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Unlocking Hidden Grid Capacity: Risk-Based Line Overloading for Cost-Effective Congestion Management

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Germany's power system is undergoing a rapid transformation driven by the large-scale expansion of renewable energy sources, particularly wind and solar power, as part of its decarbonization strategy. While generation capacity has grown substantially over the past decades, the expansion of the electricity transmission network has lagged due to lengthy planning and permitting processes. Consequently, market data reveal increasing network congestion, rising redispatch volumes, and growing congestion management costs, raising concerns about the economic efficiency of current grid operation practices. Beyond long-term grid reinforcement and expansion, identifying short- to medium-term strategies that utilize existing transmission capacities more efficiently is therefore of high importance.

In Germany, transmission line ratings are typically defined based on conservative ambient conditions that rarely occur throughout the year. Empirical evidence suggests significantly higher admissible power flows than those implied by static ratings. For instance, German grid development guidelines indicate a technically feasible increase in line capacity of up to 150% under typical weather conditions. Dynamic Line Rating (DLR) exploits this weather dependency by adjusting admissible line capacities in real time based on temperature, wind speed, wind direction, and solar radiation, enabling higher utilization of existing transmission assets. Although several European transmission system operators (TSOs) have introduced seasonally or event-based adjusted ratings for selected lines, a systematic framework for identifying suitable line candidates and for evaluating the techno-economic benefits remains largely underexplored.

Building on DLR principles, this paper investigates systematic transmission line overloading as a risk-based congestion management strategy for the German transmission network. We develop a system-theoretic modeling framework that replaces deterministic line-flow limits with probabilistic constraints via chance-constrained programming. This approach allows line limits to be relaxed within a predefined range and with a controllable probability, explicitly balancing economic benefits with operational risk.

Using the European transmission grid model ELMOD, we quantify the marginal economic benefits and risks of systematic line overloading across different renewable penetration levels and security thresholds, focusing on Germany for 2017, 2023, and 2030. Furthermore, we assess three approaches for pre-selecting candidate lines for overloading: historically identified Critical Network Elements by German TSOs, lines most frequently congested before redispatch, and lines with the highest marginal congestion management cost values.

The results indicate substantial potential for reducing congestion management volumes and costs. However, the marginal effect of grid overloading is found to be exponentially decreasing with increasing probability levels. Overall, the findings highlight the importance of dynamic and more flexible grid operation strategies for effective congestion mitigation, as risk-aware, flexible line rating strategies can meaningfully enhance short-term operational efficiency in high-renewable power systems. The developed system-theoretic framework provides a foundation for systematically integrating probabilistic line ratings into operational planning and offers valuable insights for TSOs and researchers seeking to harmonize competing demands of grid reliability and economic efficiency.

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