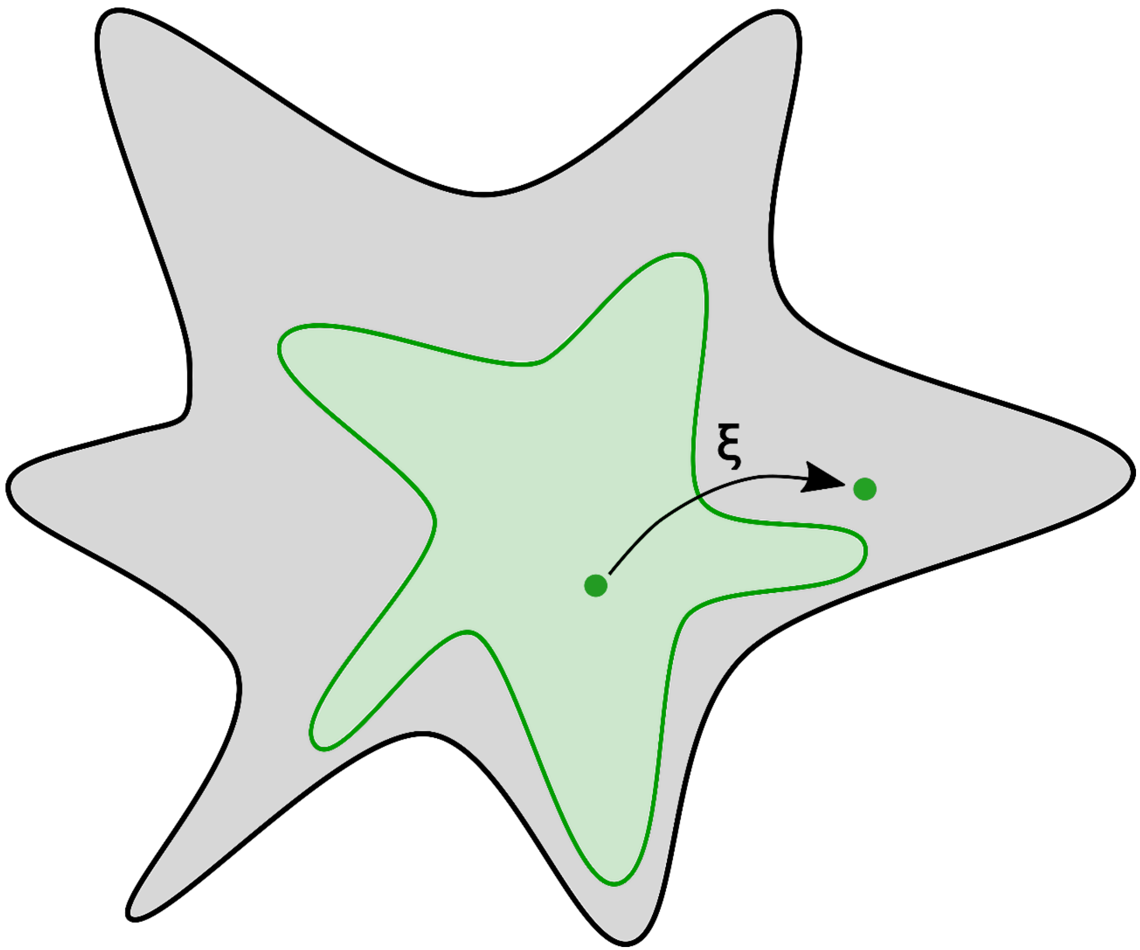
\+ Stability limits

\+ Other security criteria (e.g., N-1)

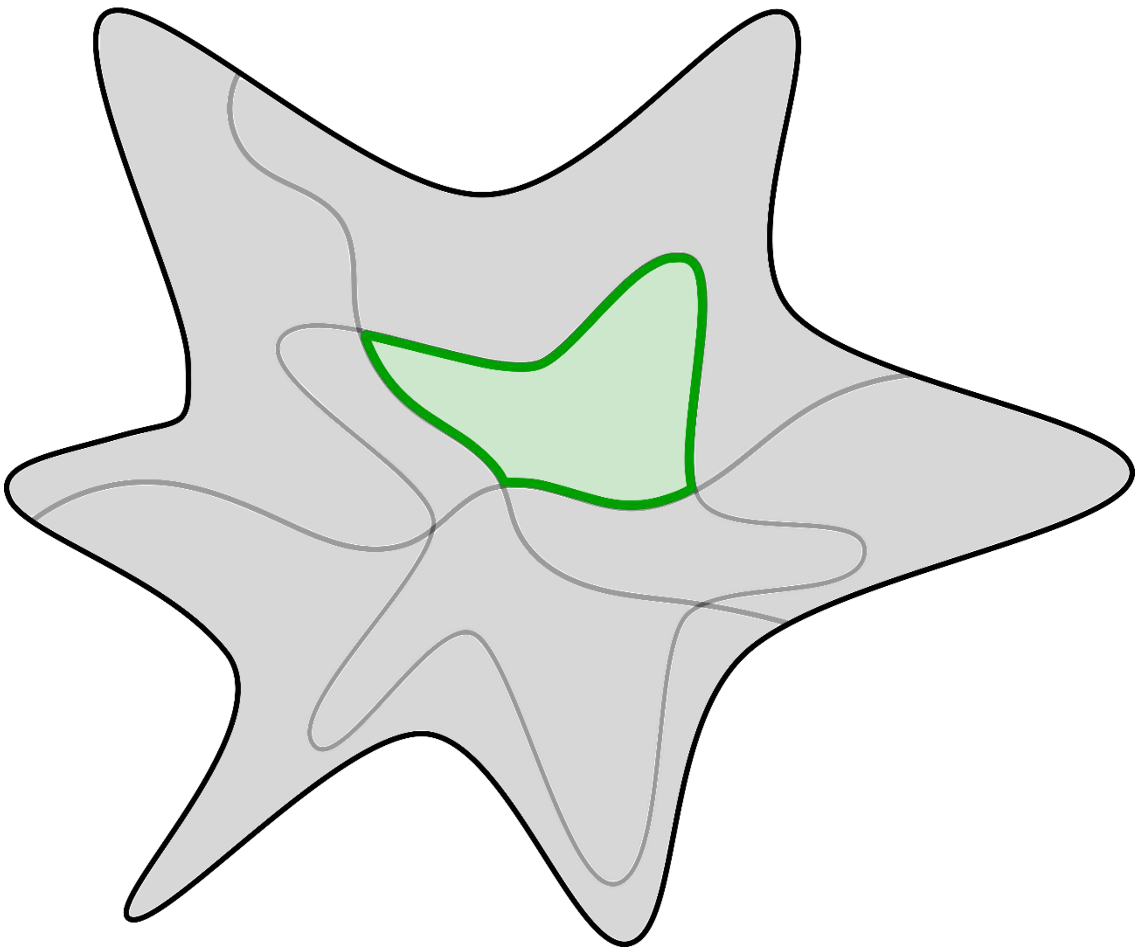
The feasible space of power system operations



- Nonlinear and nonconvex AC power flow equations
- Component limits

+ Stability limits
+ Other security criteria (e.g., N-1)
+ Uncertainty **ξ** in nodal power injections

The feasible space of power system operations



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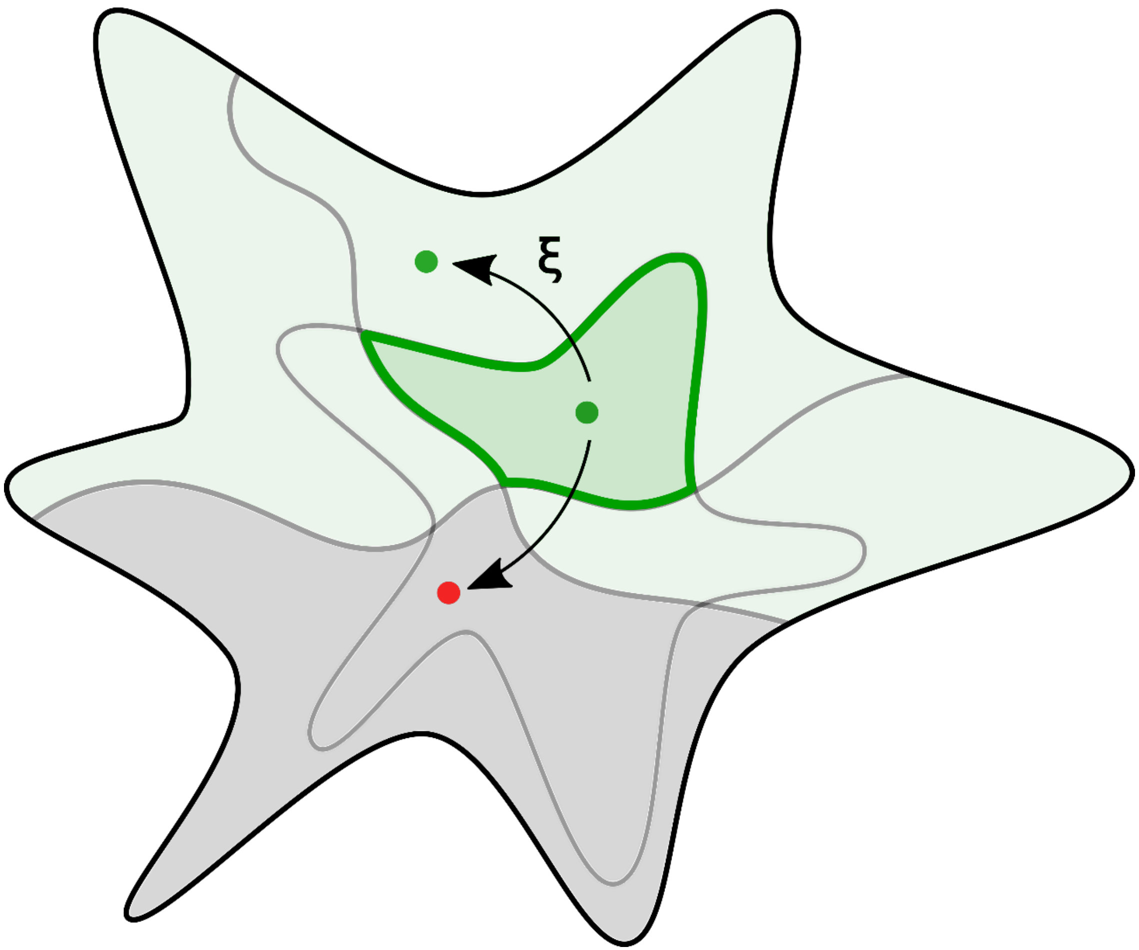


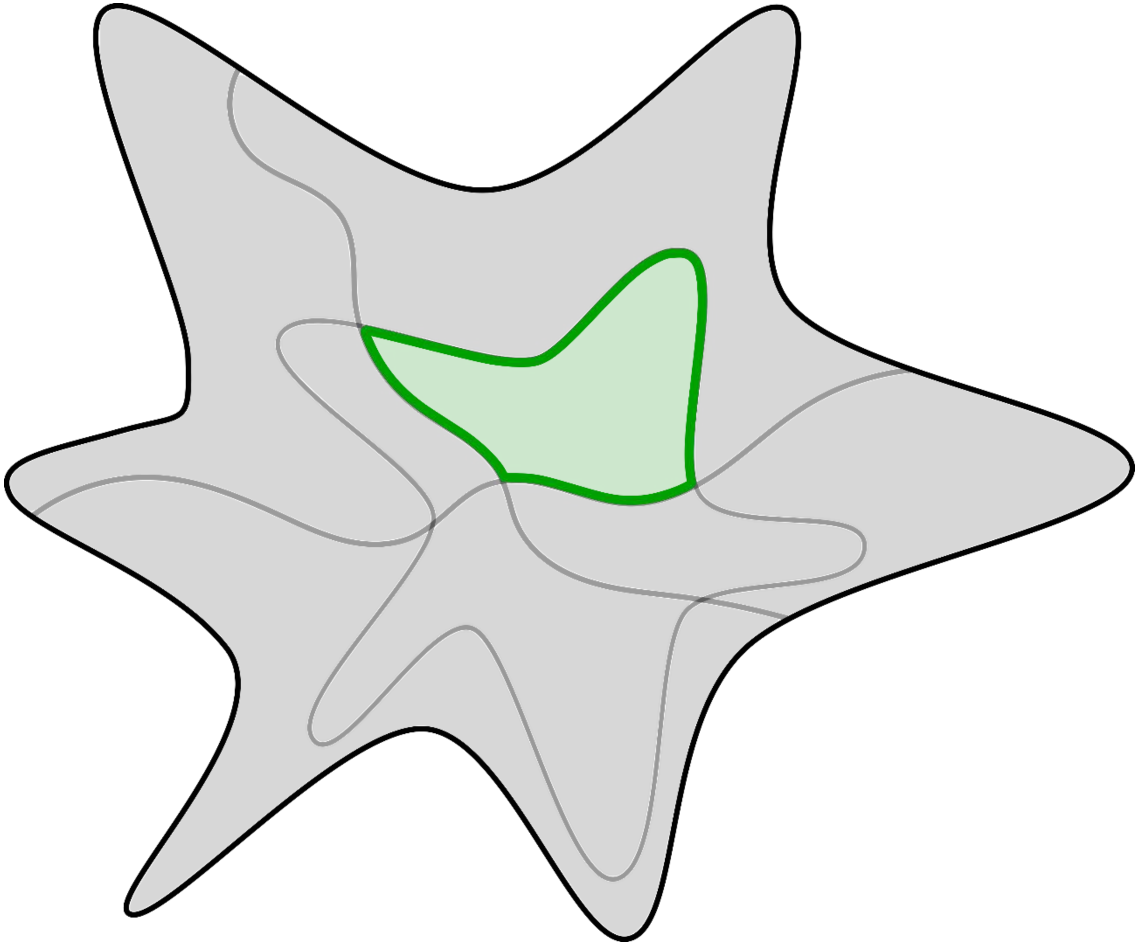
- Nonlinear and nonconvex AC power flow equations
- Component limits

\+ Stability limits

\+ Other security criteria (e.g., N-1)

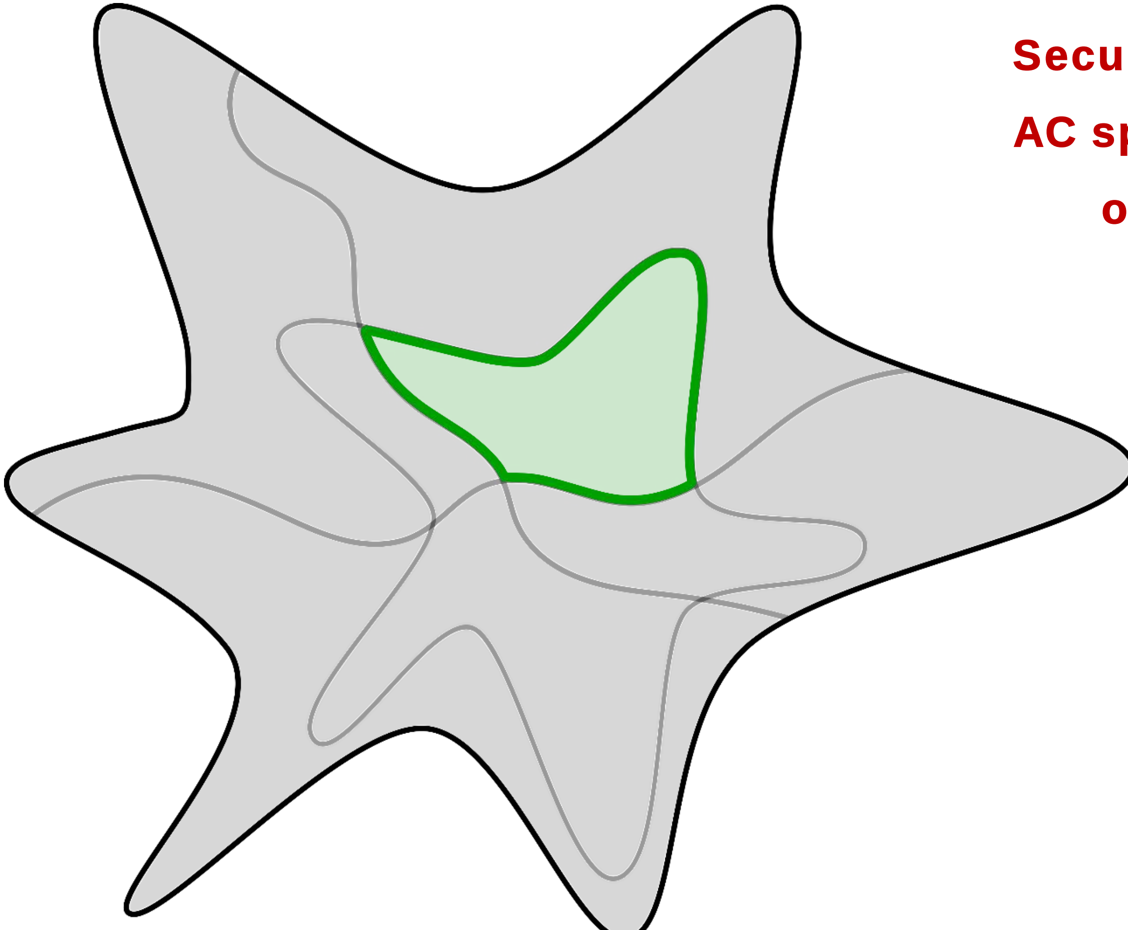
\+ Uncertainty **ξ** in nodal power injections

Operational Challenges



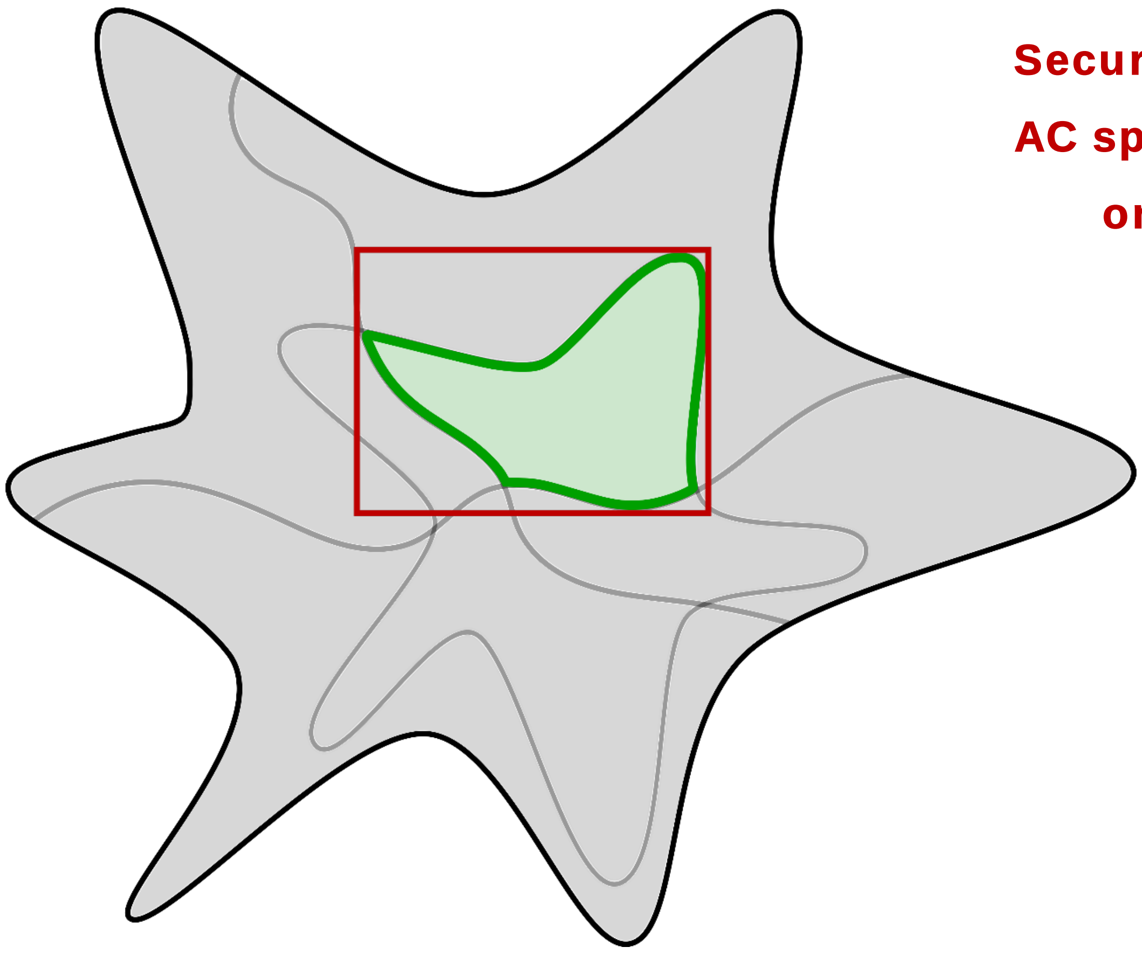
- Identifying the boundary of the feasible operating region
- Incorporating the boundary in an optimization framework
- Finding the true optimal solution & maintaining computational efficiency

How to encode feasible operating region for electricity markets?



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

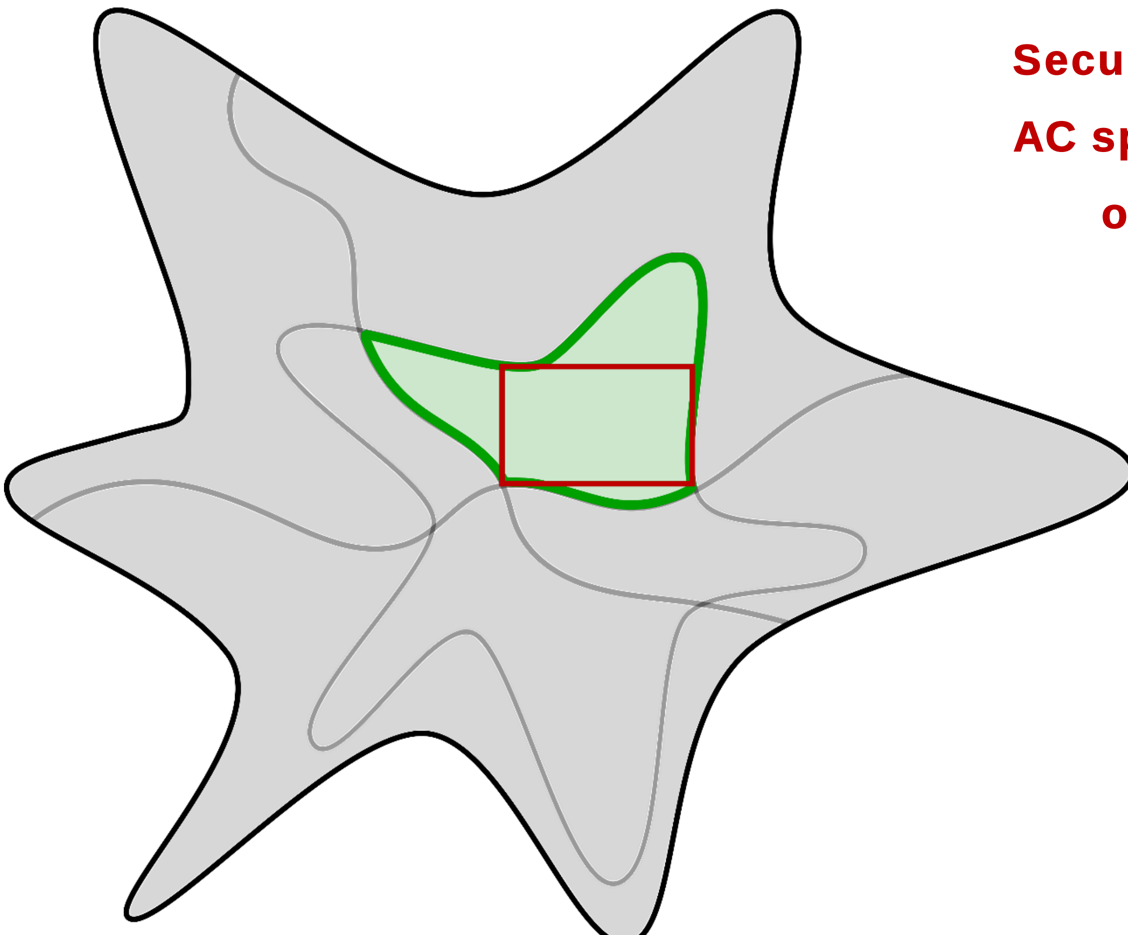
How to encode feasible operating region for electricity markets?



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

Traditionally, TSOs define Net-Transfer Capacities

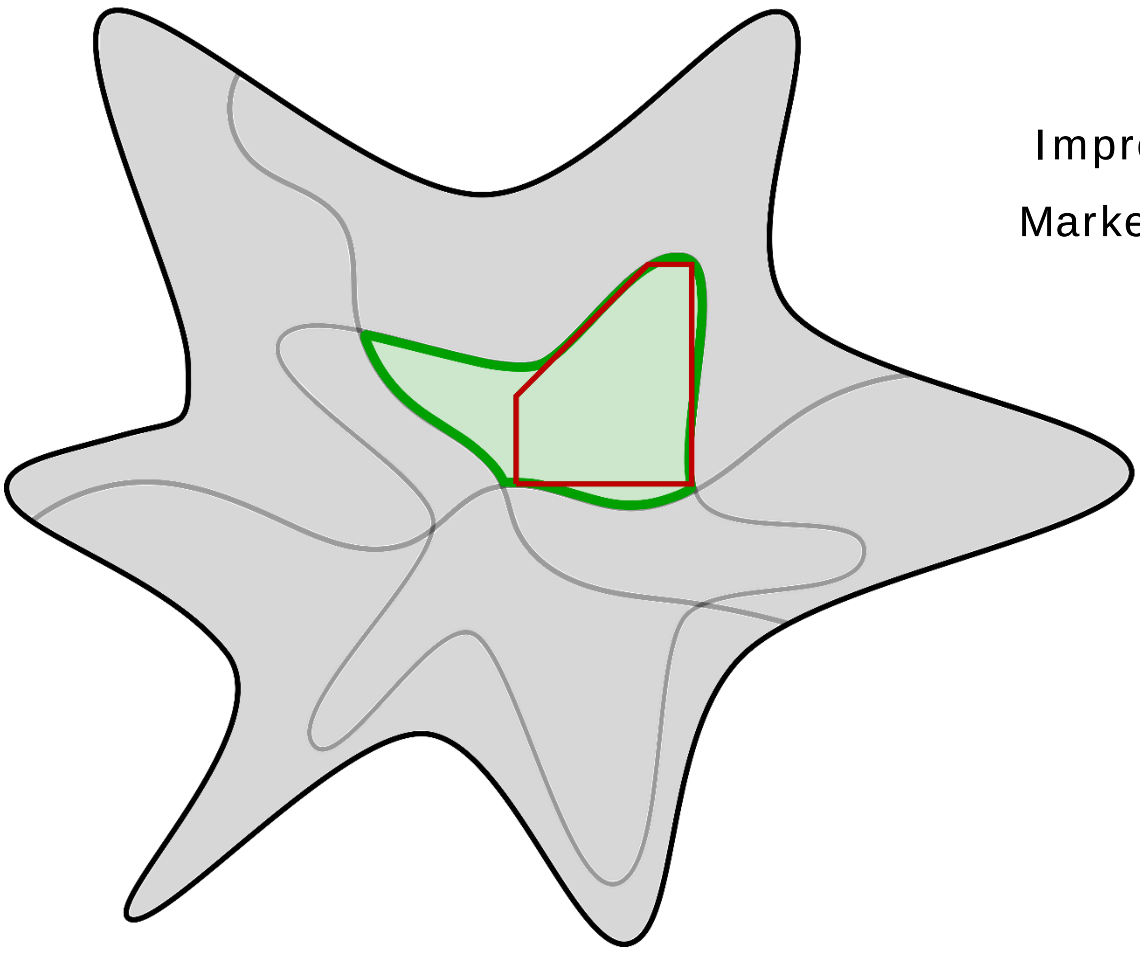
How to encode **feasible operating region** for electricity markets?



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

Traditionally, TSOs define Net-Transfer Capacities

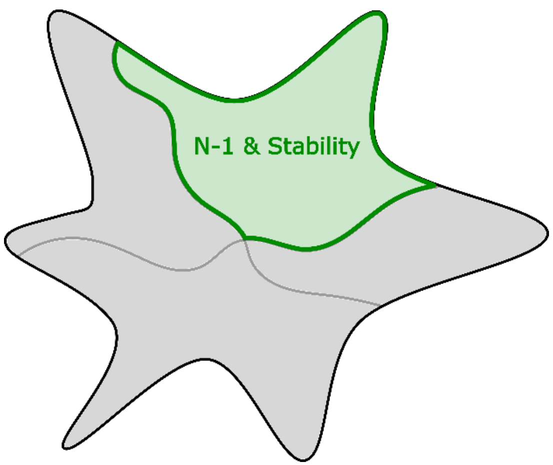
Better but reality of power system operations is nonconvex!

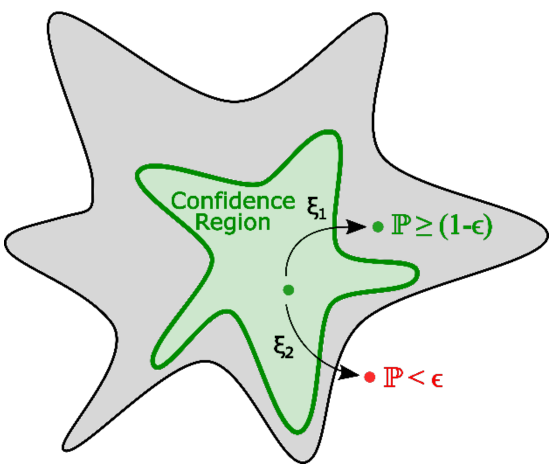


Improvements with Flow-Based

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

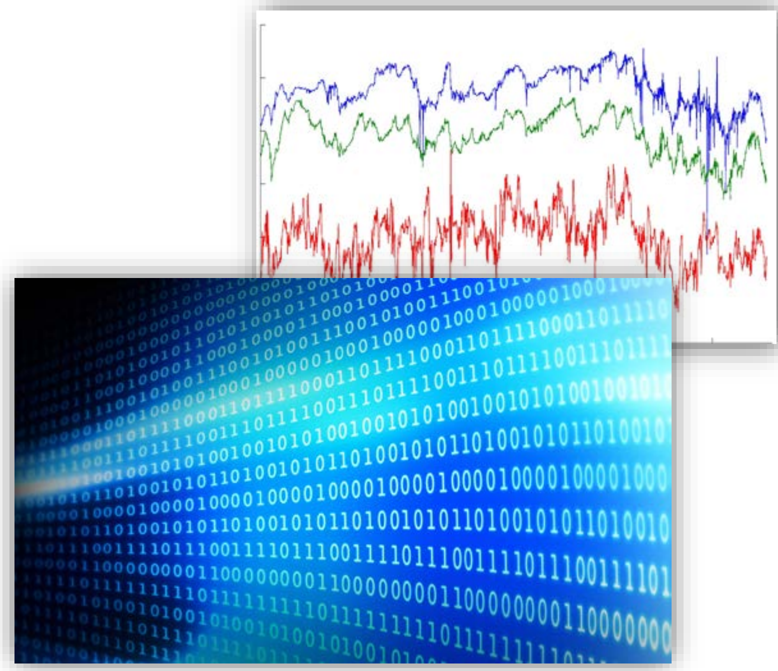
We need data!

- 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)

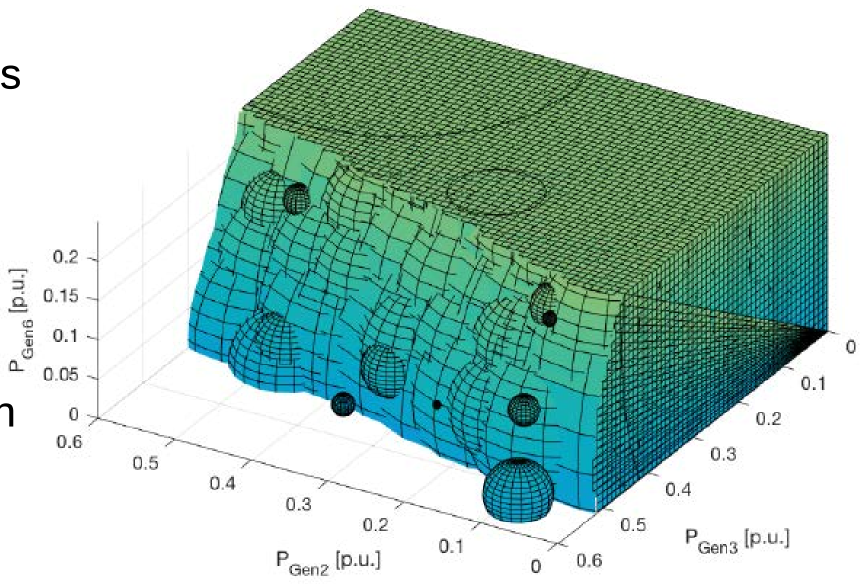
F. Thams, A. Venzke, R. Eriksson, and S. Chatzivasileiadis, "Efficient database generation for data-driven security assessment of power systems". https://www.arxiv.org/abs/1806.0107.pdf

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 $P_{g,min}$ to $P_{g,max}$ 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

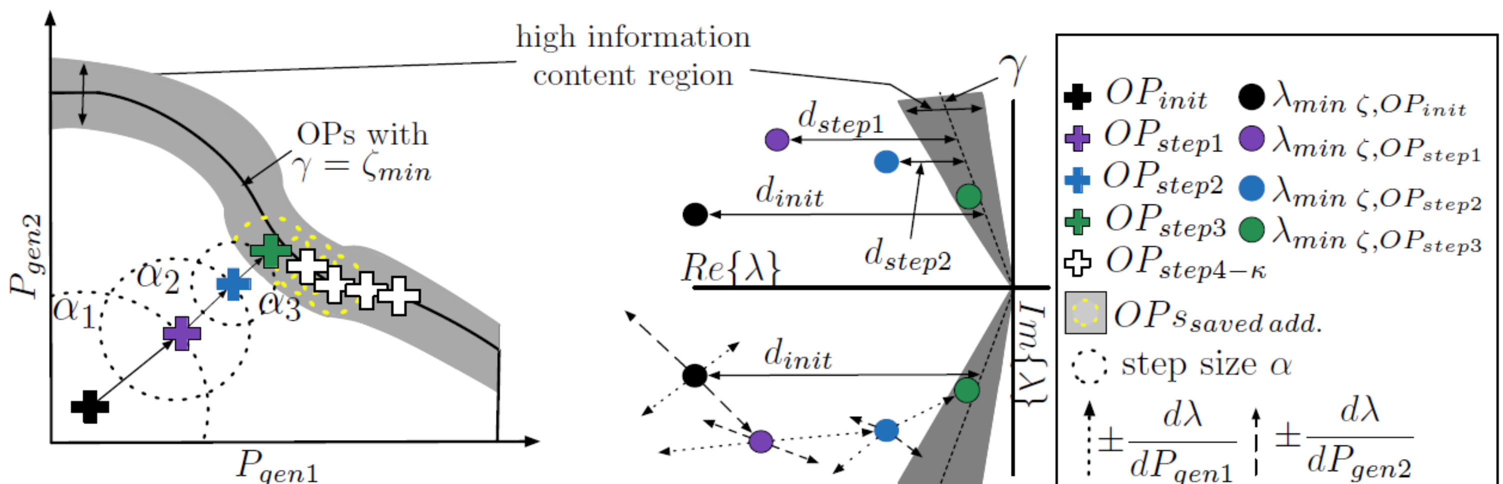


3. Discard all points inside the hypersphere

- 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



2-dim. subspace of multi-dim. space of potential generation patterns (remaining dim. held constant for illustration) | Eigenspace of all $\Gamma + 1$ analyzed systems (only lowest damped (pair) of eigenvalues of all systems shown)

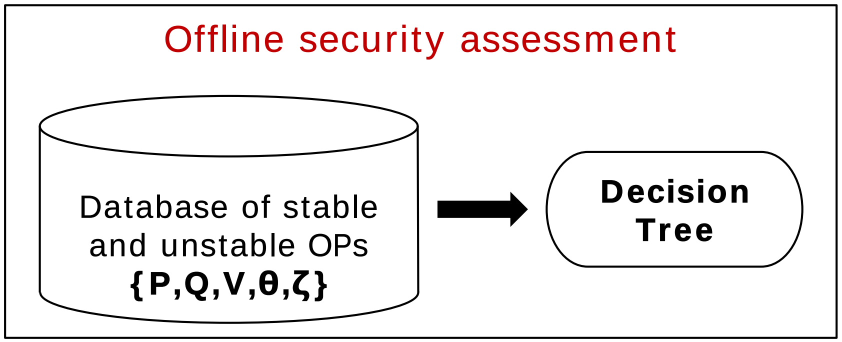
Results

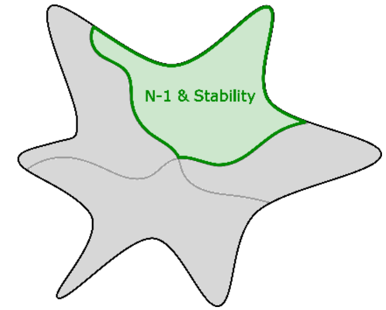
	Points close to the security boundary (within distance γ)	
	IEEE 14-bus	**NESTA 162-bus**
Brute Force	100% of points in **556.0 min**	*intractable*
Importance Sampling	100% of points in **37.0 min**	**901 points** in 35.7 hours
Proposed Method	100% of points in **3.8 min**	**183'295 points** in 37.1 hours

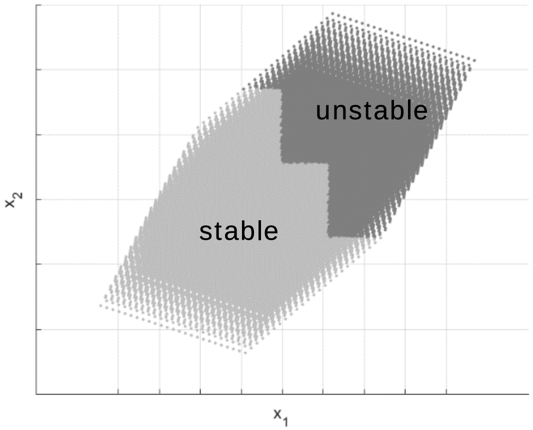
- Further benefits for the decision tree:
  - Higher accuracy
  - Better classification quality (Matthews correlation coefficient)

- Generated Database for NESTA 162-bus system online available! https://osf.io/5nax8/

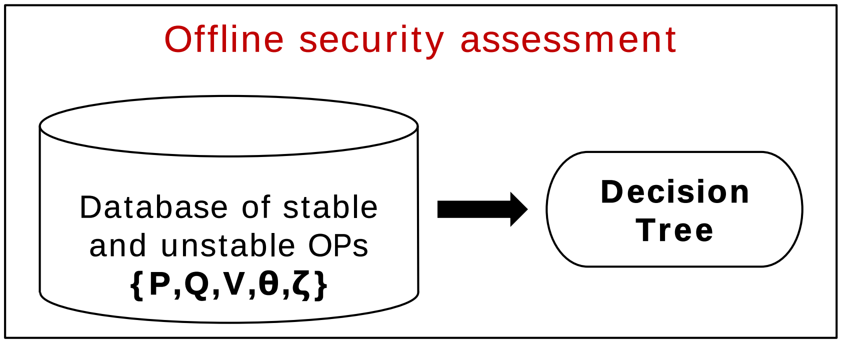
Data-driven security-constrained OPF

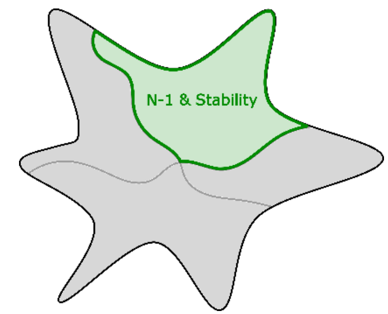




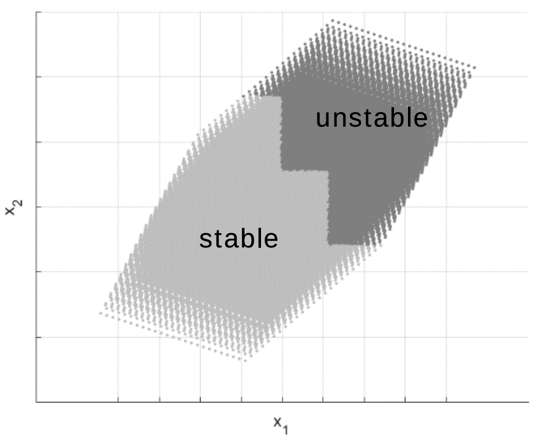


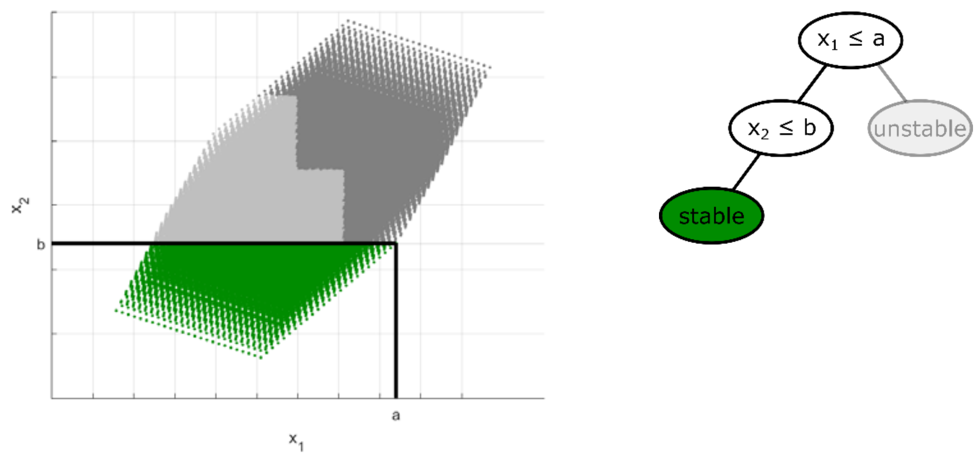
Data-driven security-constrained OPF





Partitioning the secure operating region





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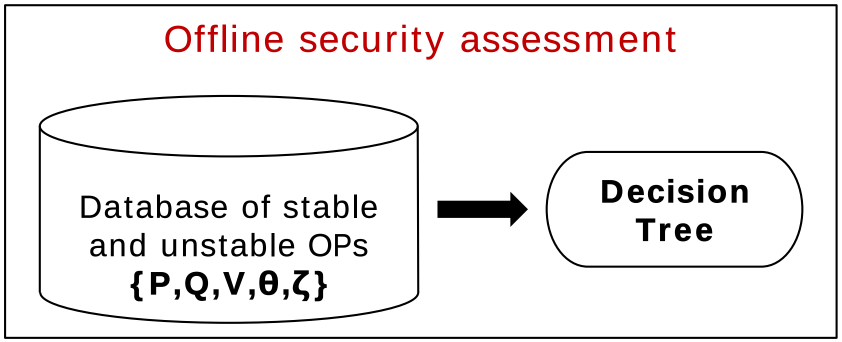

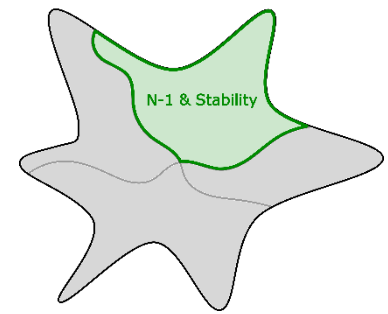

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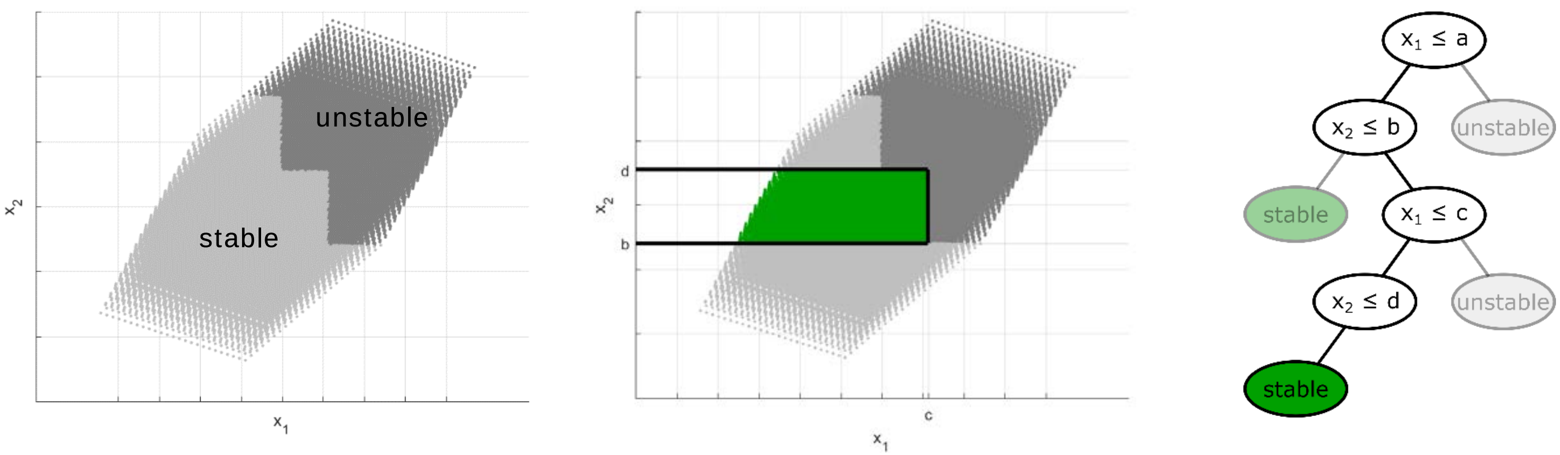

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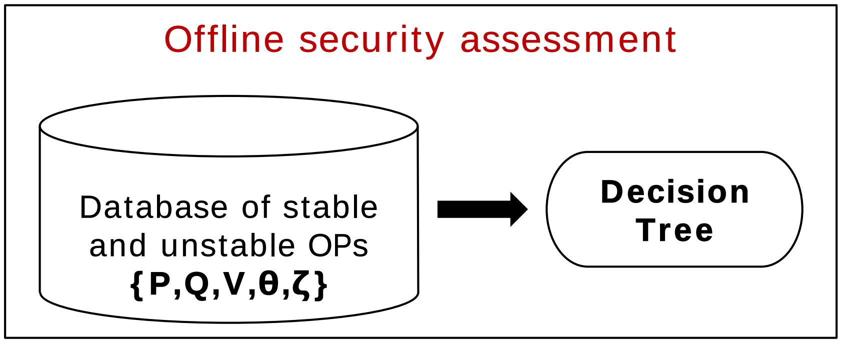

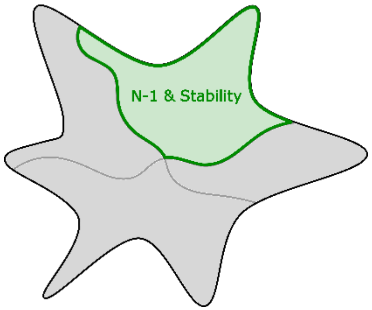

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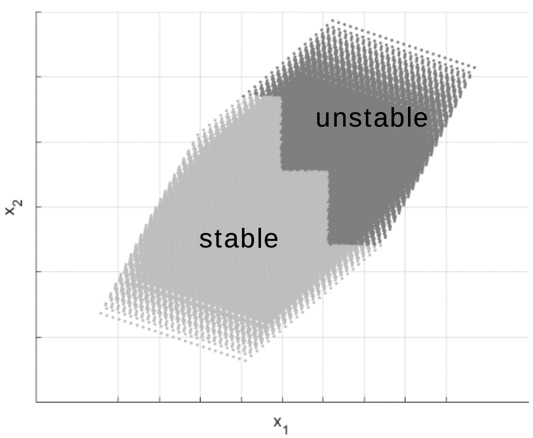
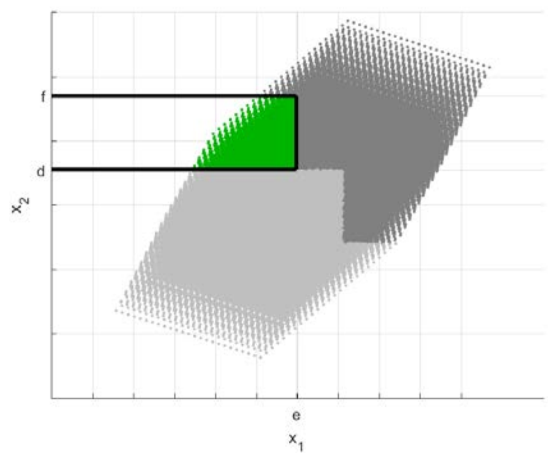
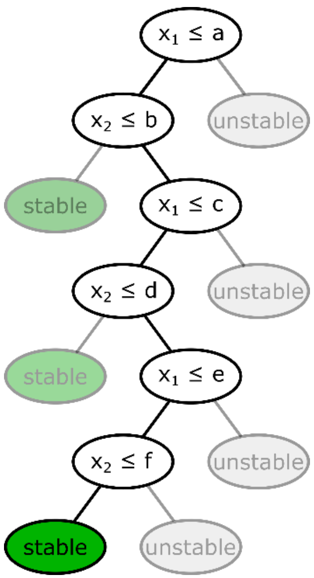






Data-driven security-constrained OPF

Offline security assessment

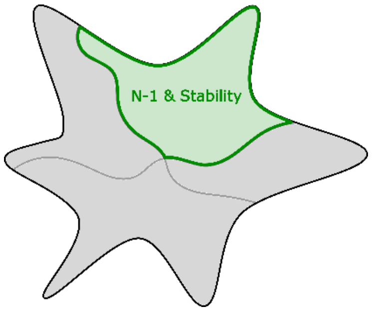
Database of stable and unstable OPs
{P,Q,V,θ,ζ}

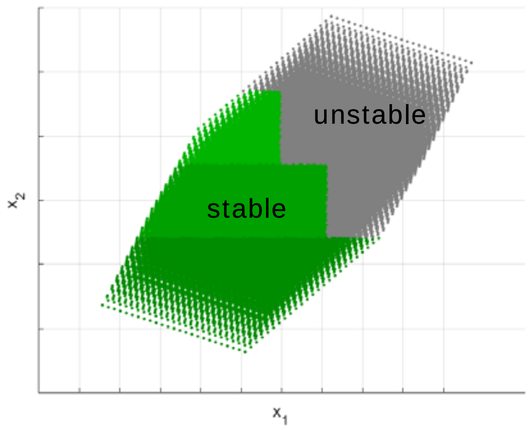
→ **Decision Tree**

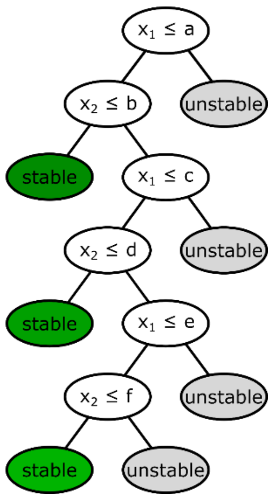
Optimization

Integer Programming to incorporate partitions (DT)

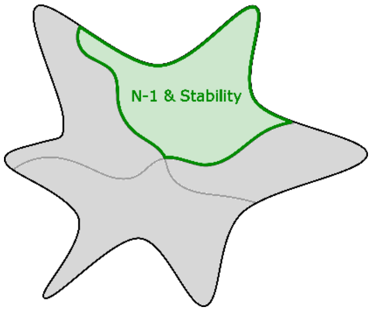
- DC-OPF (MILP)
- AC-OPF (MINLP)
- Relaxation (MIQCP, MISOCP)

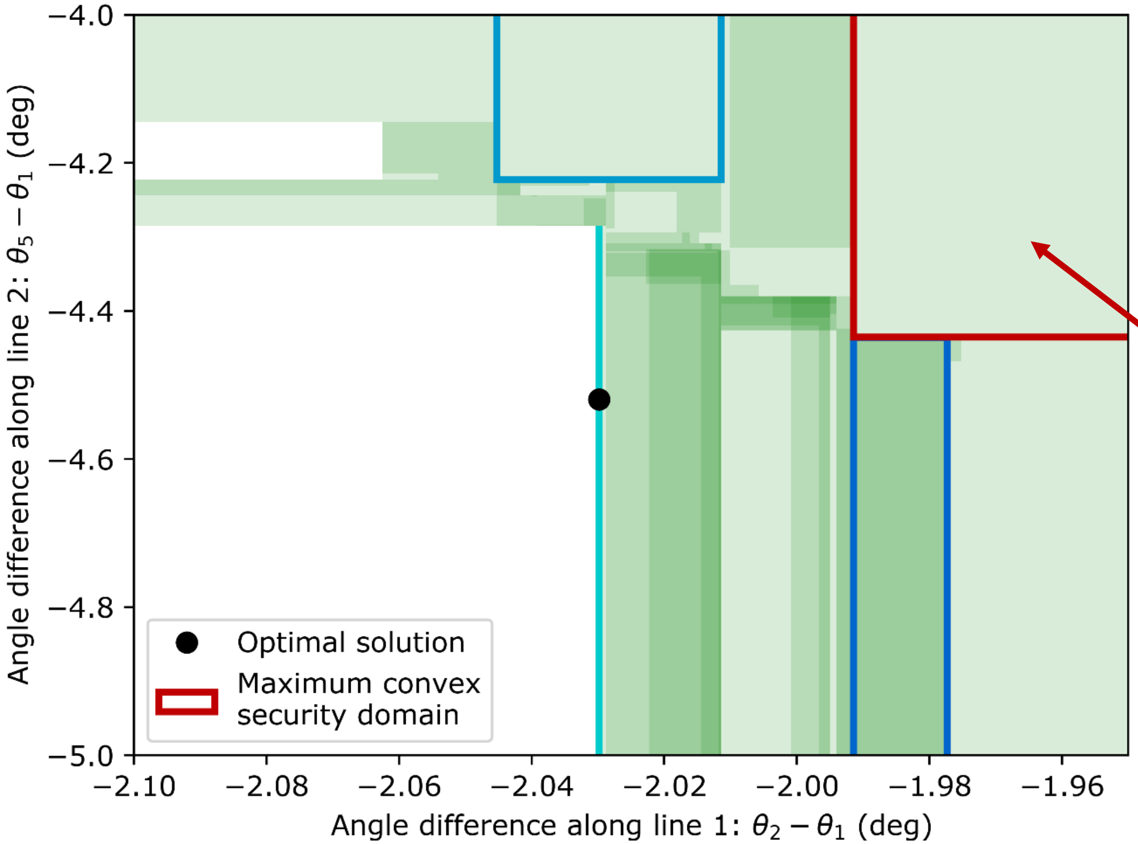




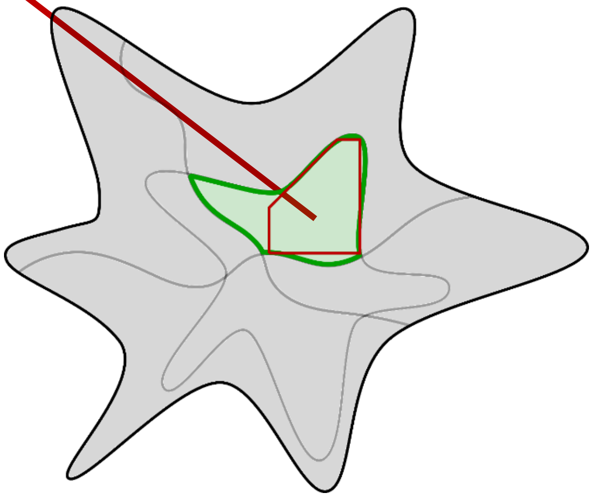


We gain ~22% of the feasible space using data and Mixed Integer Programming

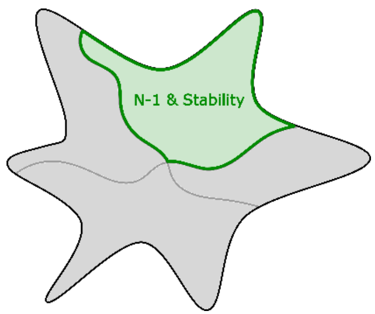


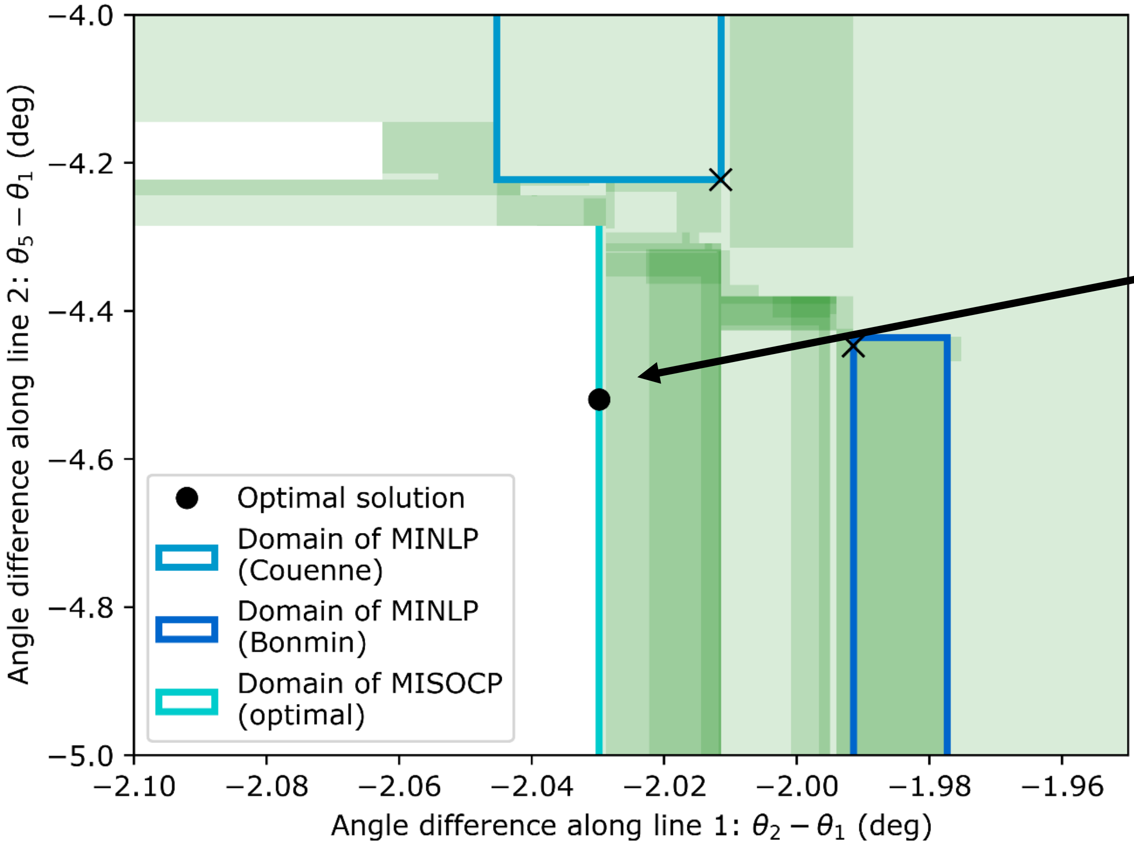


Largest convex region covers ~78%



MIP + convex AC-OPF approximation finds better solutions than nonconvex problem!

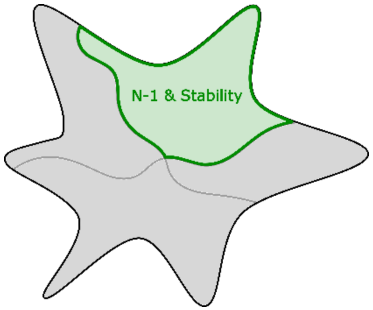


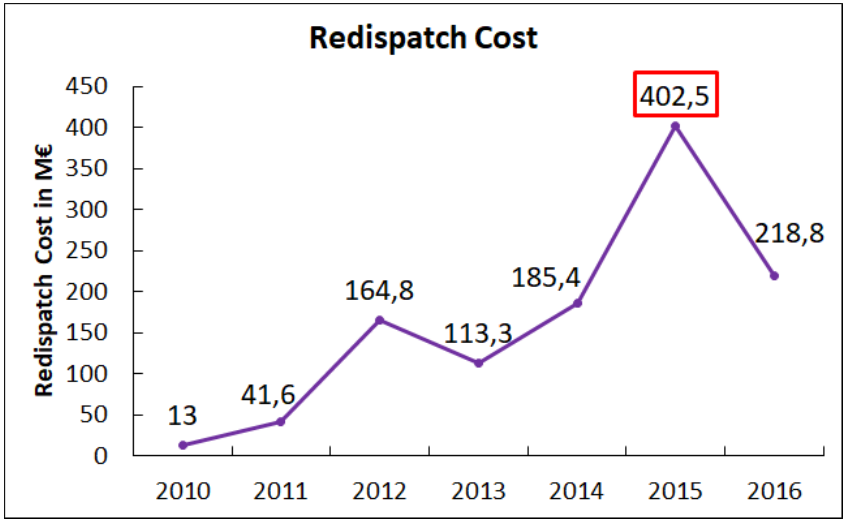


Optimum located at boundary of considered security region

Works also for DC-OPF (MILP): Market dispatch is N-1 secure and stable

Eliminate redispatching costs

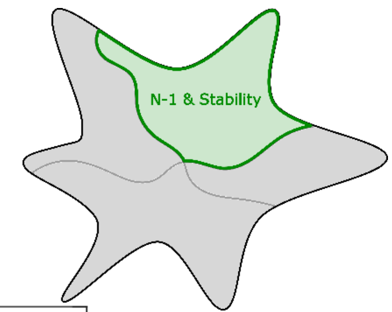


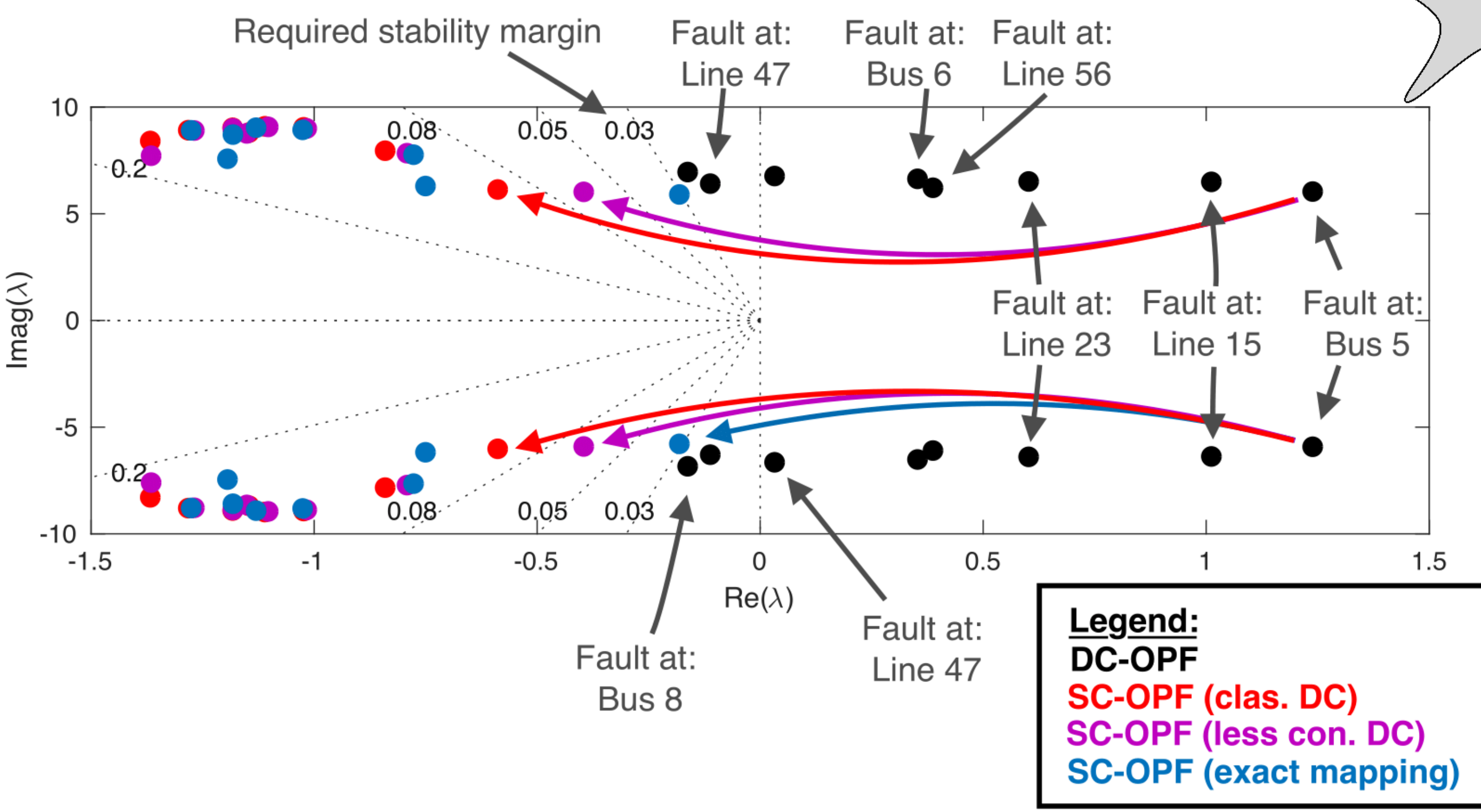


- Redispatching costs: over 400 Million Euros in a year, just for Germany
- Data-driven SC-OPF for markets: DC-OPF becomes MILP
  - **But,** MILP is already included in market software (e.g. Euphemia, for block offers, etc.)
  - Efficient MILP solvers already existing

Works also for DC-OPF (MILP): Market dispatch is N-1 secure and stable

Eliminate redispatching costs

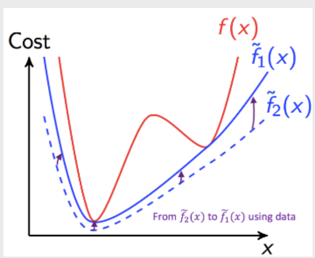


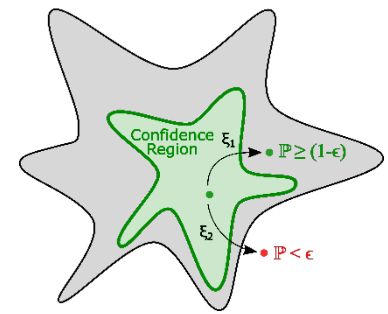


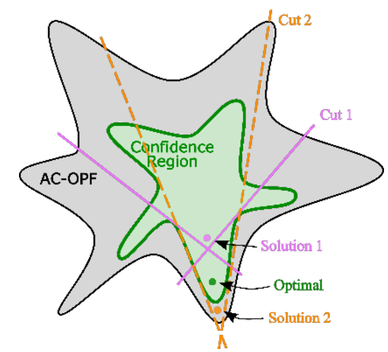
OPF under uncertainty

Approximations and relaxations of chance-constrained AC-OPF

Semidefinite programming	Second-order cone programming
• Global optimality	• + Ex-post feasibility recovery • Computational efficiency • **Better approximations of confidence region**







A. Venzke, *L. Halilbasic, U. Markovic, G. Hug, S. Chatzivasileiadis*, "Convex relaxations of chance constrained AC optimal power flow," *IEEE Transactions on Power Systems*, vol. 33, no. 3, pp. 2829-2841, May 2018.

L. Halilbašić, P. Pinson, and S. Chatzivasileiadis, "Convex relaxations and approximations of chance-constrained AC-OPF problems," *IEEE Transactions on Power Systems*, 2018, (in press).

OPF under uncertainty

Approximations and relaxations of chance-constrained AC-OPF

Second-order cone programming

(I) $\tilde{y} = y + \frac{\partial y}{\partial \xi}\xi = \Upsilon \xi$

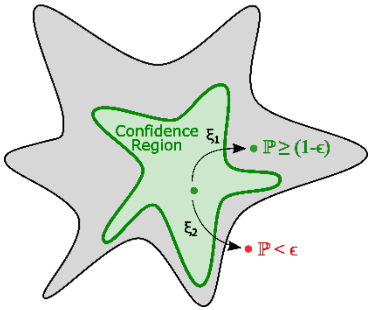
$$\mathbb{P}\left(\left(P_l + \Upsilon_l^P \xi\right)^2 + \left(Q_l + \Upsilon_l^Q \xi\right)^2 \leq (\bar{S}_l)^2\right) \geq 1 - \epsilon$$

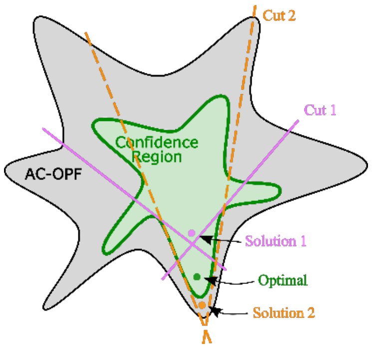
(II)*

$$(1)\ \ \mathbb{P}\left(\left|P_l + \Upsilon_l^P \xi\right| \leq k_l^P\right) \geq 1 - \beta_l \varepsilon$$

$$(2)\ \ \mathbb{P}\left(\left|Q_l + \Upsilon_l^Q \xi\right| \leq k_l^Q\right) \geq 1 - (1 - \beta_l)\varepsilon$$

$$(3)\ \ \left(k_l^P\right)^2 + \left(k_l^Q\right)^2 \leq (\bar{S}_l)^2$$

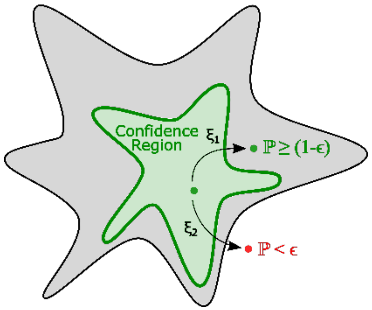




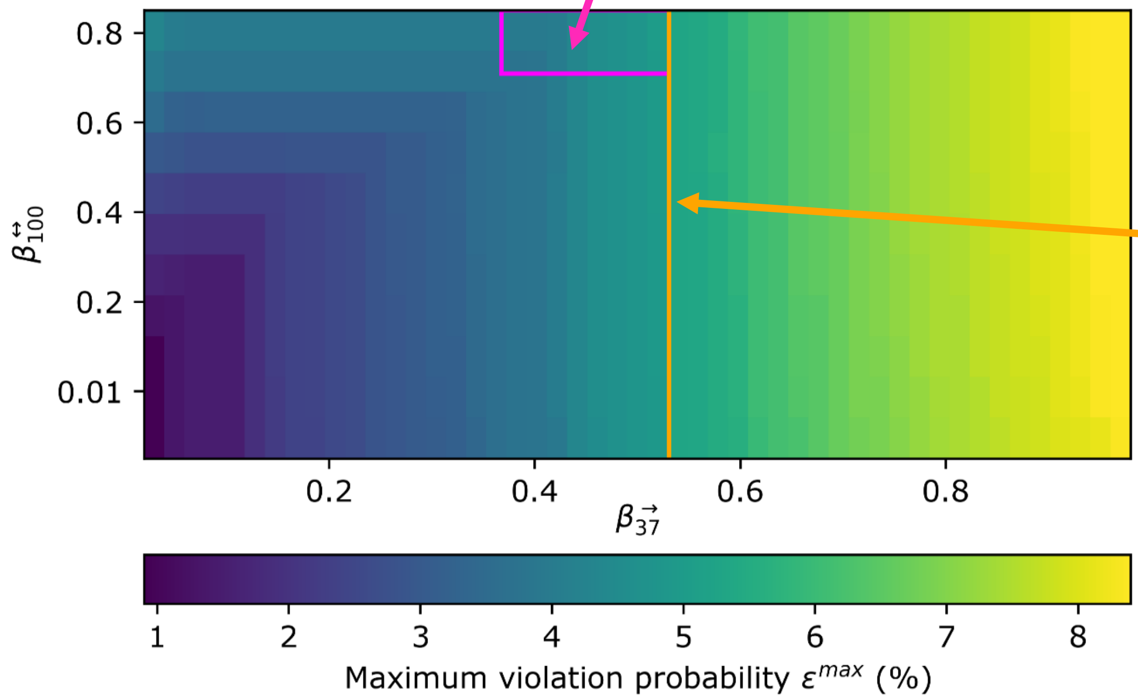
$\beta_l \in (0,1)$ ensures $\mathbb{P}\left((1) \cup (2)\right) \geq 1 - \epsilon$

* M. Lubin, D. Bienstock, and J. P. Vielma, “Two-sided Linear Chance Constraints and Extensions,” *ArXiv e-prints*, Jul. 2015.

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

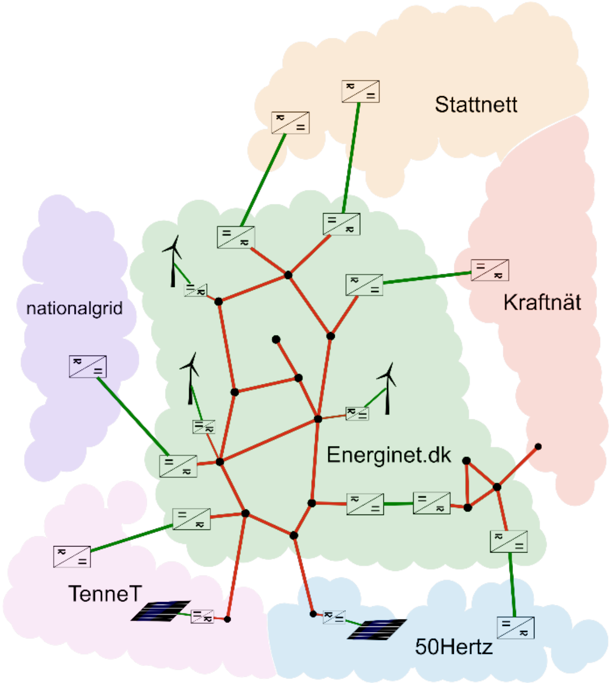
Conclusions

- 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

- Deadline: December 15, 2018

Thank you!

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