Graph topology search for power grids

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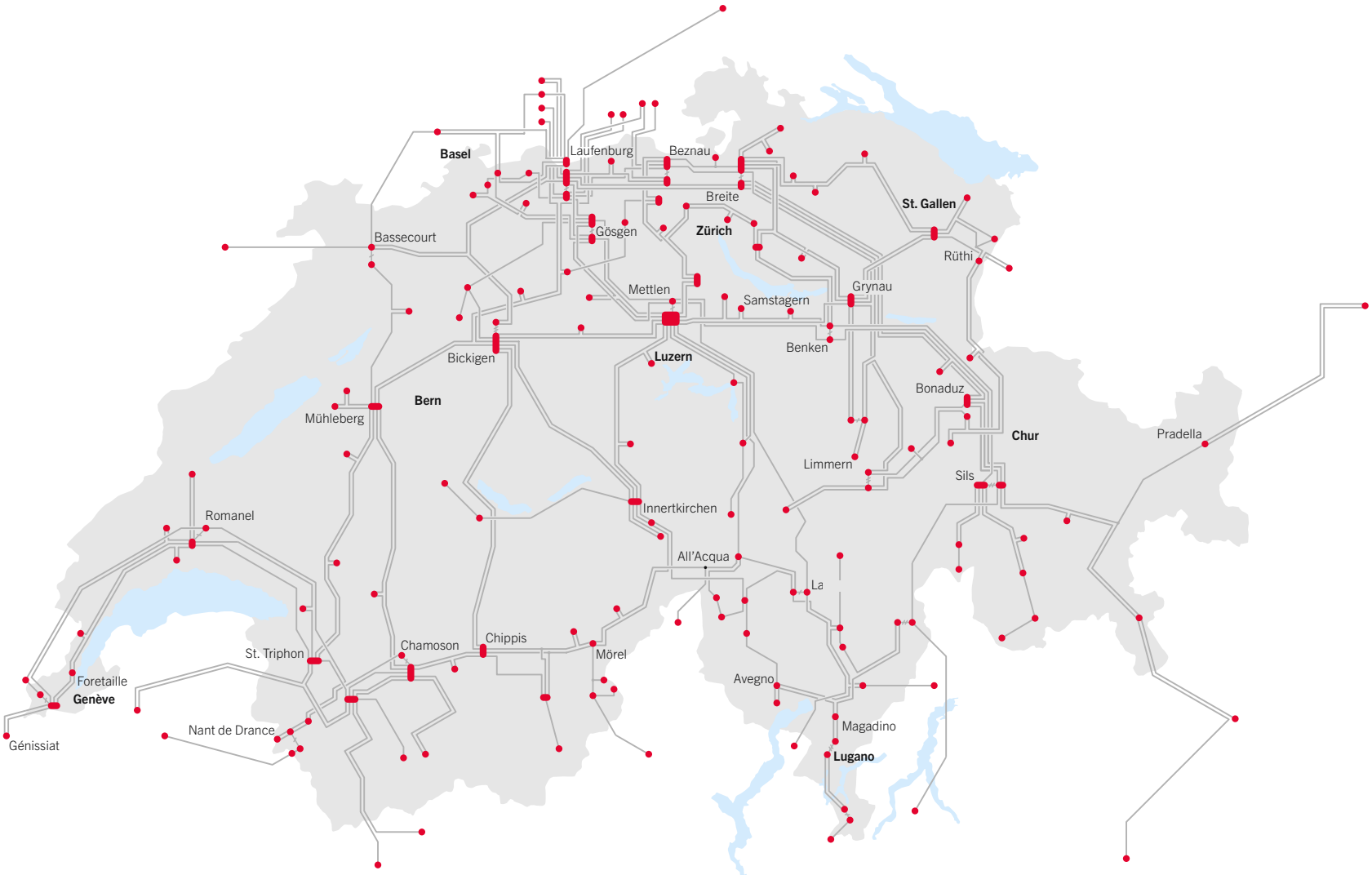
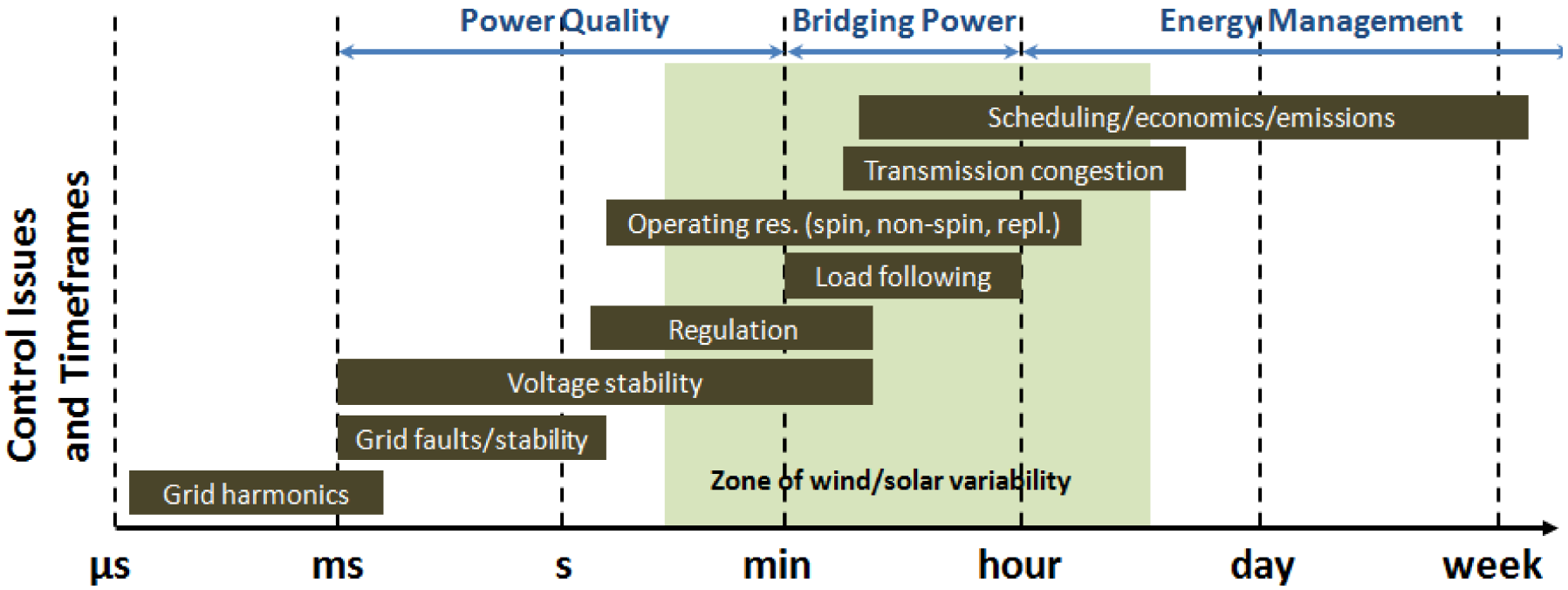
Outline

Outline

High voltage power grids



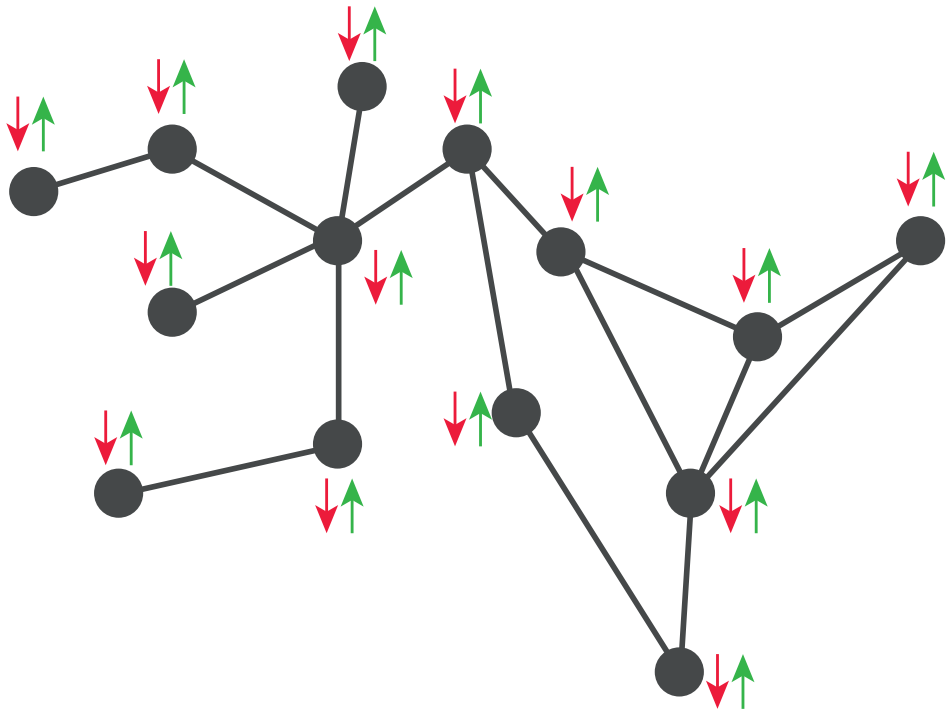
Context: contingency planning



Adapted from [1]

- Focus: the 'congestion' time scale, ranging from **minutes to hours**

Sources of uncertainty



Roughly speaking, two categories:

1. Uncertainty related to power flows **into and out of** the network
2. Uncertainty related to the **network itself**, e.g. component failures

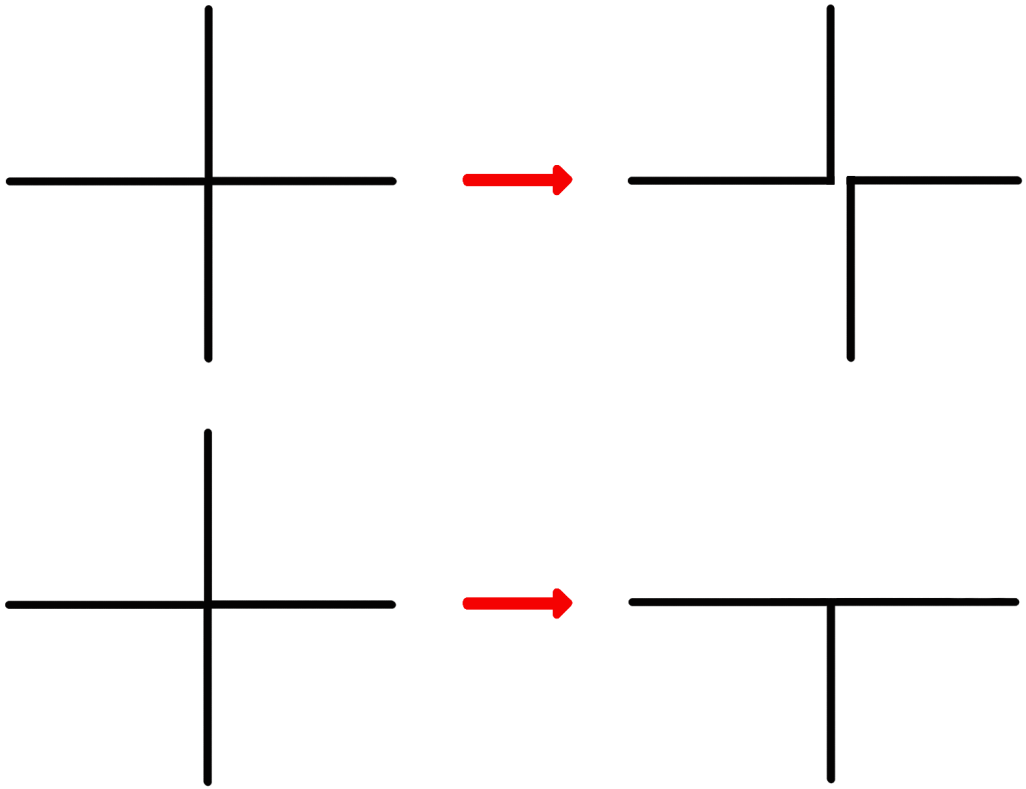
Outline

Power flow equations

$$P_i = \sum_j |V_i||V_j|\left[B_{ij}\sin(\theta_i - \theta_j) + G_{ij}\cos(\theta_i - \theta_j)\right]$$

$$Q_i = \sum_j |V_i||V_j|\left[G_{ij}\sin(\theta_i - \theta_j) - B_{ij}\cos(\theta_i - \theta_j)\right]$$

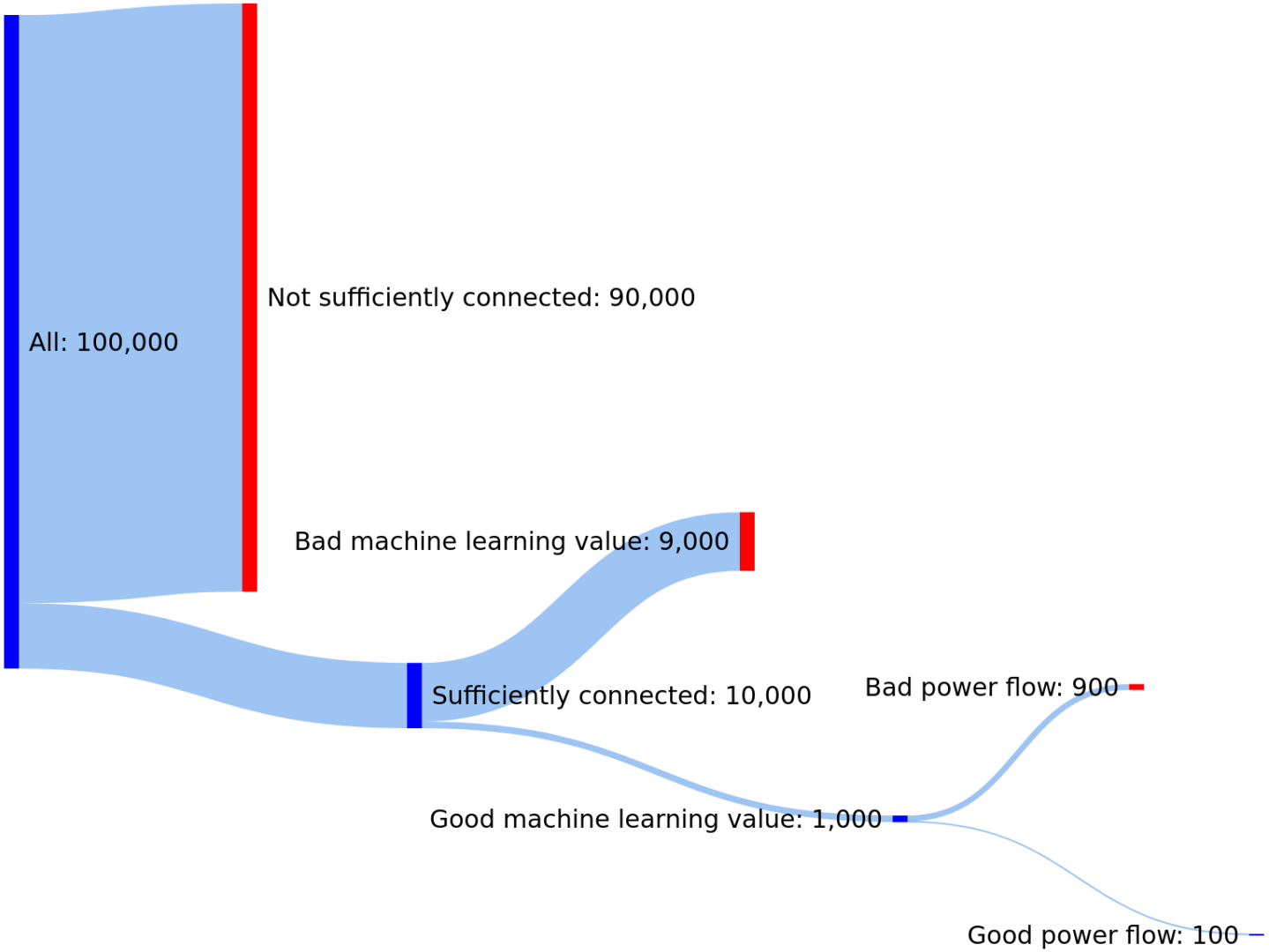
Busbar splits and line switches



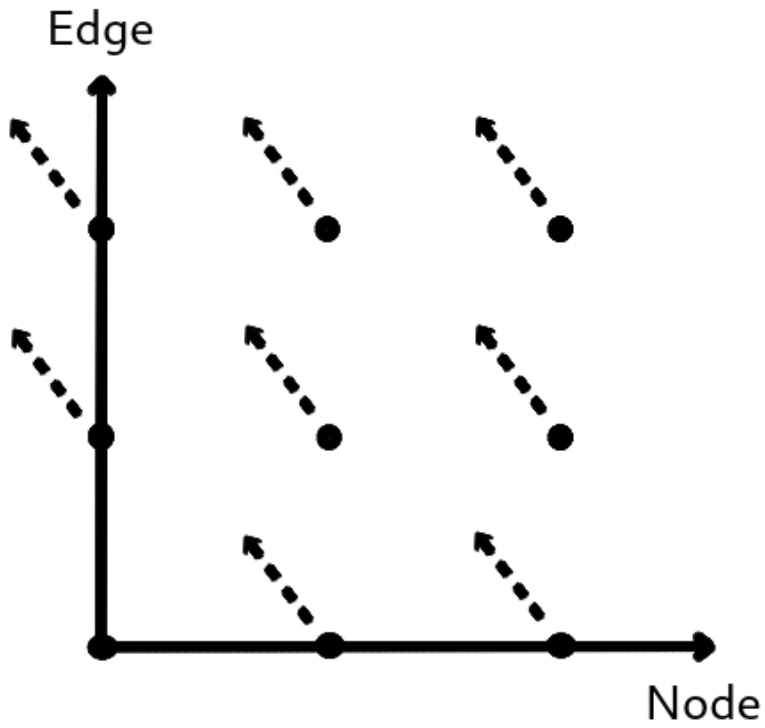
Exponential blow-up:

- On a medium-sized regional grid, around $\mathbf{10^{20}}$ possibilities

Filtering possibilities

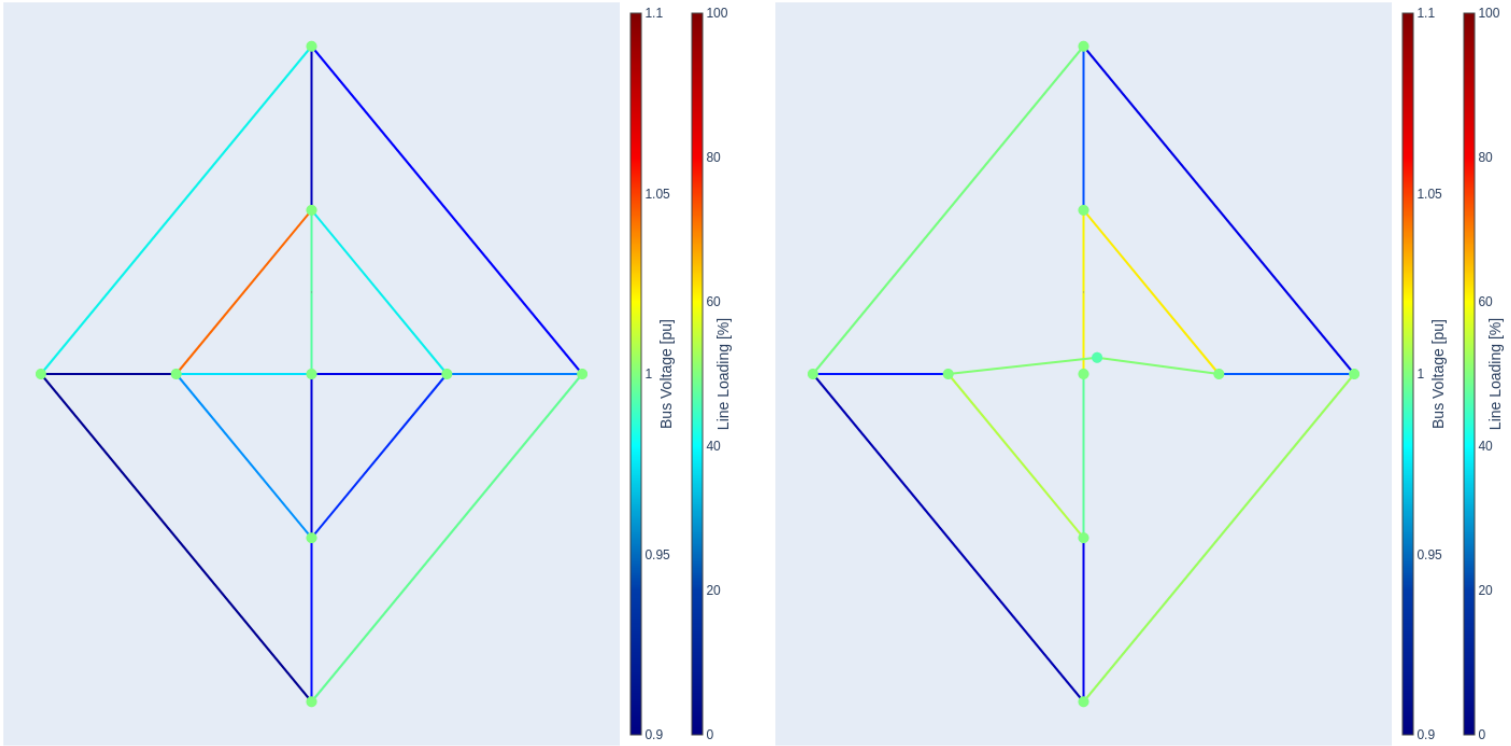


Framework for exploring

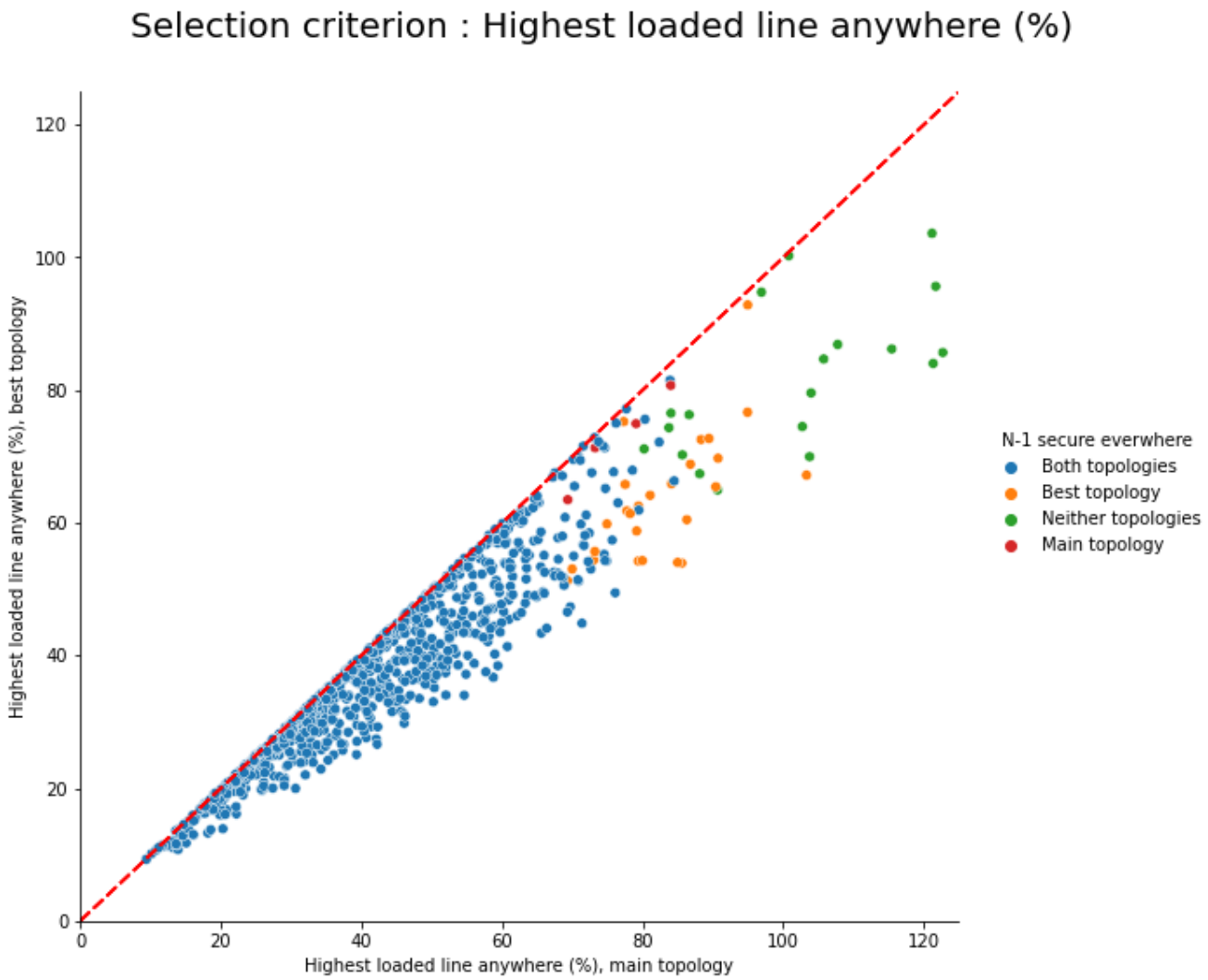


- Edge coordinate: $\{1,\ 3,\ 5\}$
- Node coordinate: $\{(1,\ \{2,\ 4\},\ \{6,\ 7\}),\ (3,\ \{8,\ 9\},\ \{10,\ 12\})\}$

Brute-forcing a toy model (1)



Toy model results (1)



Outline

Conclusion

Results:

- **Coordinate framework** for exploring the space of grid topologies
- **Fast power flow computation** for many scenarios and topologies
- **Promising results on toy model**: often able to solve or decrease congestion, even when accounting for component failure

Future work:

- Finish up brute-force work with a small real-world grid
- Beyond brute force: search strategies, graph neural network

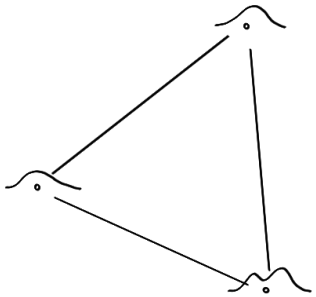
Thank you!

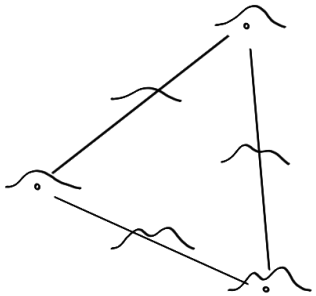
References

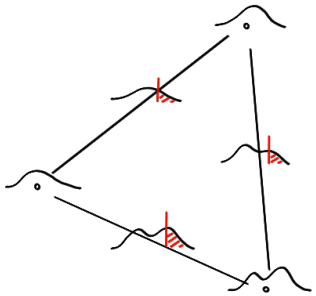
[1] Vladimir Koritarov, Tao Guo, Erik Ela, Bruno Trouille, James Feltes, and Michael Reed.
Modeling and simulation of advanced pumped-storage hydropower technologies and their contributions to the power system.
Proc. HydroVision, pages 22–25, 2014.

Appendix

Graphical depiction







1. Forecasting probability distributions of the power injections

2. Proposing alternative topologies and translating injections to power flows on grid components for each topology

3. Quantifying risks of overloading grid components and selecting an optimal topology

Combinatorial problems

The space of grid topologies is enormous. As an example, let's say:

- Around 10 ways to configure a substation
- Around 10 substations
- Around 30 lines

Result:

- 10^{10} for the substations, $2^{30} \approx 10^{10}$ for the lines
- **10^{20} possibilities in total**

Topology search: state of the art

Industry:

- Operator relies mostly on intuition and experience

Academic work mainly done in either of two directions:

- From the '80s: include one or two lines in optimization
- Present: machine learning on fully automating grid operation

Seemingly, not much done in the middle:

- **Exploring and pruning** the 'tree of possibilities'

First filter: graph theory

For N-1 security, we need to maintain **at least two independent paths** between every grid element, regardless of the scenario.

This translates to the following graph-theoretical notions:

- The graph needs to be **2-edge connected**: you need to remove at least two edges in order to disconnect the graph
- A necessary condition for this is that the degree at every node needs to be 2 or higher (this is easier to check)

Filtering iteratively

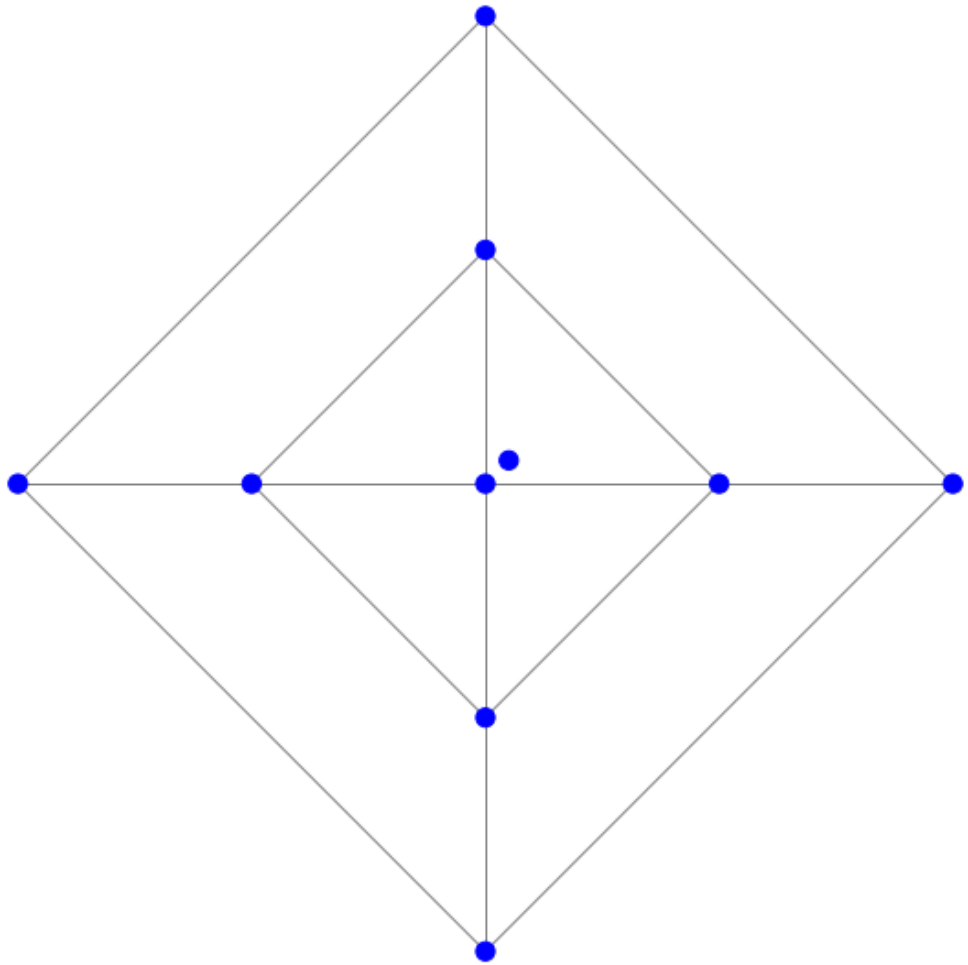
Exploring the 'graph of graphs':

1. Map out vicinity of operating state
2. Filter topologies and store relevant results
3. Map out further from the most promising topologies

Potential filters beyond 'connectedness':

- Graph neural network mapping topology plus scenario to a value
- Other graph theoretical measures
- Heuristics based on power flow quantities
- Strategies discovered empirically

Brute-forcing a toy model (2)



Brute-forcing a toy model (3)

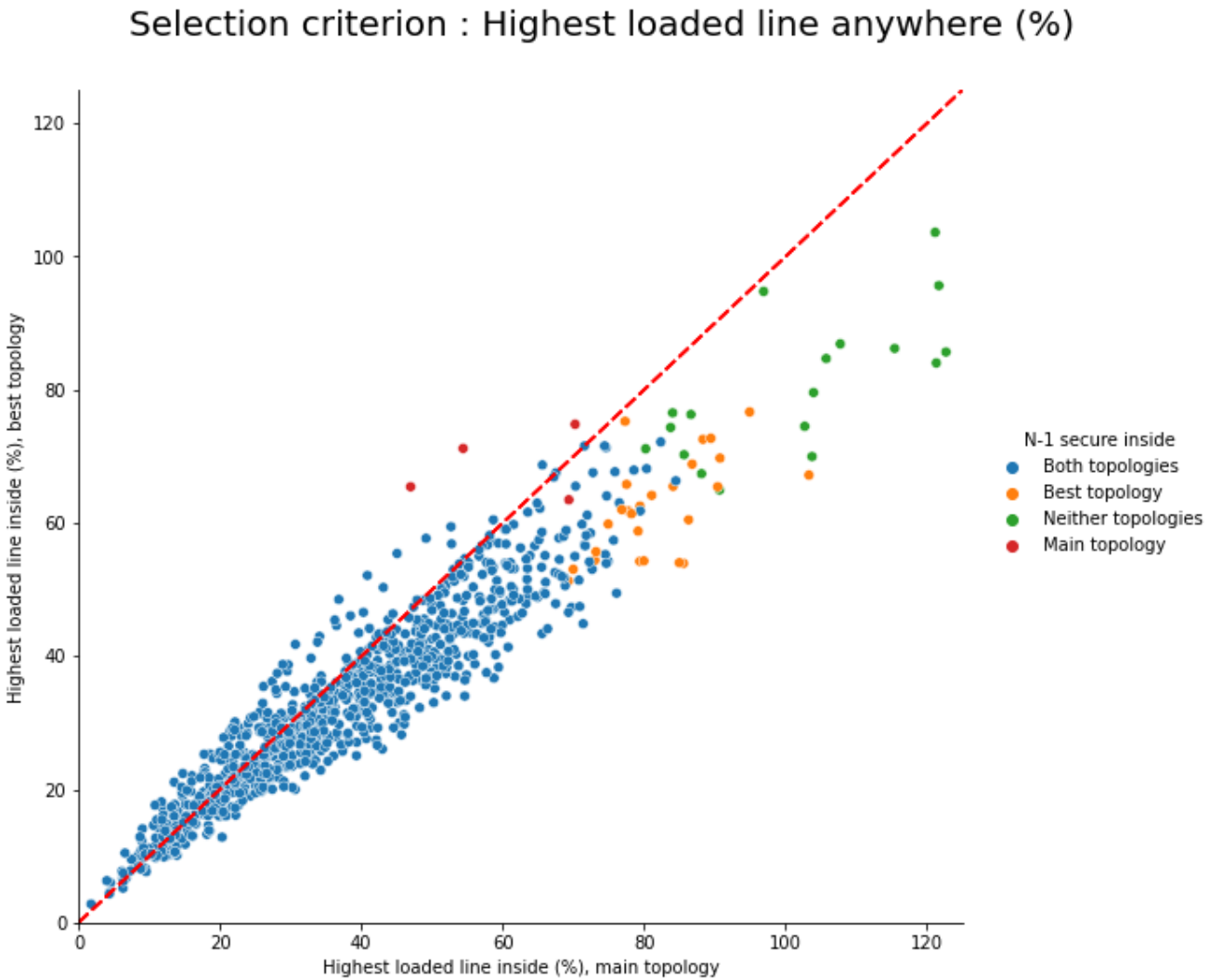
Without filters:

- 8 lines to switch on or off: 2^8 possibilities
- 4 lines on one or the other bus at substation: 2^4 possibilities
- 1 generator and 1 load on one or the other bus: 2^2 possibilities
- Total of $2^{14} =$ **16384 configurations**.

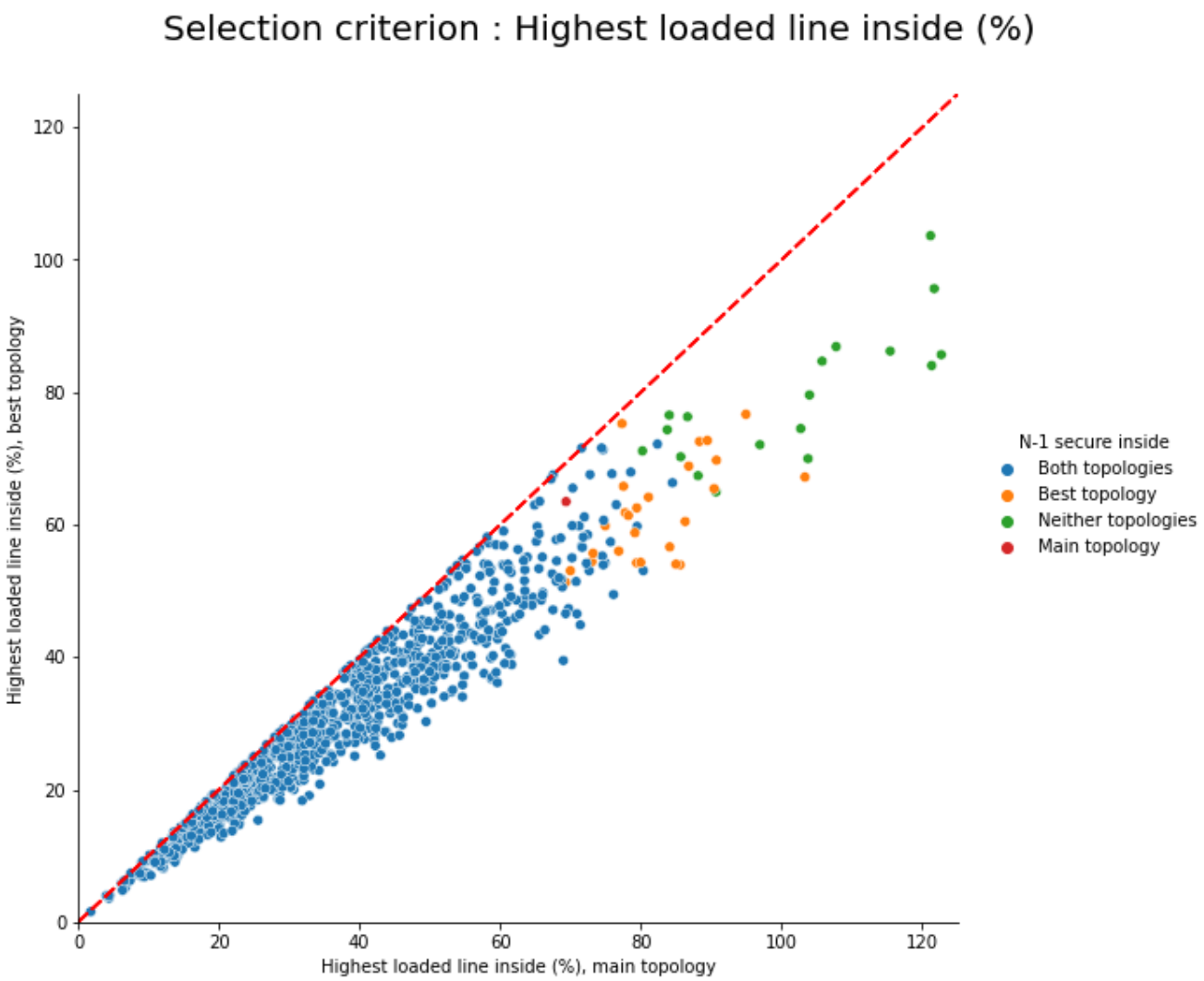
With 'connectedness' filter:

- **89 configurations**

Toy model results (2)



Toy model results (3)



Toy model results (4)