Rethinking N-1 Security: Balancing Reliability and Economy in Electricity Transmission

Applying chance-constrained congestion management optimization to evaluate the economic benefit of N-1 relaxation in the German high-voltage grid

Akshay Singh Yadav (Speaker)
Master's Student in CMS, Energy Economics, TU Dresden

Hannes Hobbie
Post-Doctoral Researcher in Energy Economics, TU Dresden

Enerday Dresden, 4 April 2025

1

Background and Approach

Alternative to strict N-1 criterion

Adaptable N-1 strategy to counteract increasing congestion management requirement

Increasing congestion management costs:

- **60% rise** in Germany's congestion management volumes (5-year trend).
- **Costs more than doubled** for grid interventions during same period.

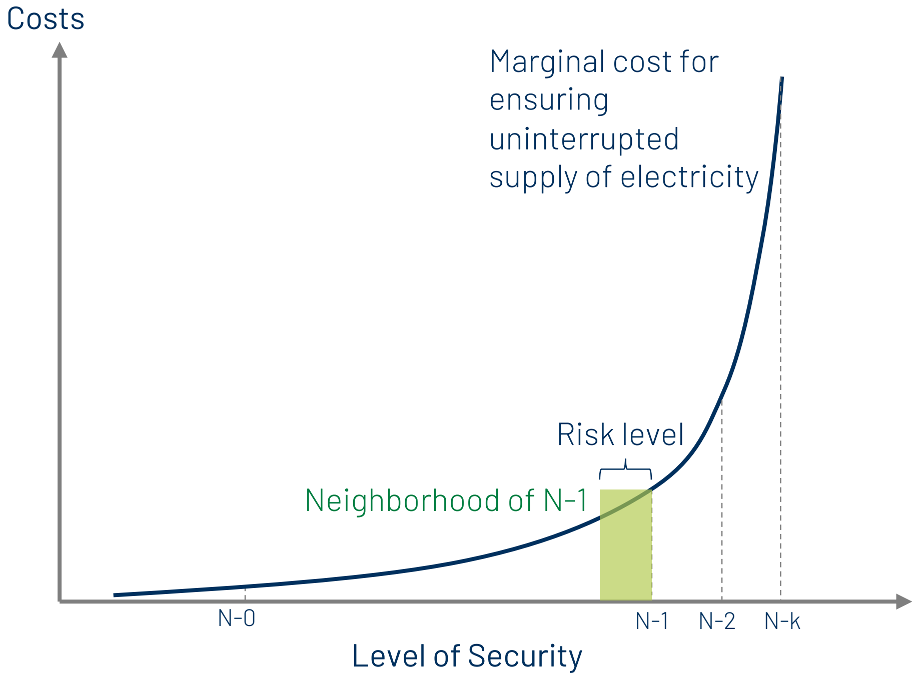
N-1 criterion:

- Although important for grid security, it 'worsens' the situation by reserving flow capacity for rare single-line failures.

Objective: Adaptable N-1 strategy

- A risk-aware relaxation of N-1: For selected lines and limited hours.

Theoretical relationship between the marginal cost and the level of supply security



ELTRAMOD determines the cost optimal power plant dispatch to serve the electricity demand

ELTRAMOD

ELMOD

Market Model
Optimisation of plant dispatch considering zonal market clearing

Grid- (Congestion Management) Model
Optimisation of congestion relief considering transmission constraints

1h time resolution

- RES capacity factors
- Electricity demand
- Plant availability
- Fuel prices
- CO_2 prices
- NTC

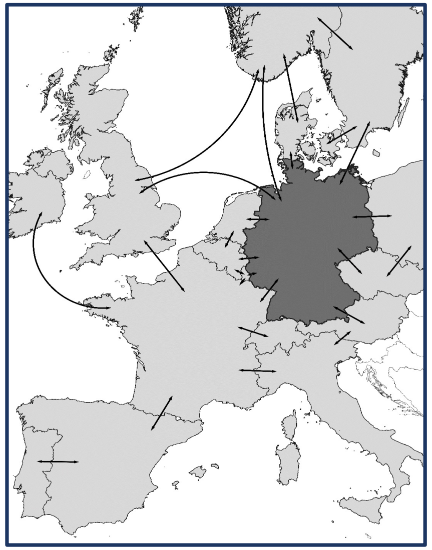
Time series data

+

Static

- Plant capacity
- Technological characteristics
- Fixed costs
- NTC Projections

Fundamental data



$$\min \sum_{p,t} G(p,t) * cost(p)$$

$$s.t. \sum_{p} G(p,t) - \sum_{n} dem(n,t) = 0$$

$$G(p,t) \leq pmax(p) * avail(p,t)$$

Simplified illustration*

- Optimsation for 8760 hours of a year

- Wholesale power prices
- **Plant dispatch**
- CO_2 – Emissions

Model Output

* … Number of equations and variables in the magnitude of millions.

ELMOD adjusts the market based power plant dispatch to correct for power flow restrictions

ELTRAMOD

Market Model
Optimisation of plant dispatch considering zonal market clearing

ELMOD

Grid-(Congestion Management) Model
Optimisation of congestion relief considering transmission constraints

Plant dispatch

1h time resolution

- Node-specific RES capacity factors
- Node-specific demand
- Fuel prices
- CO_2 prices

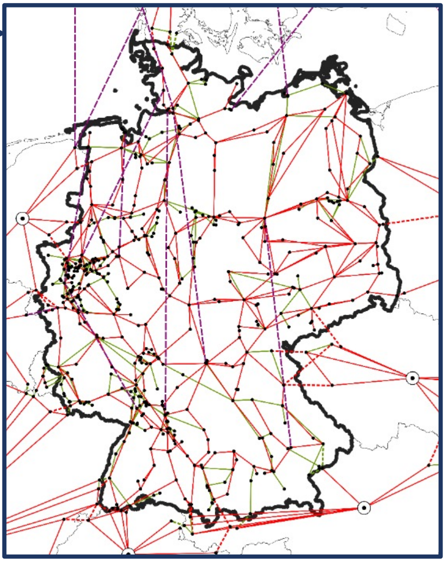
Time series data

+

Static

- Node-specific plant capacity
- Power line capacity
- Technological characteristics

Fundamental data



$$min \sum_{p,t} (RDup(p,t) - RDdown(p,t)) * cost(p)$$

$$s.t. \sum_{p} g\_da(p,t) + RDup(p,t) - RDdown(p,t) - dem(n,t) - NetI(n,t) = 0$$

$$f\big(NetI(n,t)\big) = LF(l,t)$$

$$g\big(LF(L,t)\big) \leq line\ capacity(l)$$

$$h(RDup(p,t), RDdown(p,t)) \leq z(p,t)$$

Simplified illustration*

- Rolling planning optimisation (e.g. 48 hours)

- Load flows (DC Approximation)
- **Redispatch**
- Grid congestions
- **RES curtailment**

Model Output

* … Number of equations and variables in the magnitude of hundreds of millions.

Formal definition of a Chance-Constrained Program

A **Chance-Constrained Program** is an optimization framework designed to make decisions under uncertainty. Instead of enforcing strict feasibility in all cases, it ensures constraints are satisfied with high probability – allowing controlled risk violations:

Standard Linear Program

$$\min_{\boldsymbol{x} \in \boldsymbol{X}} \quad \boldsymbol{f}(\boldsymbol{x})$$

$$\text{s.t.} \quad \boldsymbol{g}(\boldsymbol{x}) \leq \boldsymbol{0}$$

where:

- $\mathbb{P}\left(\boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}(\boldsymbol{\xi})) \leq \boldsymbol{0}\right) \geq \boldsymbol{1} - \boldsymbol{\epsilon}$ ensures that constraints, e.g., n-1 secured power flow, are satisfied with probability at least $\boldsymbol{1} - \boldsymbol{\epsilon}$.
- $\boldsymbol{\epsilon}$ represents the desired reliability level (e.g., 5%).

Mixed integer program (MIP) formulated to choose between two levels of grid security

- Two operation modes: A binary variable $(B_{t,l})$ decides whether to relax N-1 security for a line at a given time.

N-1 secured power flow restrictions:

$$\left.\begin{aligned} &\textstyle\sum_{n\in N} (Q_{t,n} \cdot cptdf_{l,n}) - M \cdot B_{t,l} \leq cap_l^{AC} \\ &\textstyle\sum_{n\in N} (Q_{t,n} \cdot cptdf_{l,n}) + M \cdot B_{t,l} \geq -cap_l^{AC} \end{aligned}\right\}$$

Enforces N-1 security for most of lines and time steps through applying contingency-based PTDFs. $: B_{t,l} = 0$

N-0 power flow restrictions:

$$\left.\begin{aligned} &\textstyle\sum_{n\in N} (Q_{t,n} \cdot ptdf_{l,n}) - M \cdot (1 - B_{t,l}) \leq cap_l^{AC} \\ &\textstyle\sum_{n\in N} (Q_{t,n} \cdot ptdf_{l,n}) + M \cdot (1 - B_{t,l}) \geq -cap_l^{AC} \end{aligned}\right\}$$

Uses relaxed constraints* for economically beneficial lines and time steps through neglecting contingency events. $: B_{t,l} = 1$

Notations:

$cptdf_{l,n}$: Contingency power transmission distribution factor

$ptdf_{l,n}$: Power transmission distribution factor

cap_l^{AC} : Thermal capacity of the transmission line

M : Sufficiently large constant

* The relaxed formulation is solved with a reduced thermal capacity to account for operational uncertainties beyond N-1 security.

Controlling risk level via binary variable activations

- The maximum number of allowed N-1 constraint relaxations is governed by a predefined risk level ($\boldsymbol{\varepsilon}$).
- Two distinct formulations are used to enforce this limit:

1) Time-based relaxation

$$\sum_{t \in T} B_t \leq \varepsilon\% \cdot |T| \quad \forall L$$

Each time step may allow one relaxation, with the total number of relaxed instances bounded by the risk threshold across the **full time horizon**.

2) Line-based relaxation

$$\sum_{t \in T} \sum_{l \in L} B_{t,l} \leq \varepsilon\% \cdot (|T| \cdot |L|)$$

Allows selective relaxation across both **time steps** and **transmission lines**, enabling more granular control of N-1 security constraints.

2

Case Study:

Implementation Across Grid Conditions and Temporal Horizons, Finding Numerical Insights.

Scenario analysis employed: Model is implemented on variety of planning horizon and grid conditions

- Chance constrained model
  - Long span planning (Annual)
    - Time based relaxation
      - 4 Methods to handle global constraint
  - Short span planning (Single-day)
    - Time based relaxation
    - Line based relaxation

Impact of global constraint handling methods on congestion management costs (risk level: 5%)

4 Methods of identifying high-value hours to relax:

- M1: Cost-Trade Evaluation Function
- M2: Estimated Economic Gain – Hourly
- M3: Estimated Economic Gain – planning horizon (Concentrated)
- M4: Estimated Economic Gain – planning horizon (Spread)

Results:

- Method 4 and 3 yield the highest cost savings, followed by Methods 2 and 1, but require balancing cost reduction with risk levels.
- Significant cost-saving days often involve relaxing N-1 security for **18–24 hours.**

Scenario analysis employed: Model is implemented on variety of planning horizon and grid conditions

- Chance constrained model
  - Long span planning (Annual)
    - Time based relaxation
      - 4 Methods to handle global constraint
  - Short span planning (Single-day)
    - Time based relaxation
    - Line based relaxation

Time and Line based relaxations on a single-day

Scenarios: Three specific days in 2017

- Day 348 (Scenario C): Highest residual demand.
- Day 153 (Scenario A): Largest positive-negative redispatch gap.
- Day 158 (Scenario B): Highest renewable generation.

3

Conclusion:
Key Takeaways

Rethinking N-1: Conditional relaxation for efficient and secure grid dispatch

I. Why relaxing from N-1 to N-0 conditionally makes sense:

- Strict N-1 criterion might be overly conservative and economically inefficient .

II. Conditional N-1 is a natural evolution in modern grid operation:

- We accept N-0 operation temporarily where the risk is low, the economic benefit is high, and system impact is manageable for specific lines and hours.
    - On annual implementation, strategic N-1 relaxation during high-value grid events can reduce congestion costs by 30% at a 5% risk level.
    - On a single-day, While computationally intensive, line-based relaxation demonstrates higher daily cost savings even at lower risk-levels compared to time-based methods.

III. Benefits of chance-constrained redispatch:

- We propose a transparent and quantifiable trade-off between costs and risks, pushing towards risk-based security models recommended by, e.g., ENTSO-E.

Thank You

Questions and suggestions please!

Akshay Singh Yadav
Email: akshay_singh.yadav@mailbox.tu-dresden.de

Dr. Hannes Hobbie
Email: hannes.hobbie@tu-dresden.de

Web: www.ee2.biz

Chair of Energy Economics
Technische Universität Dresden
Münchner Platz 3
01069 Dresden