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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

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The German power grid is undergoing a significant transformation driven by the increasing integration of renewable energy sources. While this shift supports decarbonization goals, it introduces substantial challenges for grid stability and congestion management. The variability of renewable generation, coupled with regional supply-demand imbalances, exacerbates flow bottlenecks and connected congestion management requirements. For example, total congestion management volumes have increased by more than 60% and associated cost more than twice over the past 5 years in Germany. The enforcement of the N-1 security criterion compounds these issues by reserving additional transmission capacity to account for potential component failures, such as the outage of a transmission line. This study addresses these challenges by introducing a chance constrained congestion management model to relax the N-1 criteria in the hours and for the lines where cost benefit of the relaxation is highest. The developed framework provides a viable alternative to the stringent N-1 security criterion, offering TSOs a more flexible and cost-effective approach to grid management.

Congestion arises primarily due to two factors: (1) nodal energy insufficiency, where local supply-demand imbalances create nodal deficits or surpluses, in conjunction with (2) insufficient transmission line capacities, which limit the ability to transfer power between nodes to resolve these imbalances in accordance with market-based dispatch outcomes. We simulate model-endogenous nodal power imbalance resulting from (zonal) market equilibria according to market practices as dependent random variables for 8760 hours of a year and considering historic parametric information from 2017.
Simulating single-line failures reveals that power distribution factors are centered around the mean but exhibit long tails. Nodal injections driven by market outcomes follow similar long tail pattern –resulting in significant outliers in line flow calculations and consequential costly congestion management measures. By analyzing these outlier events, we identify inherent low-probability, high-cost grid condition patterns that motivate the development of a chance-constrained optimization framework.

The aim of the developed method is to explore the potential of selective relaxation of the N-1 criterion during low-probability events that result in high redispatch volumes. Our proposed grid optimization model extends the ELMOD framework, a well-established tool for simulating electricity markets and congestion management in the German grid. To simulate N-1 contingencies, we develop a novel methodology based on contingency power transmission distribution factors (CPTDFs). These factors capture the maximum possible power flow on a given line resulting from nodal injections under simulated line failures. By combining CPTDFs with modelled nodal injection volumes, we determine line flows under contingency scenarios. These contingency flows, along with a controlled proportion of normal operating flows, are then integrated into the congestion optimization model. The model utilizes a mixed-integer program to optimize the relaxation of the N-1 security criterion by strategically switching between contingency and normal operating flows for specific lines and hours, aiming to minimize congestion management costs for pre-defined reliability values representing different N-1 security levels.

Simulations across a range of parametric settings suggest that the model can contribute to reductions in congestion management costs and volumes to varying degrees. For long-term (annual) planning, we explore four methods to allocate relaxations across different time horizons. Methods that distribute relaxations on a daily

basis indicate the potential for notable cost reductions, with estimated annual savings in the range of up to 26–30%, while hourly distributions appear to offer more moderate reductions of approximately 2–4%. However, these cost savings come at the expense of reduced system security, as relaxing N-1 constraints inherently increases the risk of unmanageable contingencies. On a daily resolution, we evaluate the model under three grid conditions: high positive and negative redispatch gaps, high renewable penetration, and high residual demand. We introduce two relaxation strategies: (1) Cumulative Time-Based Relaxation: Relaxing all lines for a given hour; and (2) Individual Line-Based Relaxation: Selectively relaxing specific lines over time.
The results show consistent cost and volume reductions across all scenarios, with the extent of savings varying by grid condition. For instance, scenarios with high renewable penetration exhibit moderate savings compared to those with high residual demand and high redispatch gaps. While cumulative time-based relaxations are computationally efficient, individual line-based relaxations offer greater cost and volume reductions.
Analyzing frequently relaxed lines and hours reveals optimal relaxation strategies. While restricting relaxations (e.g., limiting the number of relaxation hours per line) can diminish cost savings, it provides valuable insights into the trade-off between economic benefits and grid security.

The study highlights the potential of chance-constrained N-1 security relaxation for transmission lines to reduce congestion management costs and volumes. The findings underscore the importance of adaptive and more flexible grid management strategies for effective congestion mitigation. The developed system-theoretic framework offers a valuable insight for TSOs and researchers seeking to harmonize competing demands of grid reliability and economic efficiency. Its practical benefit regarding integration into transmission system operation planning and security concerns is yet to be explored.

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