A PROBABILISTIC APPROACH TO CONGESTION MANAGEMENT IN TRANSMISSION SYSTEMS OPERATION

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Introduction

The role of the Transmission System Operator (TSO) has become increasingly demanding due to the rising share of renewable energy sources and the expansion of the power grid. Maintaining system security requires reliable operation of both the domestic grid and all cross-border interconnections, while simultaneously maintaining the security criteria $(n-1)$. [1] The TSO is responsible for controlling the transmission grid and efficiently supporting the electricity market [2]. This responsibility requires continuous monitoring and analysis of large datasets, as well as the capacity to respond promptly and effectively to system disturbances [3]. Congestion management represents one of the most significant operational challenges faced by TSOs [4]. At the same time, the rapid expansion of renewable generation, occurring much faster than the development of transmission infrastructure, has increased the likelihood of congestion and renewable curtailment. Moreover, existing deterministic analysis does not sufficiently capture the variability and uncertainty associated with renewable energy. Therefore, probabilistic, scenario-based methods have been proposed to estimate congestion risk. [5]

This work investigates the advantages of introducing uncertainty-aware forecasting into TSO operation processes. It develops a probabilistic congestion forecasting model integrated into power flow calculations, remaining compatible with the $n-1$ security criteria used in TSO operations. The aim of the work is to compare operational outcomes when using deterministic versus predictive information. It examines how predictive tools can reduce uncertainty and increase security of the transmission grid.

Methodology

The analysis is performed on the standard IEEE 57-bus system using the Simplus Grid Tool, which enables fast linearized power flow calculations, contingency analysis, and curative action evaluation. This allows realistic modeling of transmission constraints while maintaining computational tractability suitable for real-time studies. The time series of the load and renewable generation are simulated over one year with hourly and 15-minute time steps. System behavior is evaluated using sequential power flow simulations based on given injections and grid topology. Curative actions are implemented as rule-based scenario modifications evaluated by re-running power flow. This corresponds to how TSOs often test short-term what-if actions in real-time operation.

Probabilistic Congestion Forecasting

For each transmission line and forecasting horizon (15 and 60 minutes ahead), a supervised classification model is trained. Tree-based models such as gradient boosting trees (XGBoost) are applied, as they perform well on structured grid-operation data and require no tailored architecture. Estimation of the probability of a line exceeding its thermal limit is based on the following input features:

- state estimator outputs for power flows and voltages
- short-term forecasts of load and generation
- topological state and switching states
- historical congestion patterns
- Power Transfer Distribution Factor (PTDF)-based sensitivity indicators

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The model calculates a scalar probability $p \in [0, 1]$ that serves as risk indicator of exceeding line´s thermal limit. Exceeding the thermal limit is operationally equivalent to a congestion event.

Simulation Cases

To be able to compare use of deterministic and predictive outcomes, two main scenarios are analyzed:

1) **Baseline (Deterministic) operation**
Baseline case serves as a reference case. Standard power flow is run for each time step, without use of information about future congestion. Observed overloads are recorded as violations.

2) Risk-based curative (Probabilistic) operation
When predicted congestion probability exceeds the threshold $p > p^*$, pre-defined rule-based actions are applied. These may include reducing generation at critical buses, activating flexible loads, predefined line switching actions. After applying modified limitations, a new power flow is calculated to evaluate whether congestion is relieved.

System assumptions and software

All simulations are performed using the Simplus Grid Tool, which enables efficient power flow analysis and sensitivity computation. Machine learning models are implemented in Python using standard libraries.

Expected results

Results will be obtained by comparing the baseline scenario with scenarios that incorporate curative actions. Effectiveness will be evaluated using several Key Performance Indicators (KPIs): number and severity of overloads, the rate of required curative actions, the margin between actual flows and thermal limits, and the accuracy of ML-based congestion warnings. The analysis will demonstrate whether, and to what extent, forecasting reduces overload occurrences and improves operational security. These outcomes will indicate whether the proposed approach is suitable as an additional decision-support layer for TSOs.

Outlook

Probabilistic congestion forecasting, combined with efficient grid-analysis tools, offers a practical path toward predictive control in future power systems. As renewable generation increases, such approaches can serve as a foundational component of advanced decision-support systems in TSO control centers.

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