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Data-Driven Security-Constrained OPF

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1. Introduction:
This work unifies electricity market operations with power system security considerations. Using data-driven techniques, we address both small signal stability and N-1 security, derive tractable decision rules in the form of line flow limits, and incorporate the resulting constraints in market clearing algorithms. Our goal is to minimize redispatching actions, and instead allow the market to determine the most cost-efficient dispatch while considering all security constraints.

2. Methodology

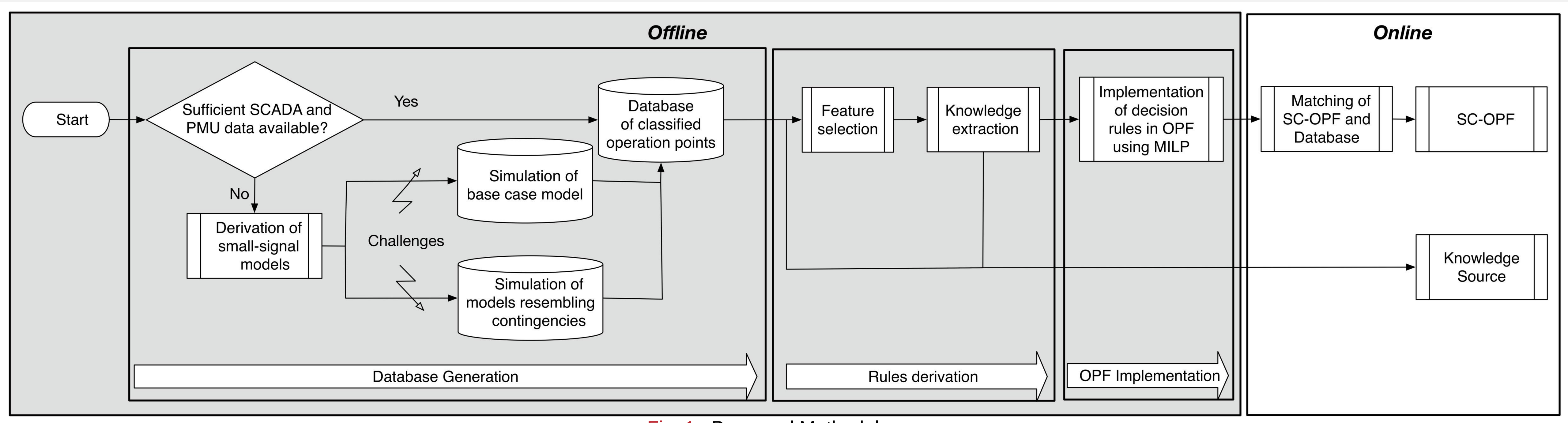

Fig. 1.: Proposed Methodology

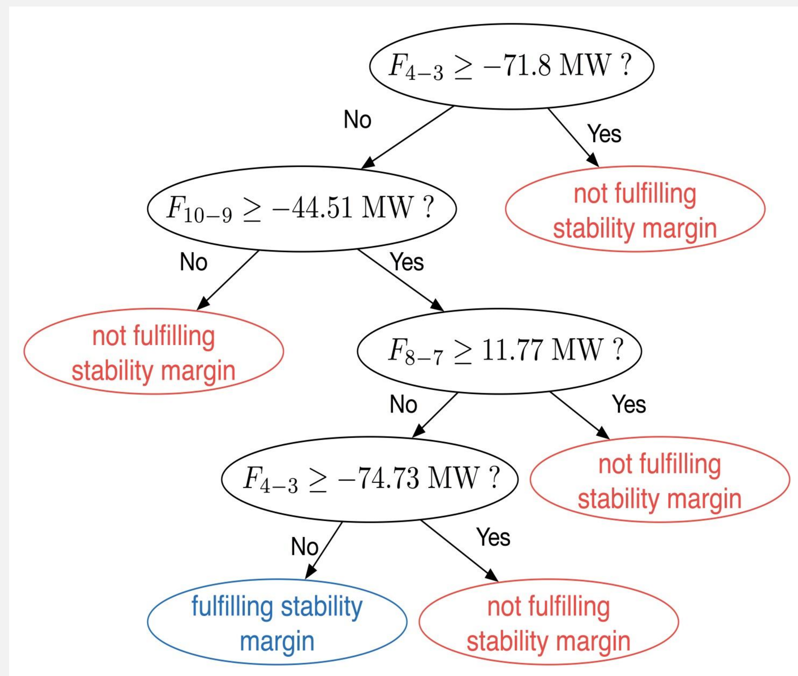

Fig. 2.: A simple example of a decision tree

2.1. Data Generation

Derivation of small-signal models:
- Symbolic derivation of multi-machine system without contingency as base case
  - Sixth order synchrounous machine model with AVR and delay
- N-1 security considered by adjusting small-signal model to contingencies:
  - $\Gamma + 1$ small signal models for Γ contingencies

Simulation:
- All models are initialized for all credible generation patterns using Matpower 6.0
- Considering loadlevels between -20% to +20%
- Operating points are classified as "fulfilling stability margin" or "not fulfilling stab. margin"

Challenges:
- keeping the database as small as possible to minimize computational demand
- determining the stability boundary as precise as possible

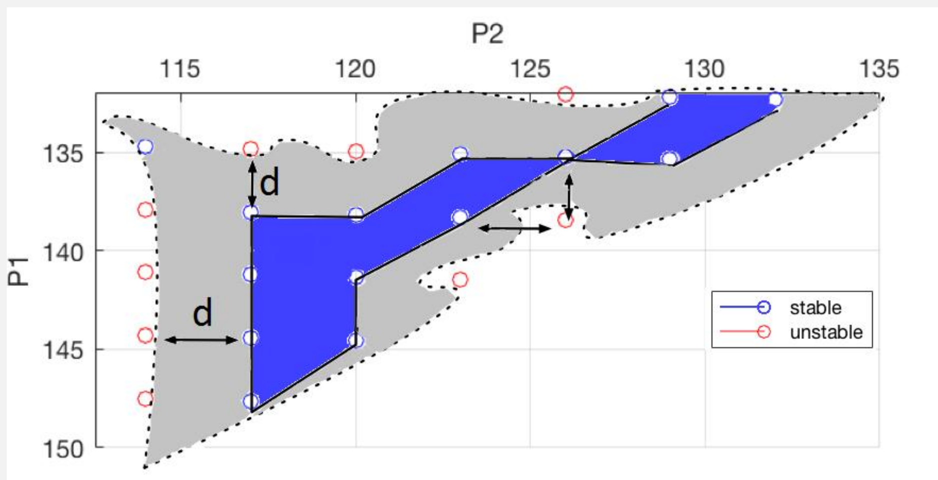

Fig. 3.: Step size (d) of simulation needs to be chosen in a way that the area of stable operating points (purple) is maximized while the area of uncertain / potentially stable operating points (grey) which lies between stable (blue) and unstable (red) operating points is minimized.

2.2. Rules Derivation

Feature selection:
- Good mapping between security analysis using AC power flow and market clearing using DC power flow required (line flows can differ significantly)
- Accuracy of mapping determines level of conservatism of line flow limits
- Three approaches:
  - Standart DC Approximation: $F_{nm}^{dc} = \frac{\theta_n - \theta_m}{x_{nm}}$
  - Less conservative approximation: $F_{nm}^{dc} = \frac{|V_n||V_m| \sin(\theta_n - \theta_m)}{x_{nm}}$
  - Exact Mapping of DC and AC operating point:
    - Incorporating the mapping in data generation:
    - Line losses of AC power flow are included as additional loads in a subsequent dc power flow as follows:

$$P_{Loss,n} = \frac{1}{2} \cdot \sum_{m \epsilon I_n} (F_{nm}^{ac} + F_{nm}^{ac})$$

I_n:Set of nodes connected to node n
F_{nm}^{ac}:line flows from AC power flow

    - Line flows of subsequent DC power flow augmented with losses from AC power flow represent exact mapping

Knowledge Extraction:
- Decision trees (DTs) are proposed as knowledge extraction method due to the possibility to define conditional transfer limits based on derived rules (Fig. 1)
- DT is trained using a subset A of the whole database and tested using another subset B of the database with $A \cup B = \emptyset$
- Issue of skrewed classes adressed by raising cost of misclassifying the minority class
- Danger of misclassifying unstable case as stable reduced by:
  - Increasing cost of misclassifying stable cases
  - Introduction of stab. margin of min 3% damp. ratio instead of stable vs unstable
  - Over-fitting avoided by an appropriate pruning

2.3. OPF Implementation

Standart DC-OPF:

$$\min_{P_G} \sum_{i=1}^{N_G} c_{G,i} P_{G,i}$$
$$s.t. \sum_{i=1}^{N_G} P_G - \sum_{n=1}^{N_B} P_{D,n} = 0,$$
$$-F_L^{max} \leq PTDF \cdot (P_G - P_D) \leq F_L^{max}$$
$$0 \leq P_G \leq P_G^{max}$$

N_G: Number generators
N_D: Number buses
$P_{G/D}$: Power gen. / demand
F_L^{max}: Line flow limit
$PTDF$: Power Transfer Distribution Factors
P: Set of full paths of decision tree
y_p: binary variable correspond. to a specific path of the tree

SC-OPF:

$$PTDF \cdot (P_G - P_D) \leq F_{L,p}^{max} y_p + F_L^{max}(1 - y_p) \quad \forall p \in P$$
$$PTDF \cdot (P_G - P_D) \geq F_{L,p}^{min} y_p - F_L^{min}(1 - y_p) \quad \forall p \in P$$
$$\sum_p y_p = 1.$$

Matching of SC-OPF and Database:
- Losses are not inherently considered
  - ➢ operating points need to be matched
- OPF is not know apriori but line flows and losses depend on generation pattern
  - ➢ initial best guess of the operating point is crucial to achieve a good matching
  - ➢ database is searched for cheapest operating point fulfilling the stability margin
- Losses of this "best guess" are used to augment DC-OPF and SC-OPF

3. Results

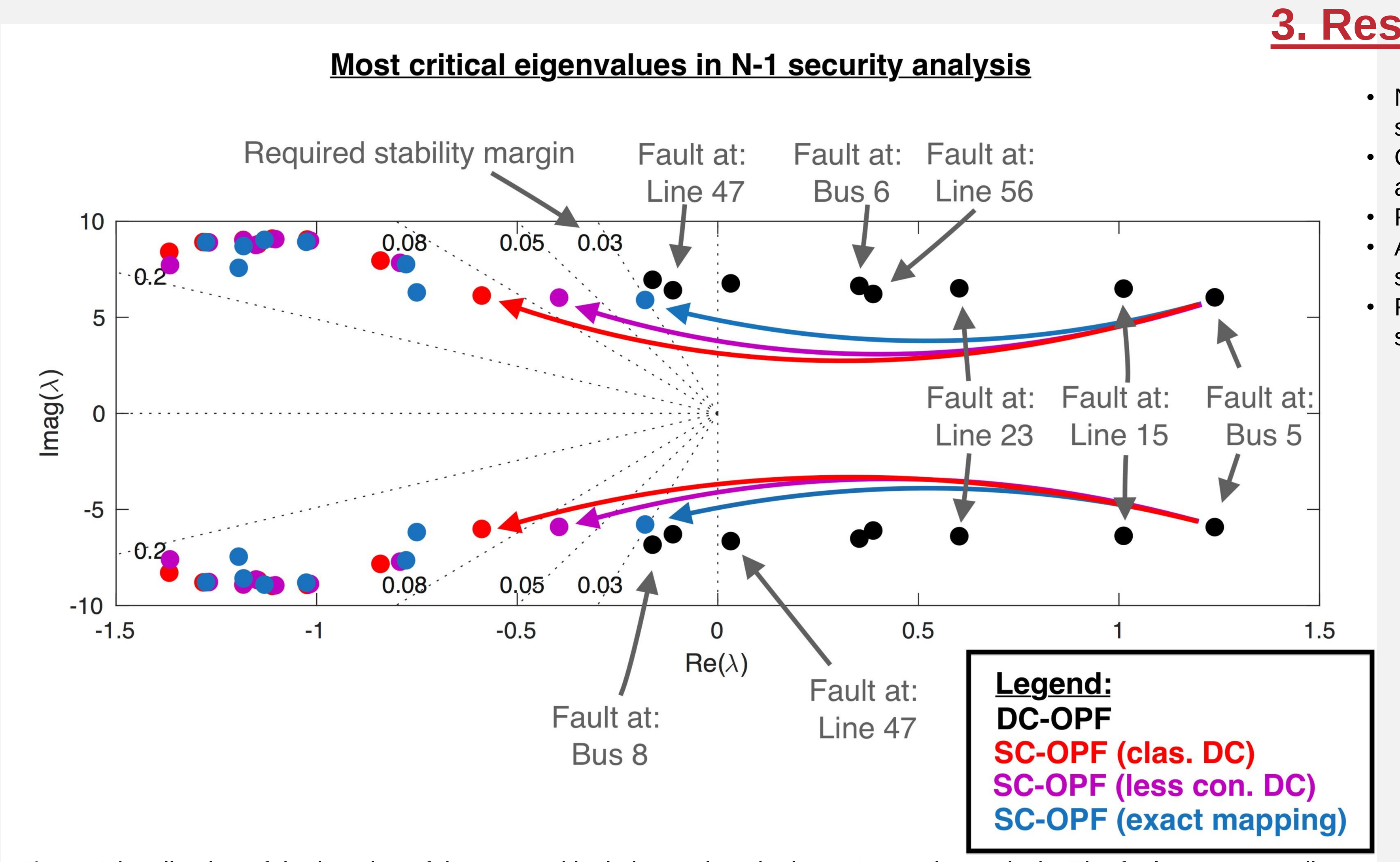

Fig. 4.: Visualization of the location of the most critical eigenvalues in the N-1 security analysis. The faults corresponding to the critical eigenvalues are denoted in grey. The small signal models resembling the faults differ by the base case in that way that they consider the disconnection of the corresponding elements. Any contingency not violating the required stability margin of 3% is neglected.

- Novel data-driven SC-OPF ensures small-signal stability and N-1 security
- Conditional line flow limits capture security considerations accurately while being less conservative than current approaches
- Results show importance of a good mapping approach
- Additional analyses in [1] indicate the importance of a small step size during data base generation
- Fast execution time (between 0.98s and 26.64s depending on tree size / database size)

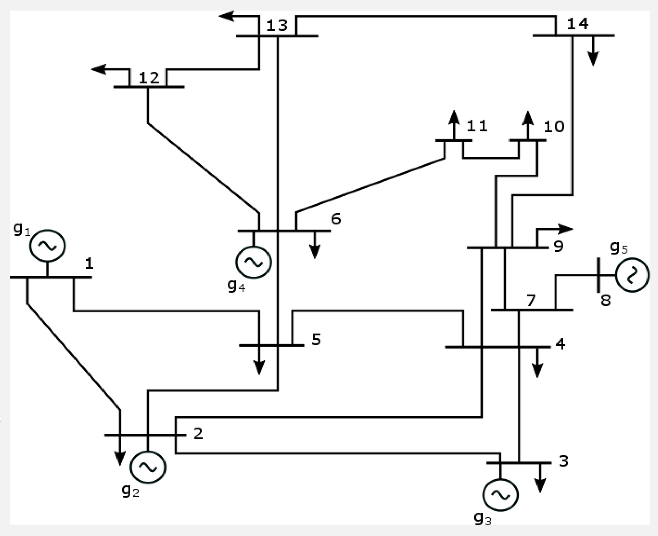
Fig. 5.: IEEE 14 Bus System [1]

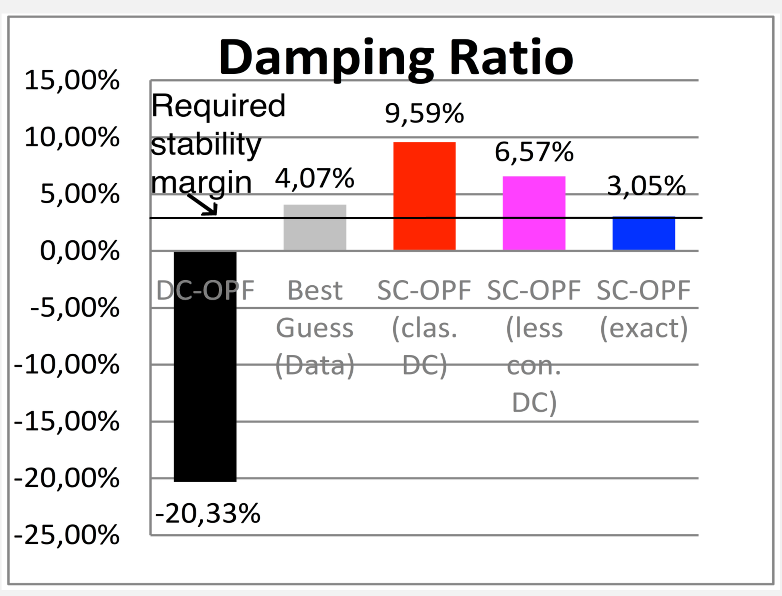

Fig. 6.: Minimum damping ratio for all contingencies depending on mapping approach

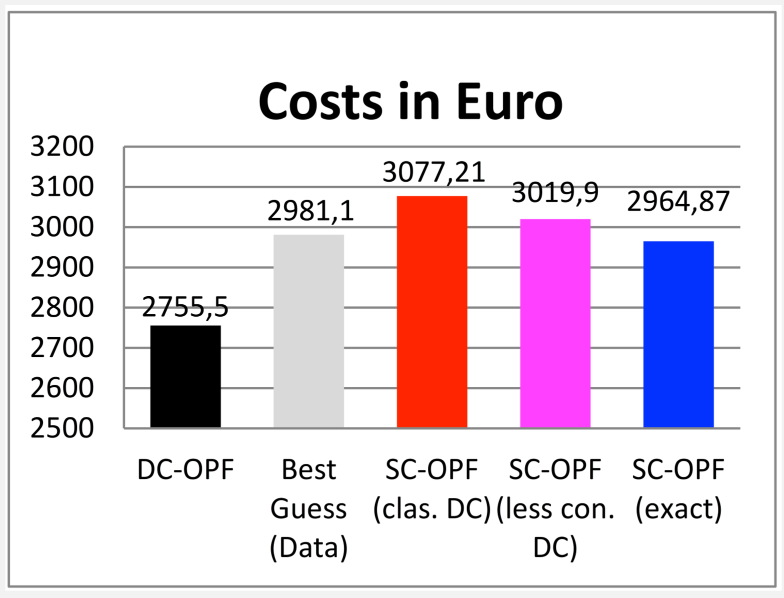

Fig. 7.: Costs for a specific load level depending on mapping approach

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[1] F. Thams, L. Halilbašić, P. Pinson, S. Chatzivasileiadis, and R. Eriksson,*"Data-Driven Security-Constrained OPF",* accepted for presentation at IREP 2017.