Data-driven Security Constrained OPF

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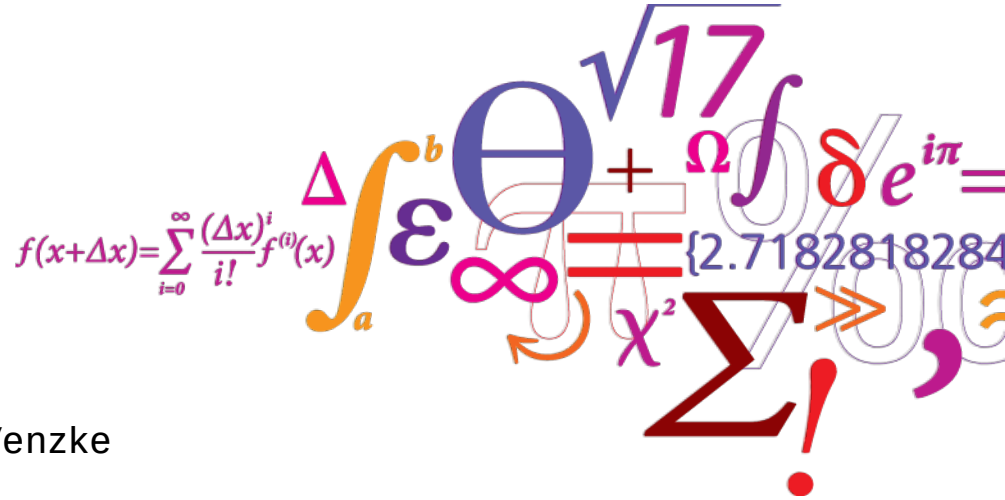
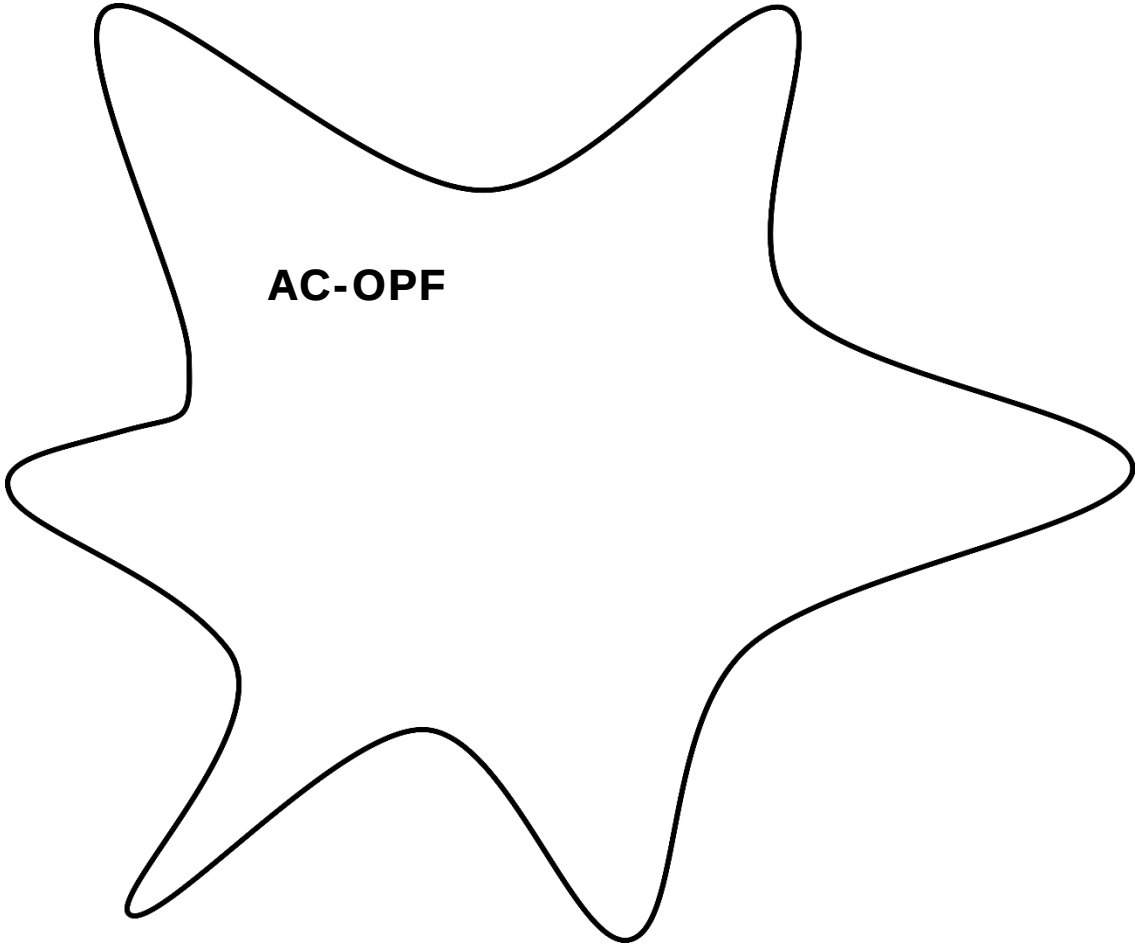
Associate Professor, DTU



work with:
Lejla Halilbasic, Florian Thams, Andreas Venzke

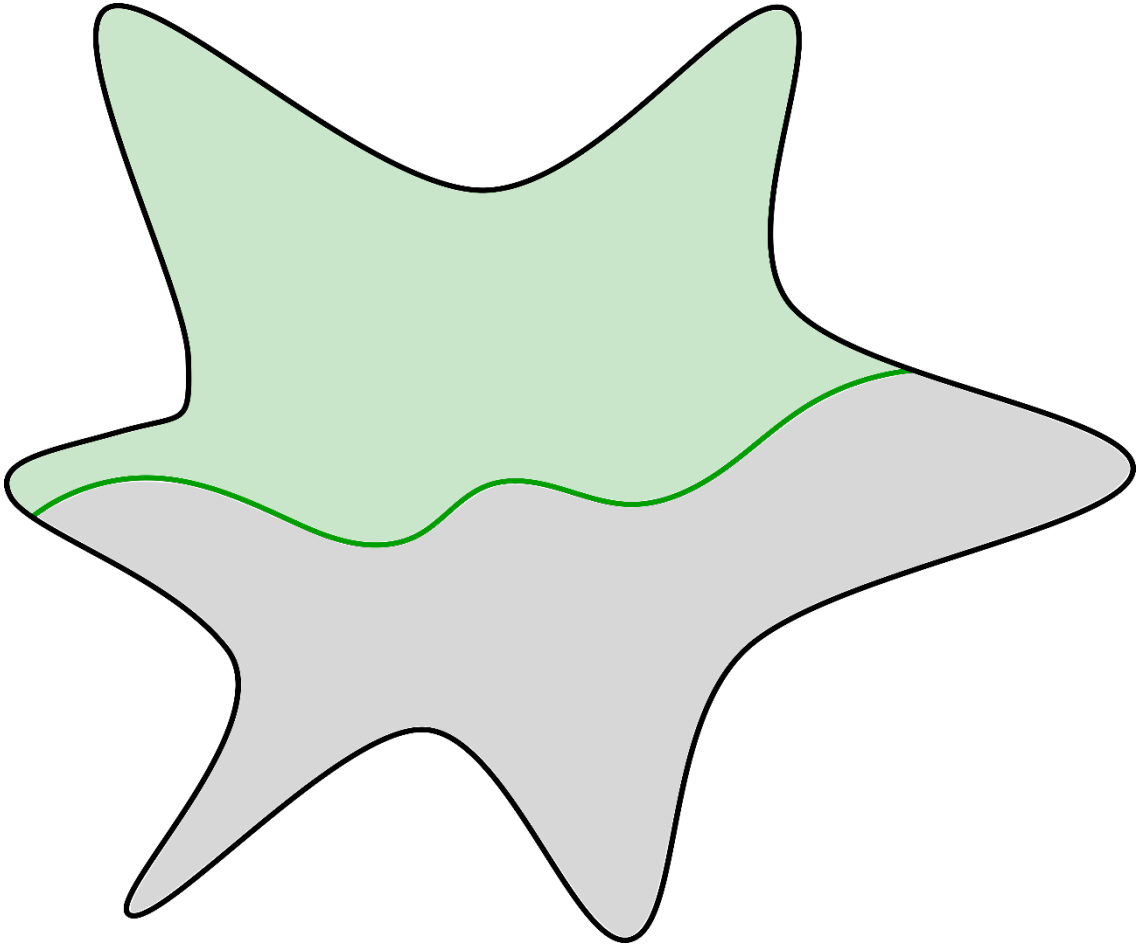
DTU Electrical Engineering
Department of Electrical Engineering

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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\+ Stability limits

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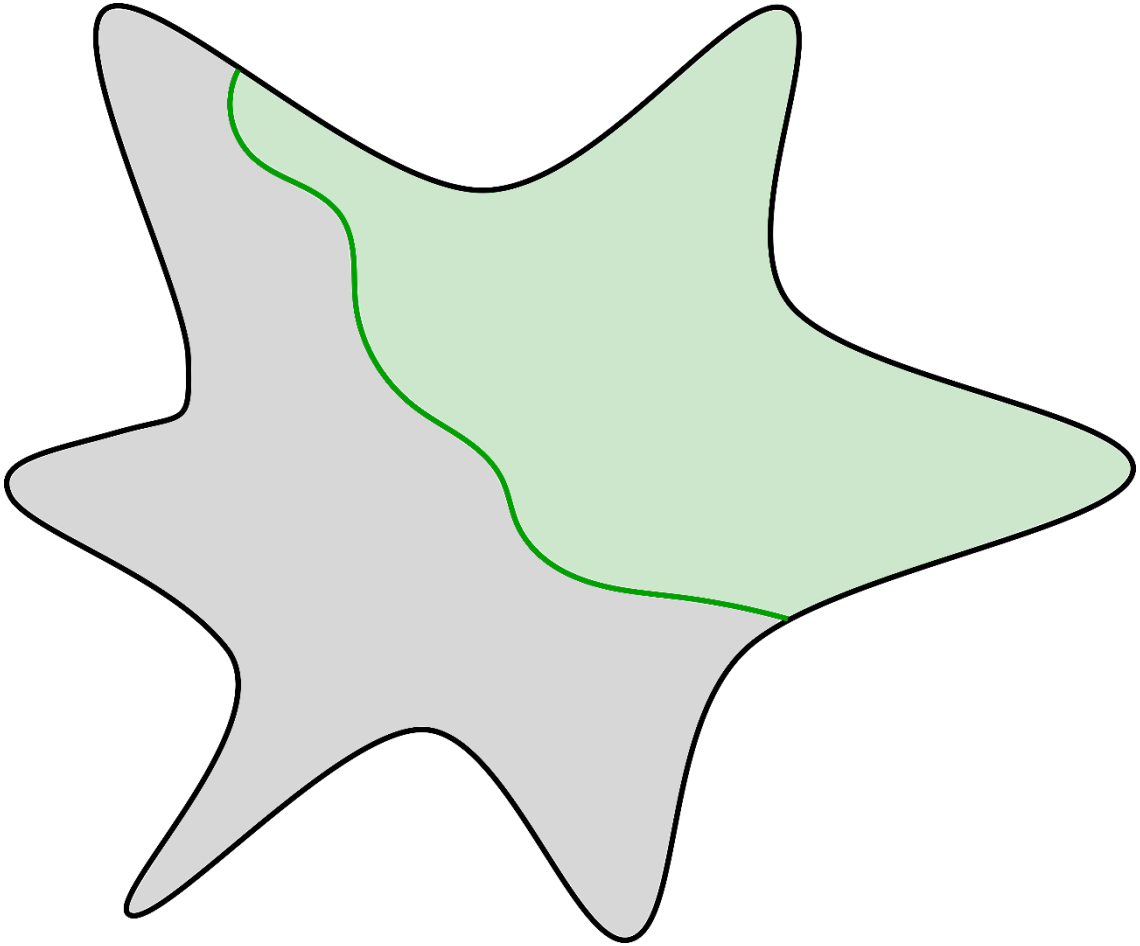

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\+ Stability limits

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

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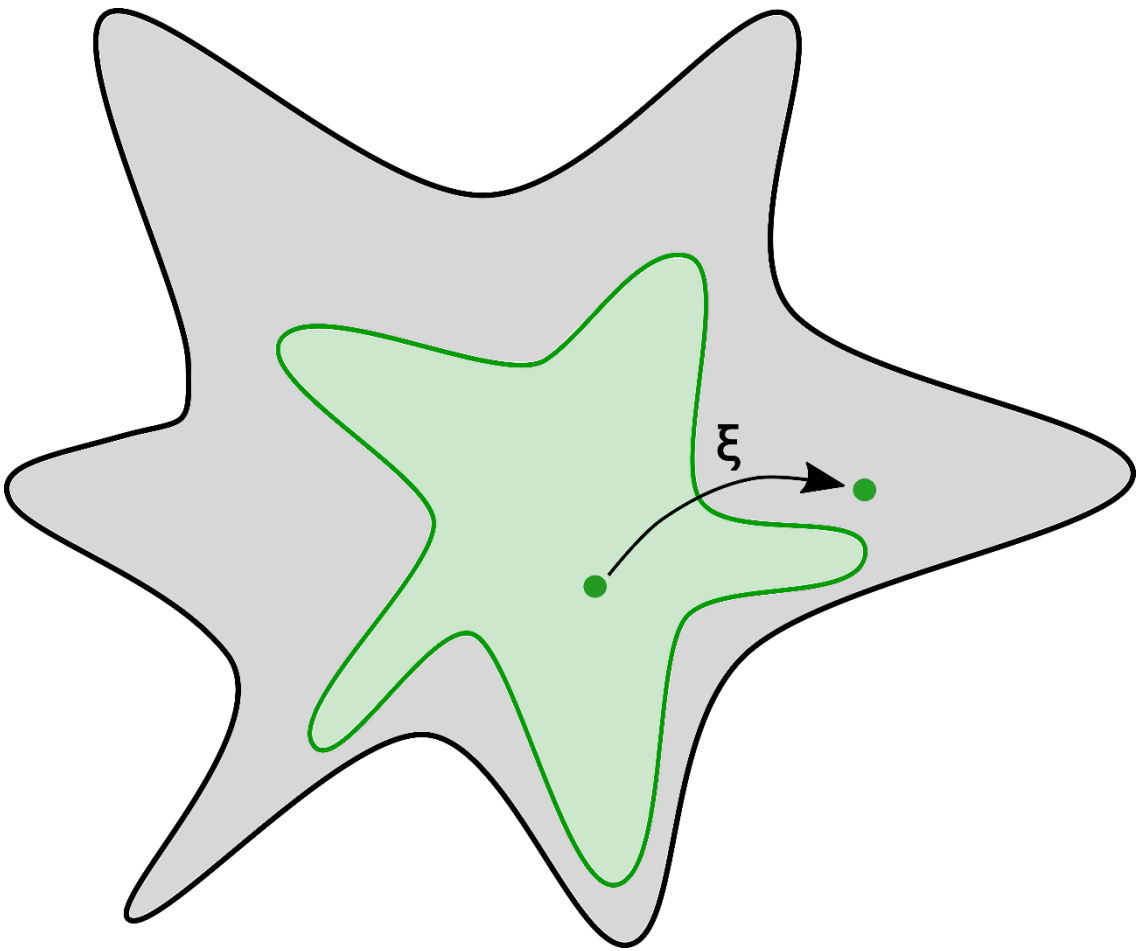

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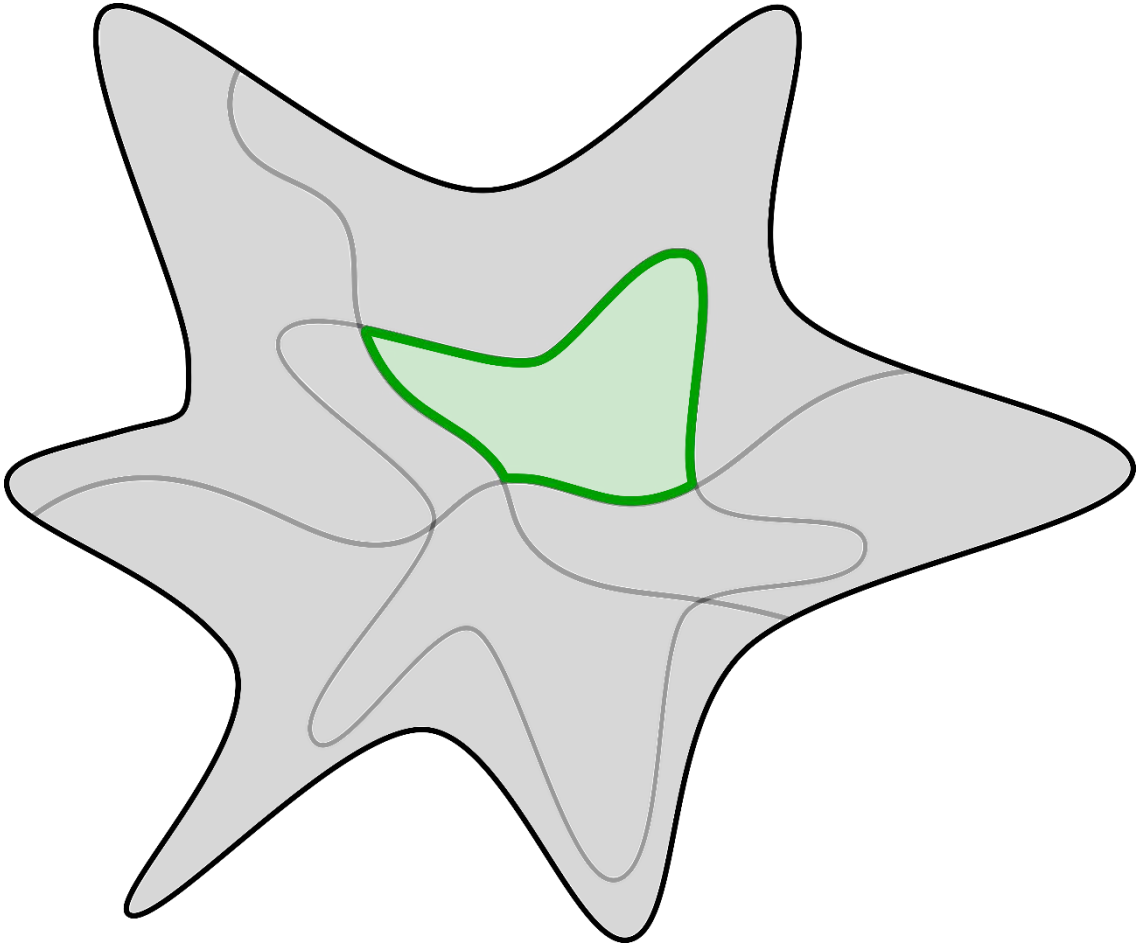
\+ Uncertainty **ξ** in nodal power injections

The feasible space of power system operations



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

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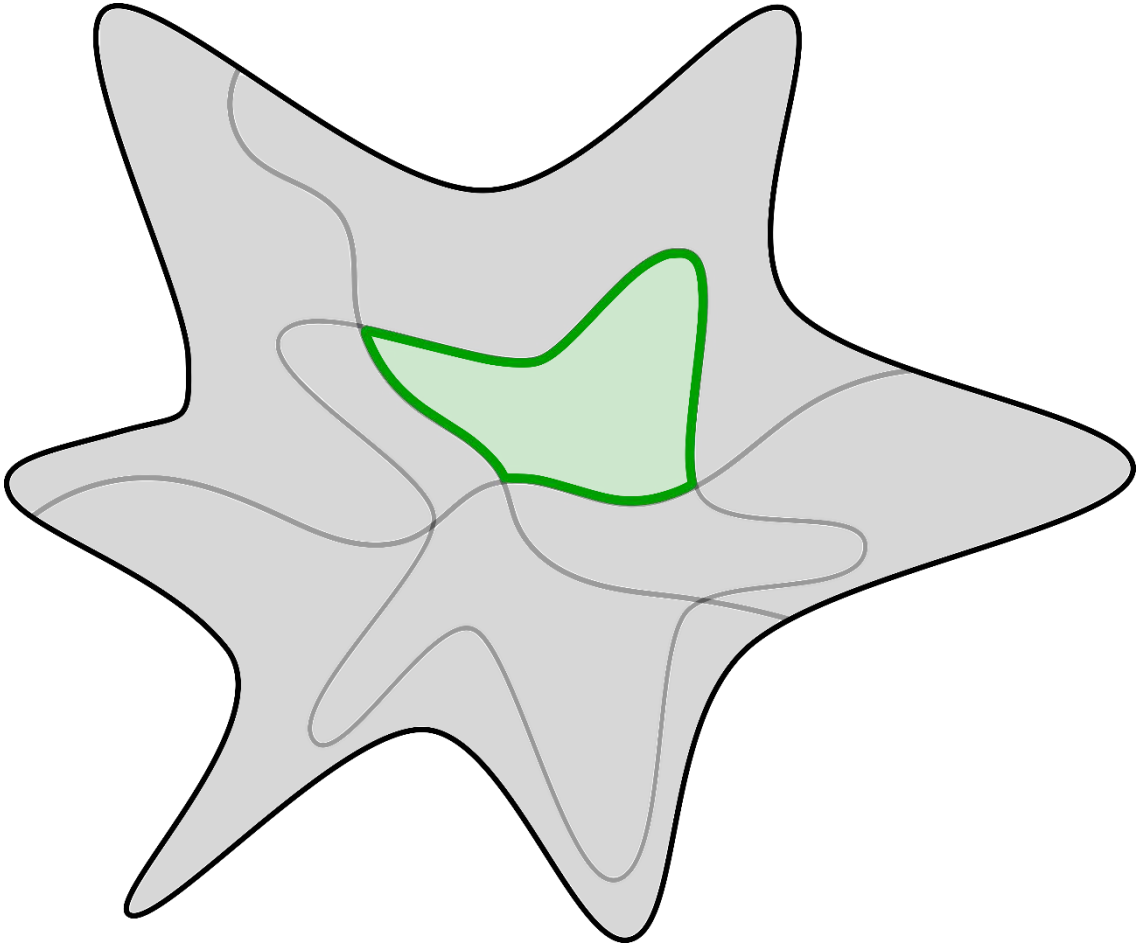
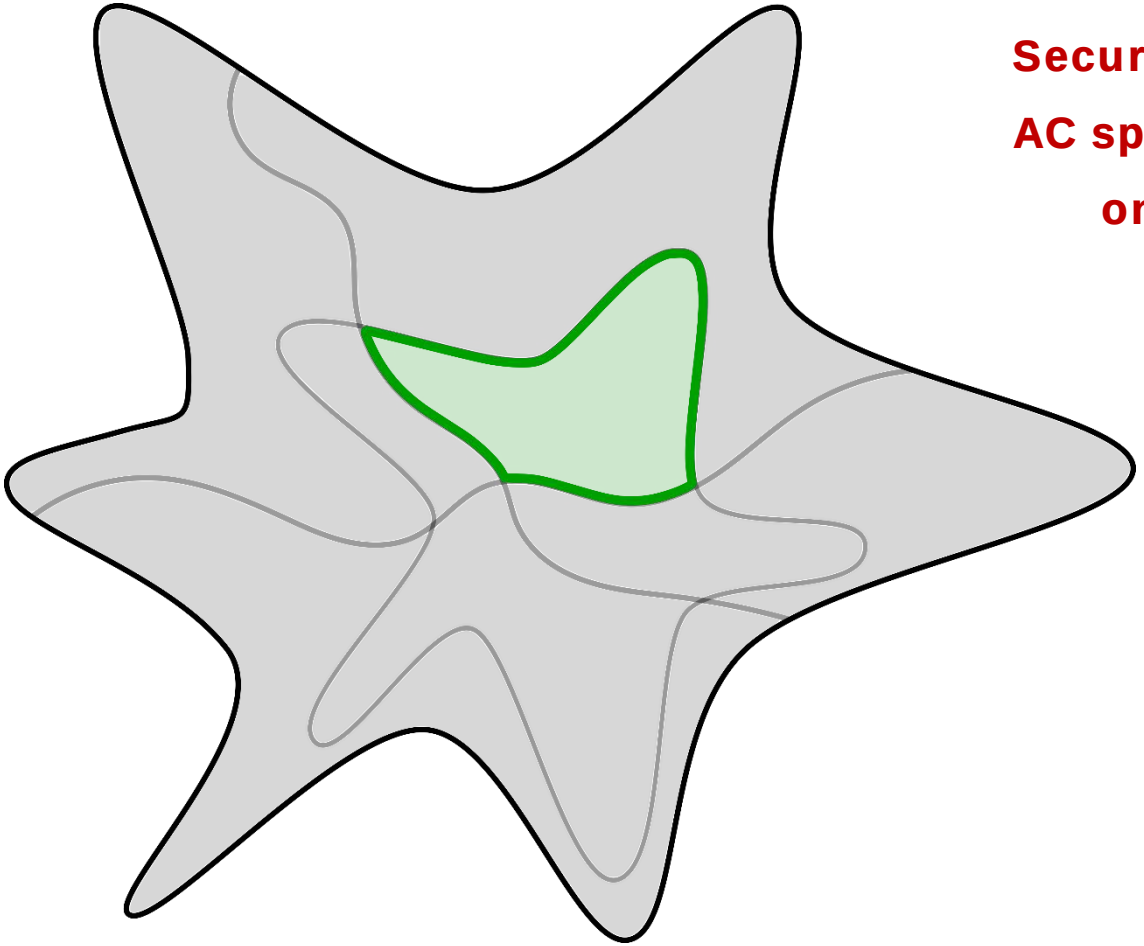
Operational Challenges



- 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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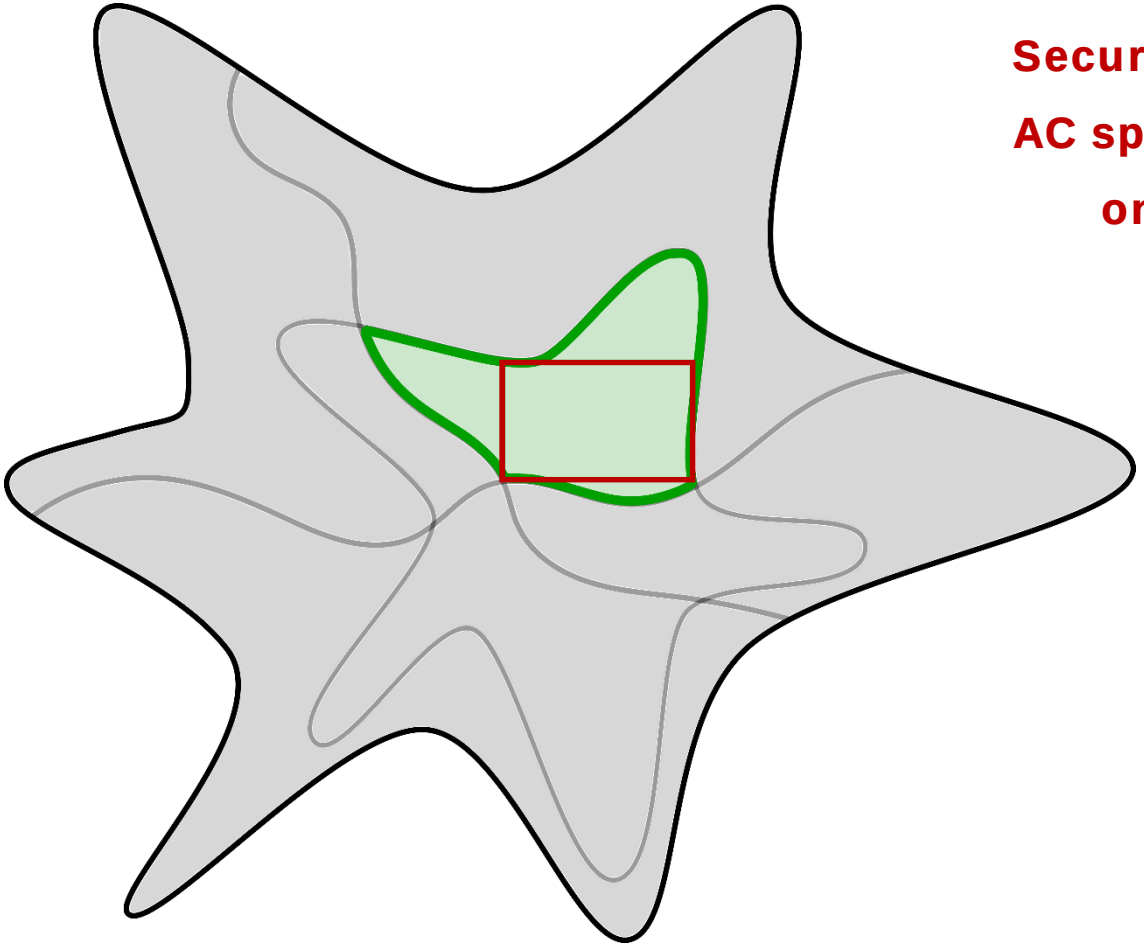

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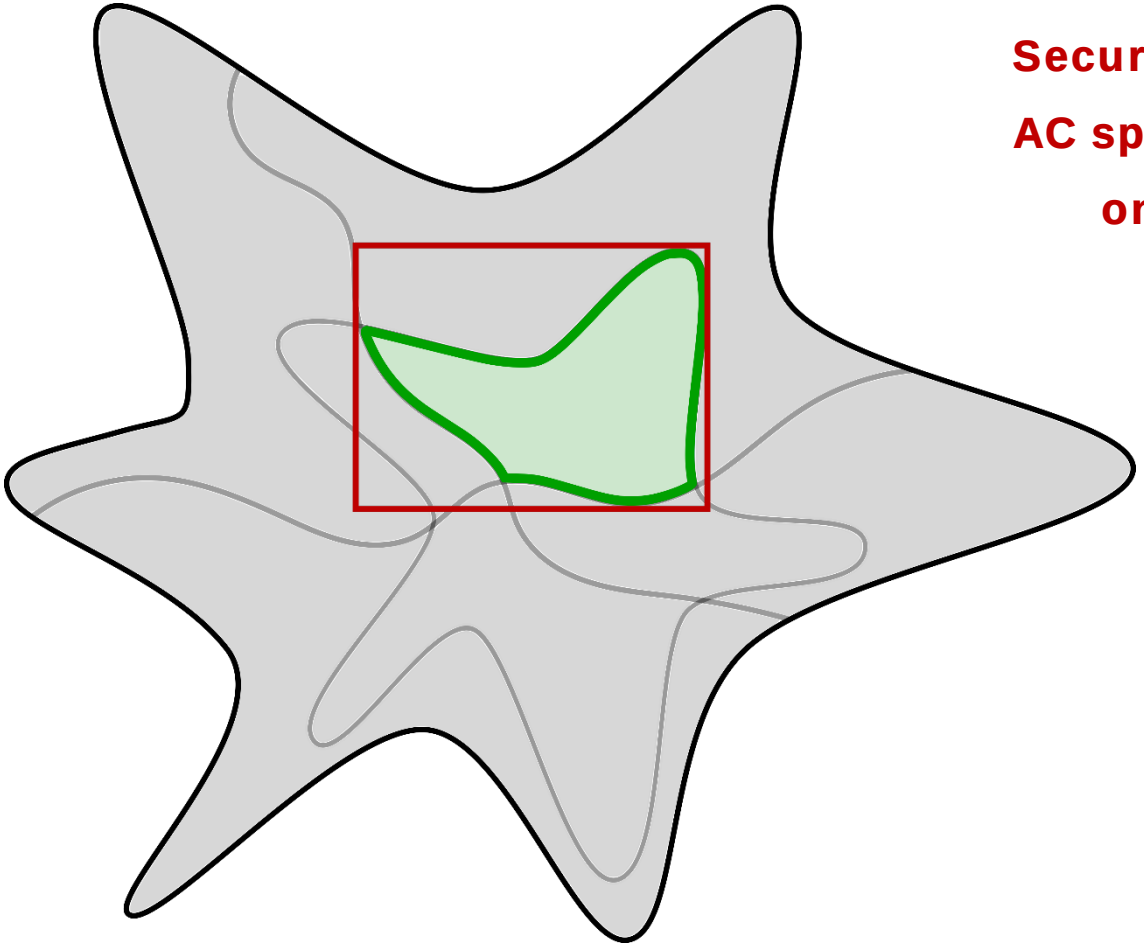
Traditionally, TSOs define Net-Transfer Capacities

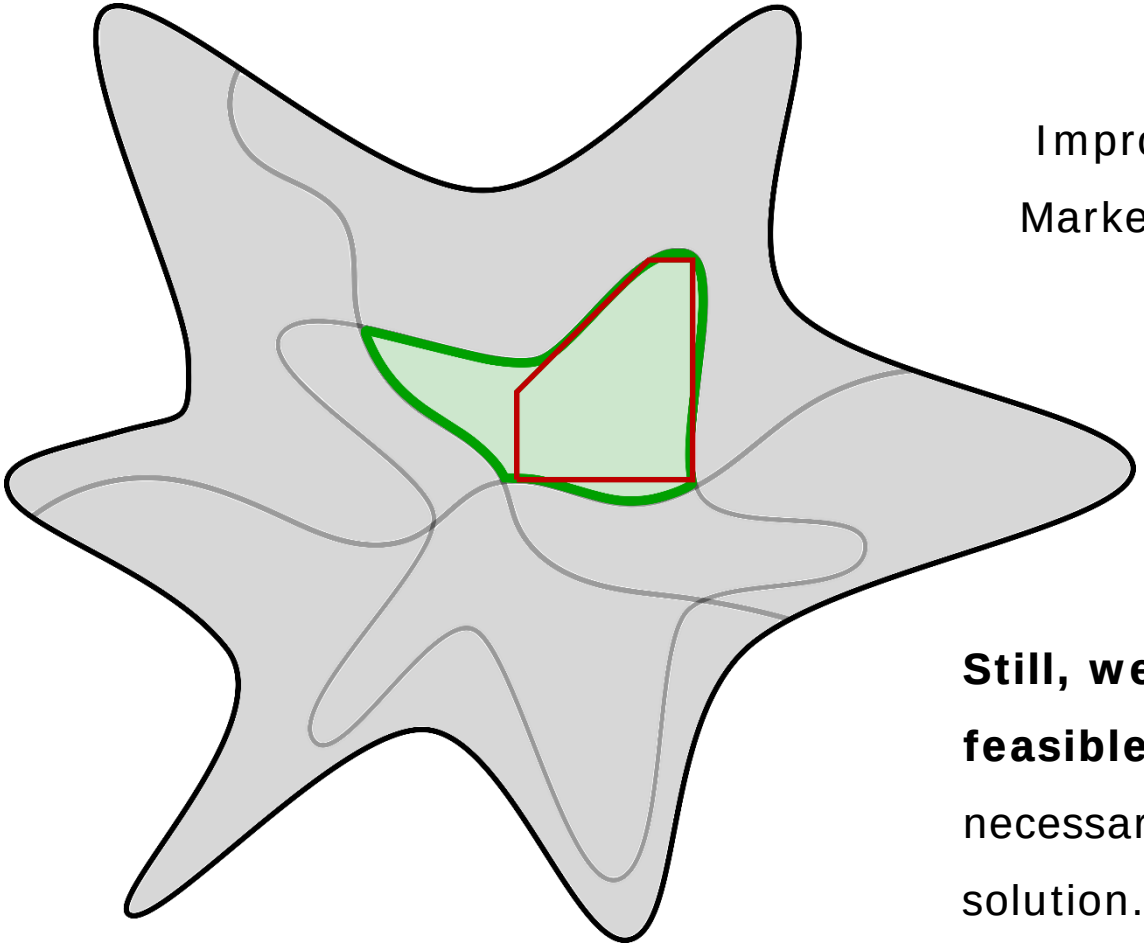
How to encode feasible operating region for electricity markets?



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

Traditionally, TSOs define Net-Transfer Capacities

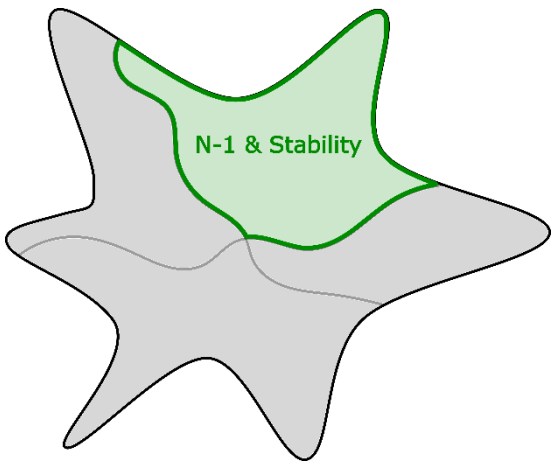
Better but reality of power system operations is nonconvex!



Improvements with Flow-Based Market Coupling but still convex!

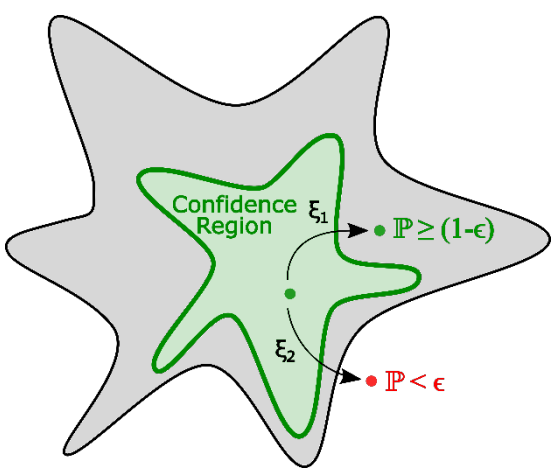
Still, we do not capture the whole feasible space, and do not necessarily find the true optimal solution.

What we work on



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

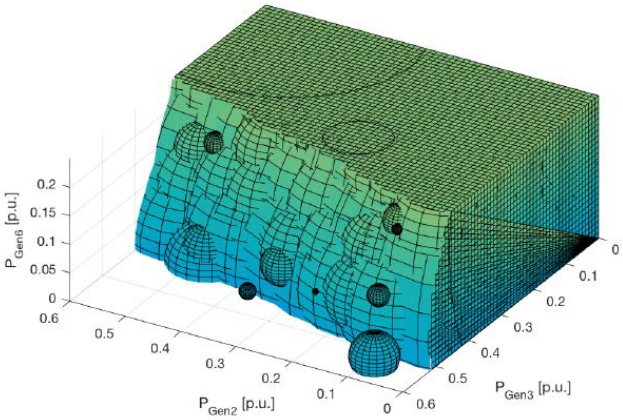
- **Mixed Integer Convex Programming** to integrate N-1 & stable space in optimization framework (MILP, MISOCP)



- **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**
- **Our approach: Convex relaxations and “directed walks”**



Efficient Database Generation - Results

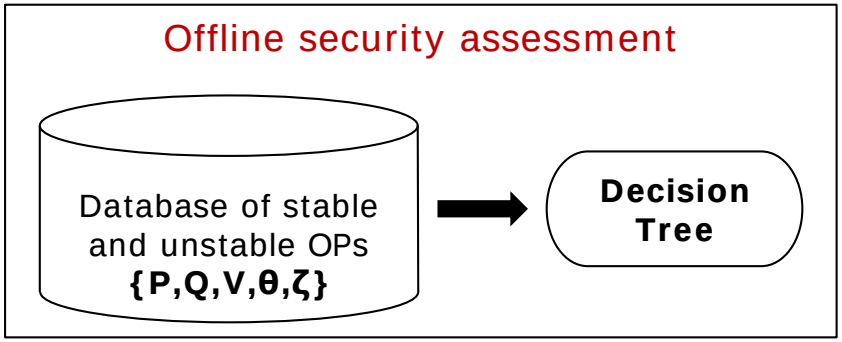
- **10-20 times faster** than existing state-of-the-art approaches
- Can accommodate numerous definitions of power system stability
- Our case: N-1 security and small-signal stability

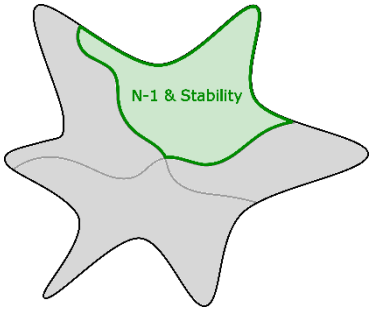
	Points close to the security boundary (within distance γ)	
	IEEE 14-bus	NESTA 162-bus
Brute Force	100% of points in **556.0 min**	*intractable*
Importance Sampling	100% of points in **37.0 min**	**901 points** in 35.7 hours
Proposed Method	100% of points in **3.8 min**	**183'295 points** in 37.1 hours

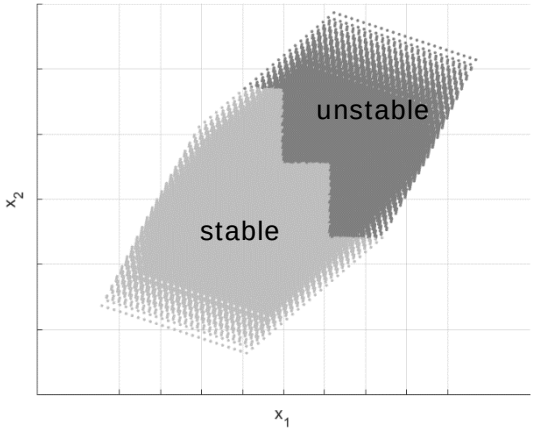
- Generated Database for NESTA 162-bus system online available! https://github.com/johnnyDEDK/OPs_Nesta162Bus (~1,000,000 points)

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

Data-driven security-constrained OPF







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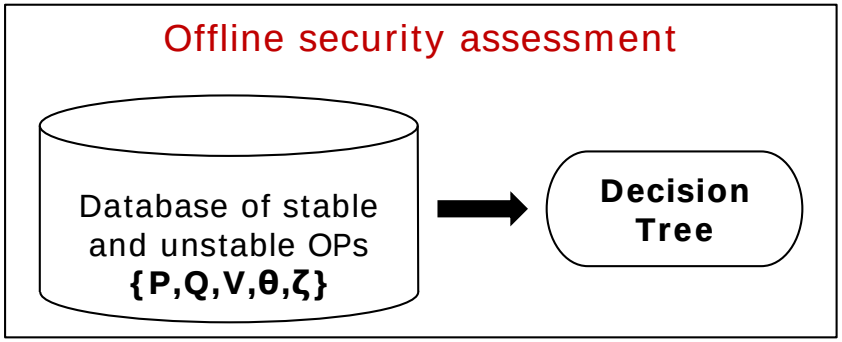
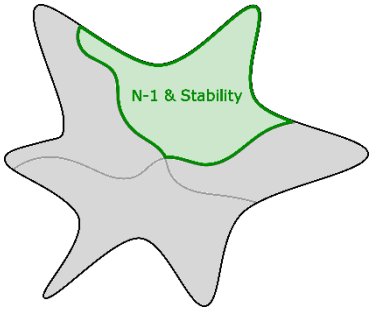
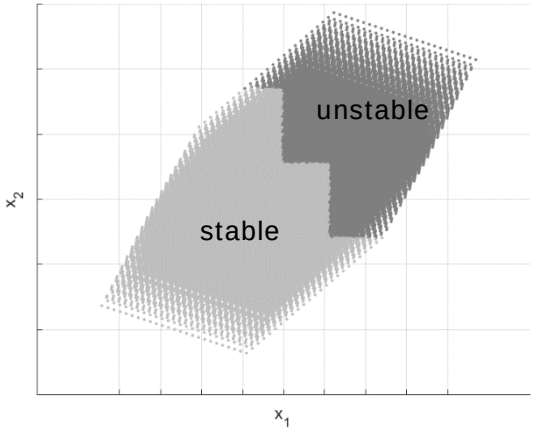
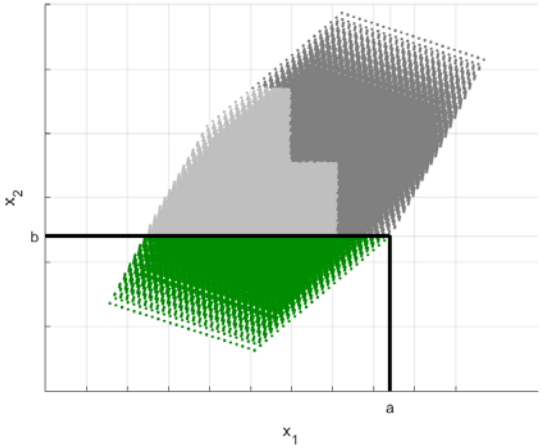
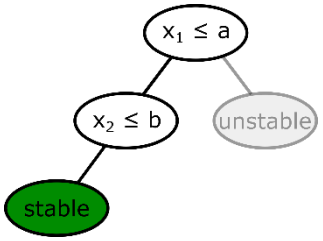




Partitioning the secure operating region







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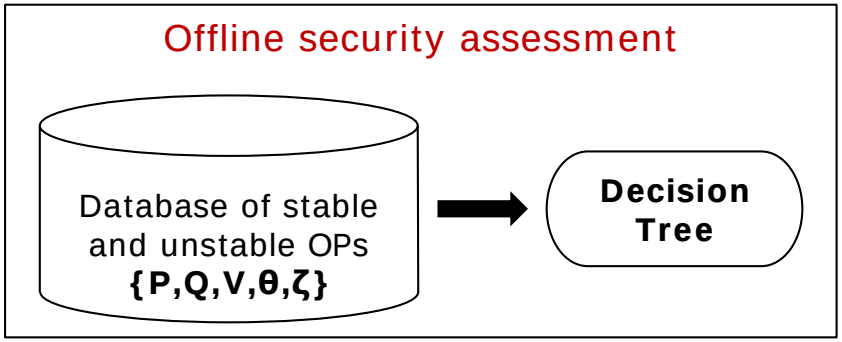

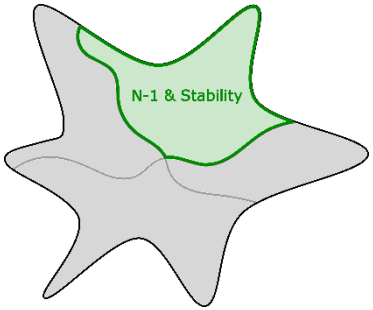

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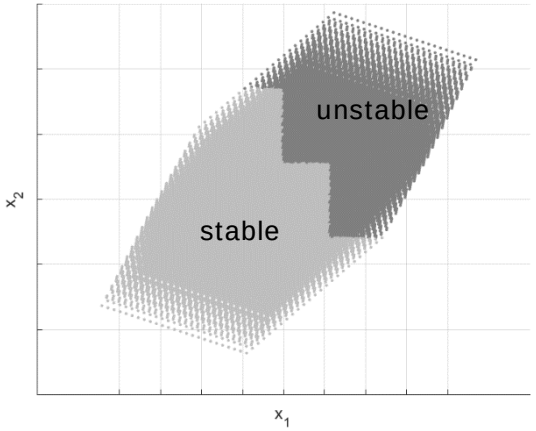

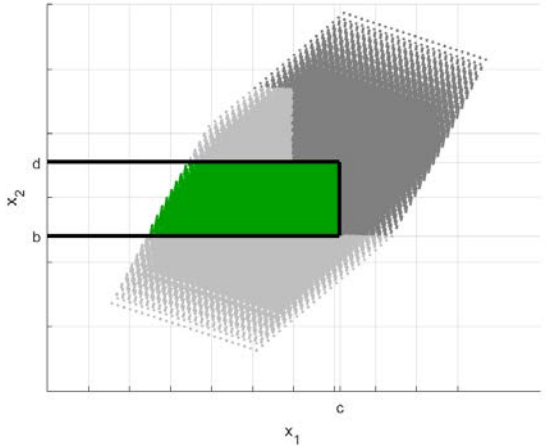

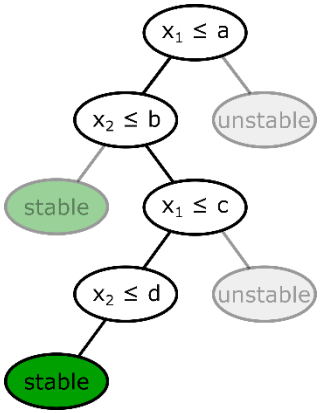

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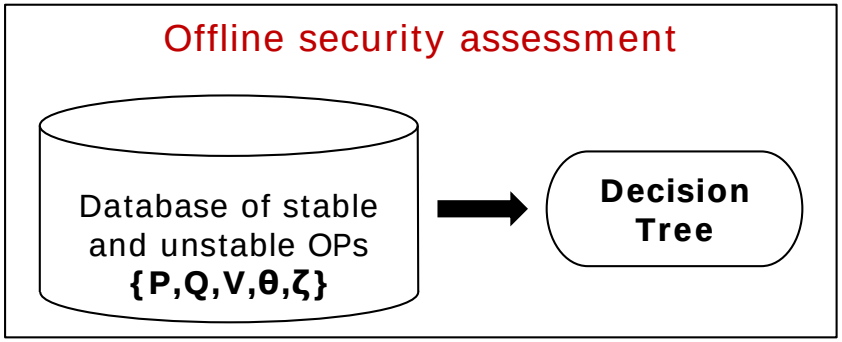

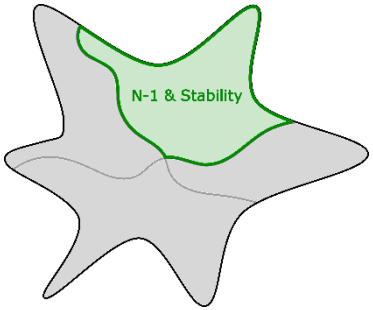

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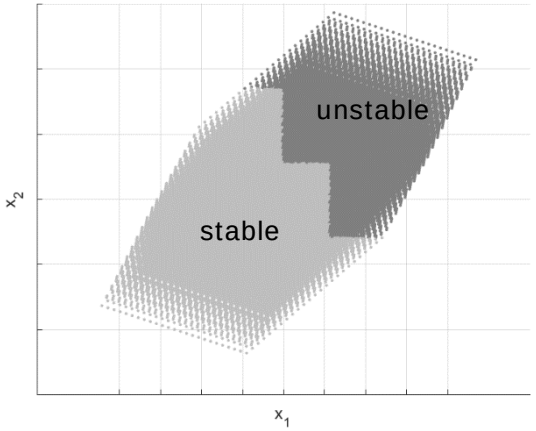
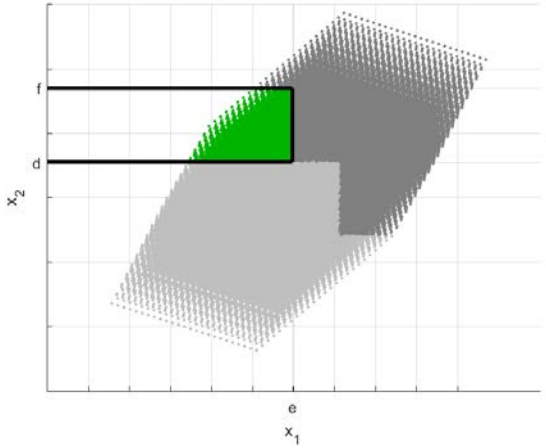
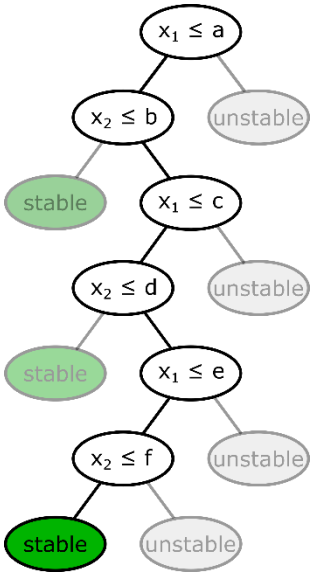






Data-driven security-constrained OPF

Offline security assessment

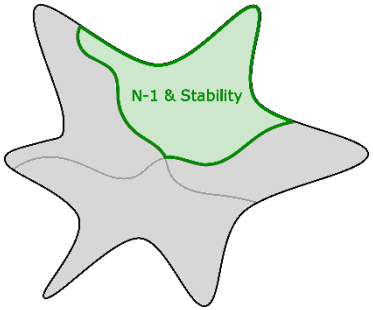
Database of stable and unstable OPs
{P,Q,V,θ,ζ}

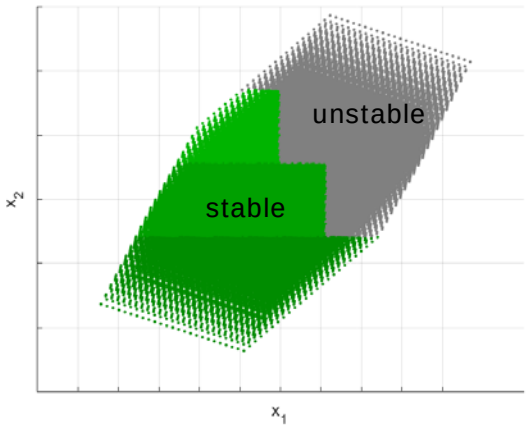
→ **Decision Tree**

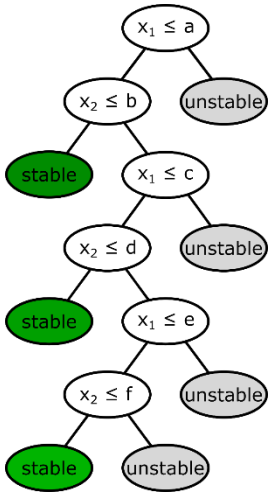
Optimization

Integer Programming to incorporate partitions (DT)

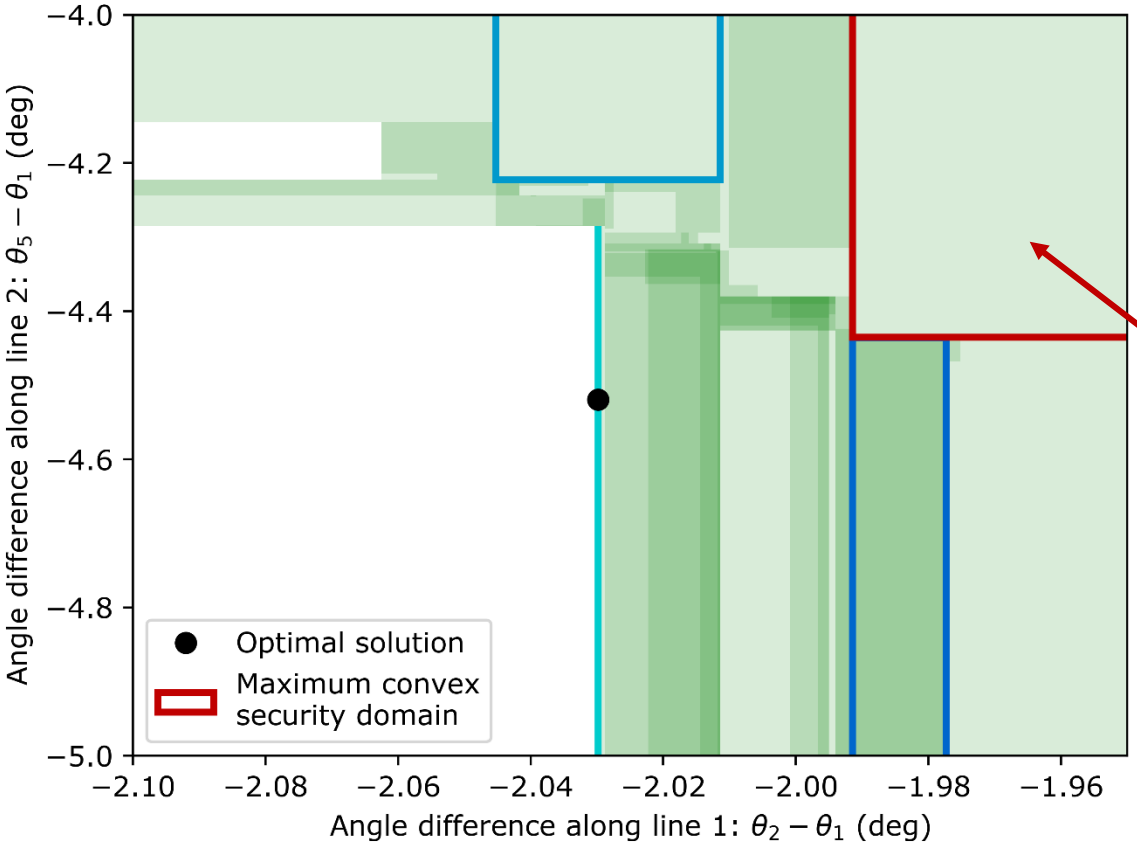
- DC-OPF (MILP)
- AC-OPF (MINLP)
- Relaxation (MIQCP, MISOCP)

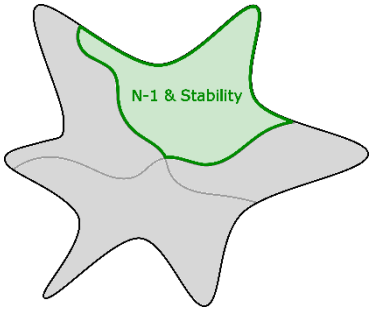




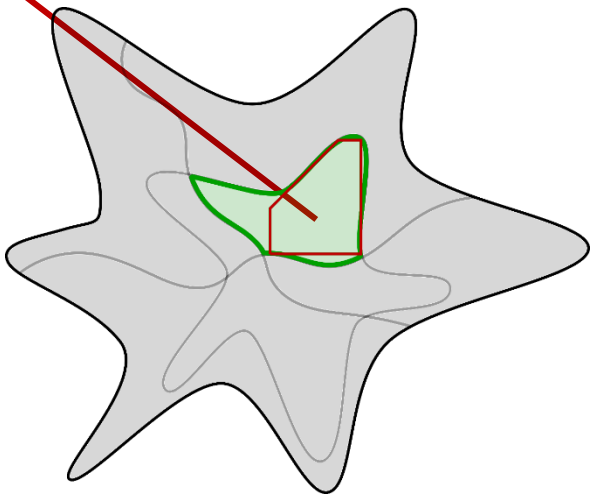


We gain ~22% of the feasible space using data and Mixed Integer Programming





Largest convex region covers ~78%



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

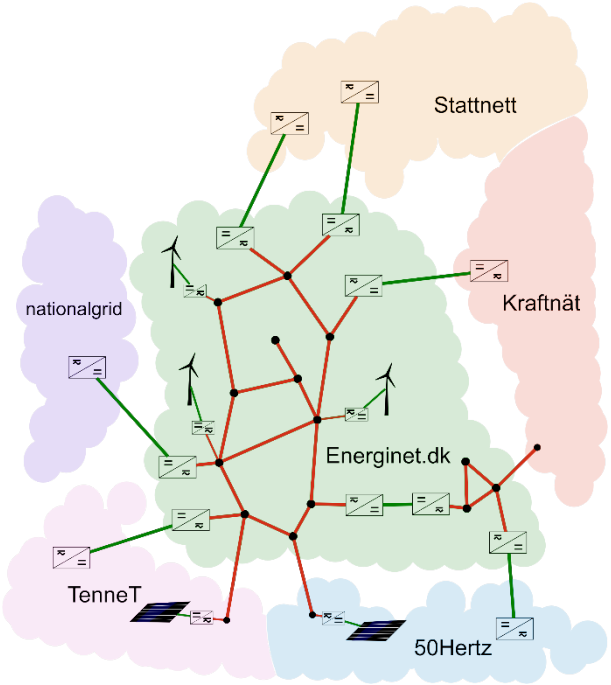
Interested in a PhD?

- Open position

- Topic:

  Data-driven Security and Optimization for AC and HVDC Grids

- Contact: spchatz@elektro.dtu.dk



Thank you!

www.chatziva.com/publications

spchatz@elektro.dtu.dk

References:

L. Halilbašić, F. Thams, A. Venzke, S. Chatzivasileiadis, and P. Pinson, ”Data-driven security-constrained AC-OPF for operations and markets,” in *2018 Power Systems Computation Conference (PSCC)*, 2018.

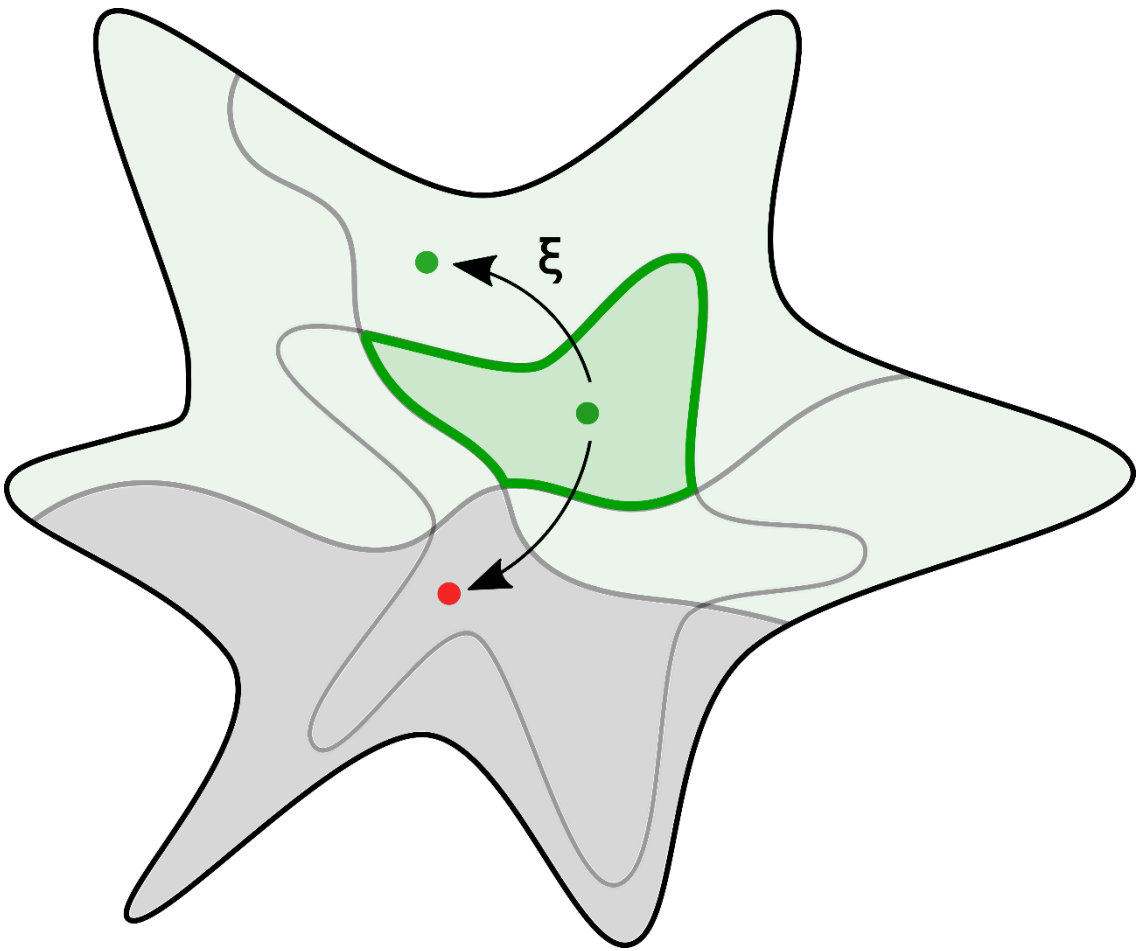
F. Thams, L. Halilbašić, P. Pinson, S. Chatzivasileiadis, and R. Eriksson, ”Data-driven security-constrained OPF,” in *10th IREP Symposium – Bulk Power Systems Dynamics and Control*, 2017.

F. Thams, A. Venzke, R. Eriksson, and S. Chatzivasileiadis, ”Efficient database generation for data-driven security assessment of power systems”. IEEE Transactions on Power Systems, 2018. arXiv: http://arxiv.org/abs/1806.01074.pdf (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).

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.

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

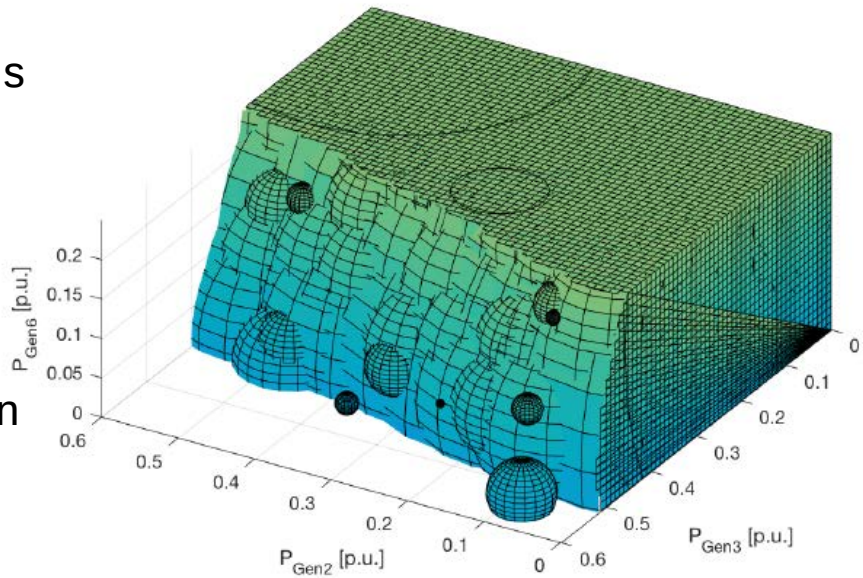
Efficient Database Generation: Convex Relaxations and Directed Walks

- 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

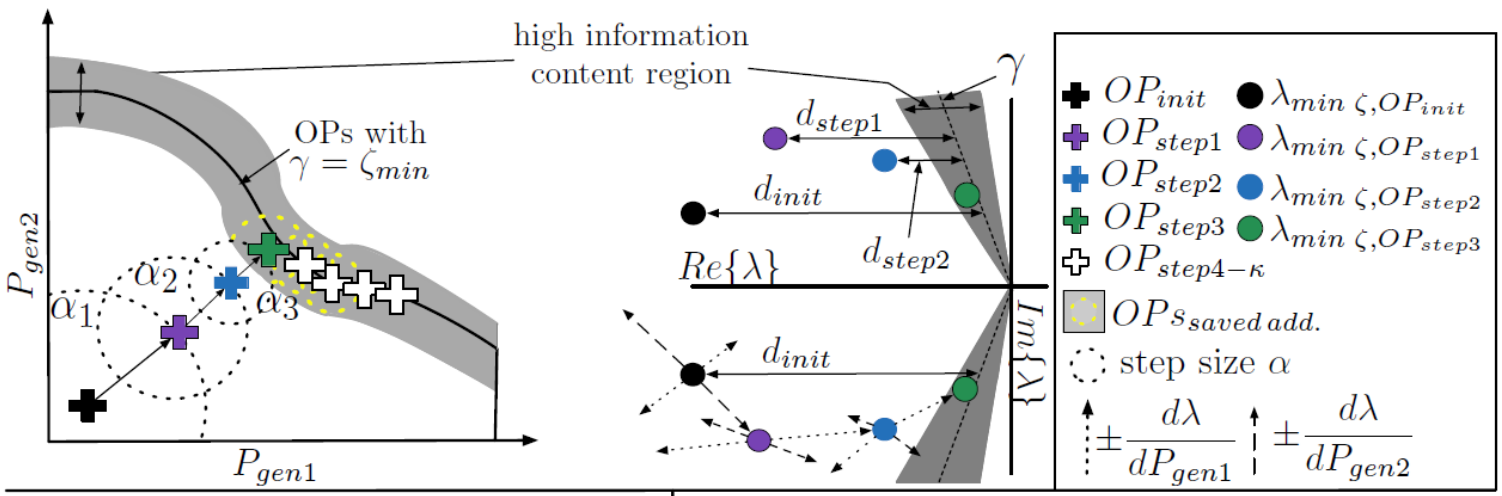
3. Discard all points inside the hypersphere



- Convex optimization! And drastically reducing search space!

Efficient Database Generation: Convex Relaxations and Directed Walks

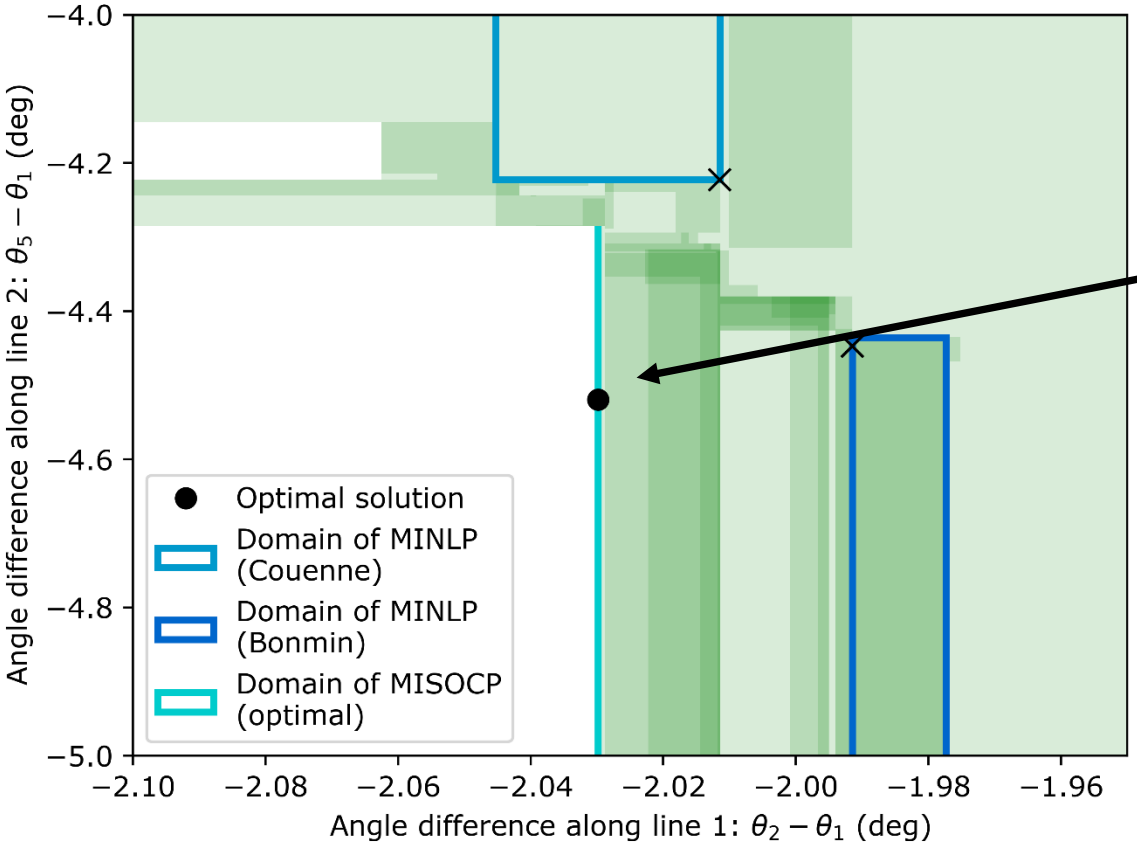
- "Directed walks": steepest-descent based algorithm to explore the remaining search space, focusing on the area around the security boundary
  1. Variable step-size
  2. Parallel computation
  3. Steepest descent: sensitivity of damping ratio (small-signal stability)
  4. Exhaustive search of the space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

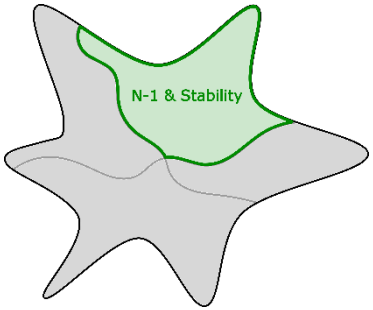


2-dim. subspace of multi-dim. space of potential generation patterns (remaining dim. held constant for illustration)

Eigenspace of all $\Gamma + 1$ analyzed systems (only lowest damped (pair) of eigenvalues of all systems shown)

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

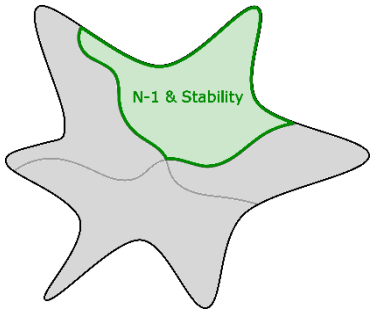


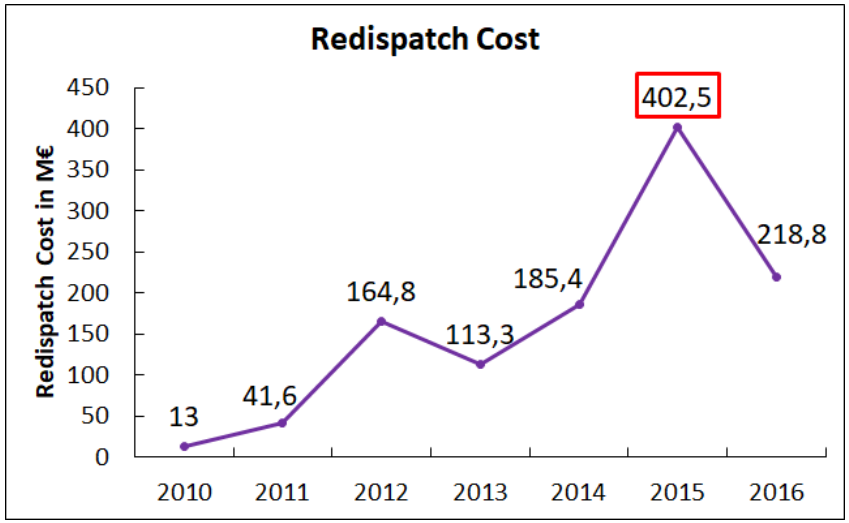


Optimum located at boundary of considered security region

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

Eliminate redispatching costs

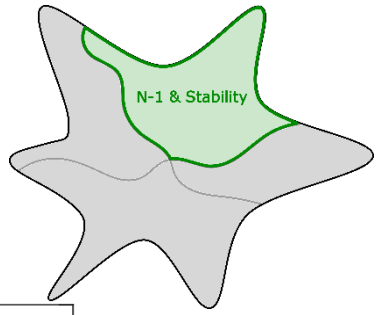


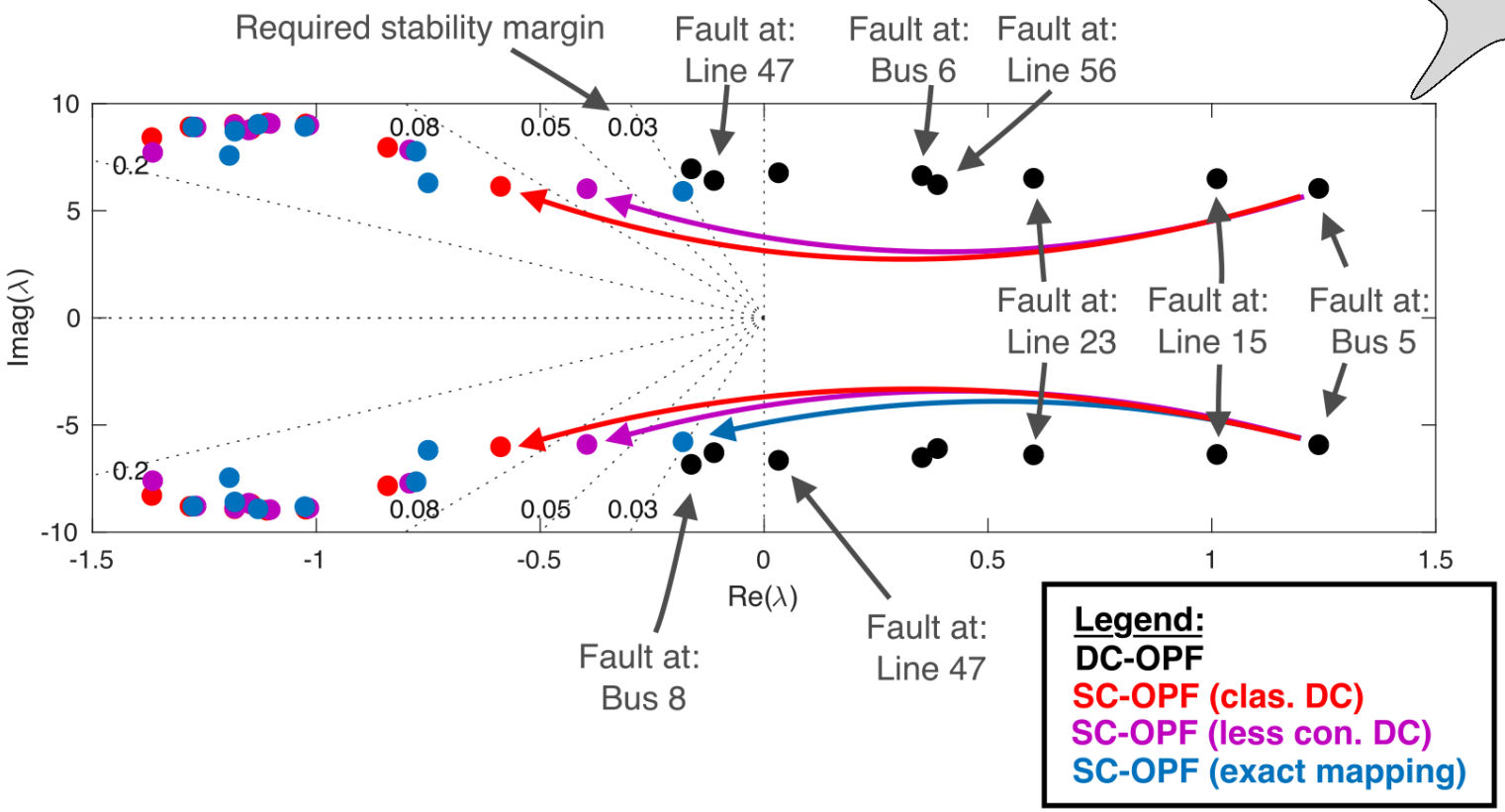


- Redispatching costs: over 400 Million Euros in a year, just for Germany
- Data-driven SC-OPF for markets: DC-OPF becomes MILP
  - **But,** MILP is already included in market software (e.g. Euphemia, for block offers, etc.)
  - Efficient MILP solvers already existing

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

Eliminate redispatching costs

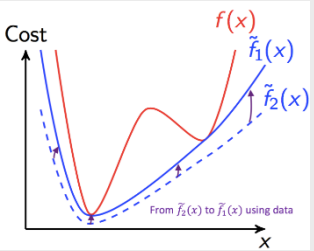


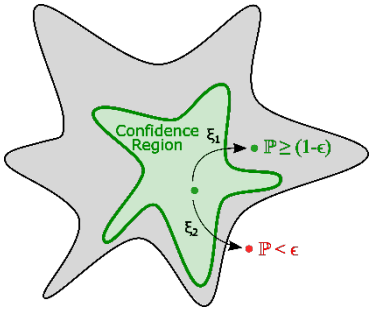


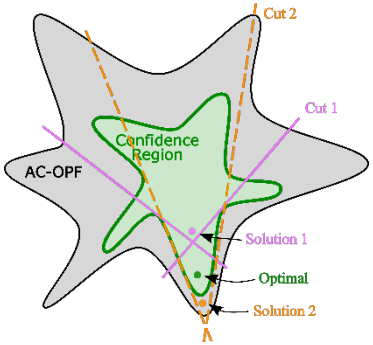
OPF under uncertainty

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

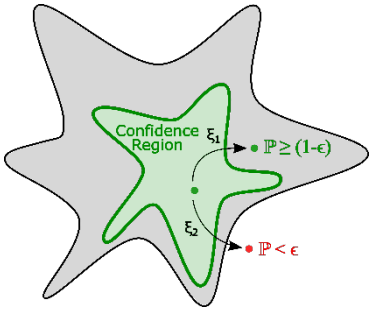
$$\mathbb{P}\left(\left(P_l + \Upsilon_l^P \xi\right)^2 + \left(Q_l + \Upsilon_l^Q \xi\right)^2 \leq (\bar{S}_l)^2\right) \geq 1 - \epsilon$$

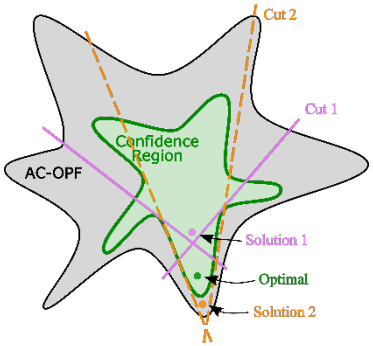
(II)*

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

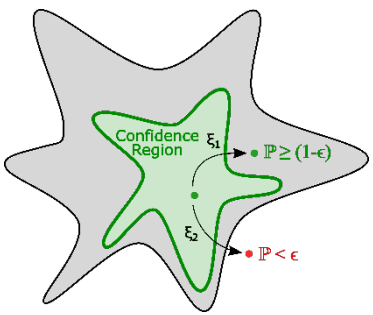




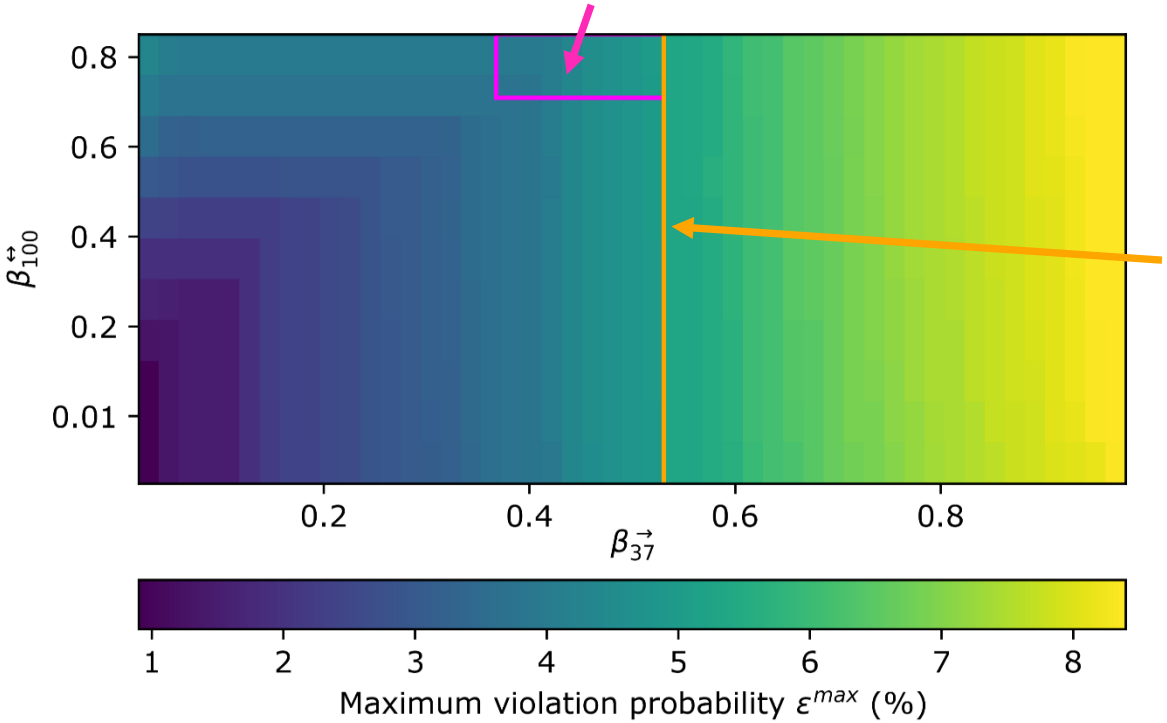
$\beta_l \in (0,1)$ ensures $\mathbb{P}\big((1) \cup (2)\big) \geq 1 - \epsilon$

* 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

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)

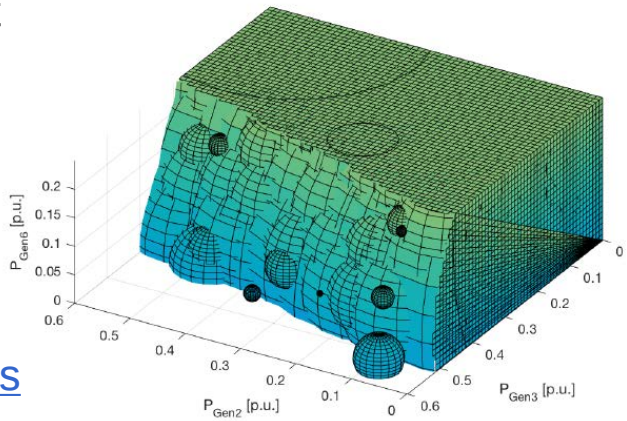
- Generated Database for NESTA 162-bus system online available! https://github.com/johnnyDEDK/OPs_Nesta162Bus

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)
- Convex relaxations and “directed walks”
- **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://github.com/johnnyDEDK/OPs_Nesta162Bus

  (~1,000,000 points)



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