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A PROBABILISTIC APPROACH TO CONGESTION MANAGEMENT IN TRANSMISSION SYSTEMS OPERATION

EnInnov 2026

as part of POWER *SYSTEM SECURITY* 2030+ program

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Agenda

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- Motivation
- Problem statement
- Methodology
  - Simulation Setup
  - Probabilistic Congestion Forecasting
  - From Probability to Action
- Preliminary Insights
- Limitations & Current Challenges
- Outlook

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Limitations & Current Challenges

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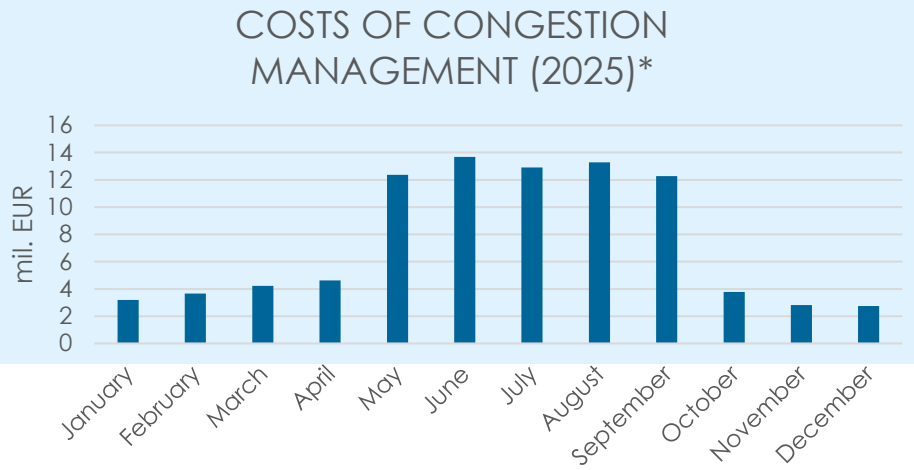
Motivation



INCREASING RES / POWER GRID COMPLEXITY → HIGHER OPERATIONAL UNCERTAINTY

CONGESTION EVENTS : COSTLY, OFTEN DETECTED *TOO LATE*

TSO OPERATION: LARGELY DETERMINISTIC, LIMITED ANTICIPATION OF RISK

*SOURCE: MARKT.APG.AT/EN/TRANSPARENCY

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TSO operation:

- Deterministic congestion evaluation

deterministic analysis:

- not sufficiently capturing the variability and uncertainty

Lack of operational integration of uncertainty-aware forecasting (n−1 compatible)

Missing link between probabilistic congestion risk and curative actions

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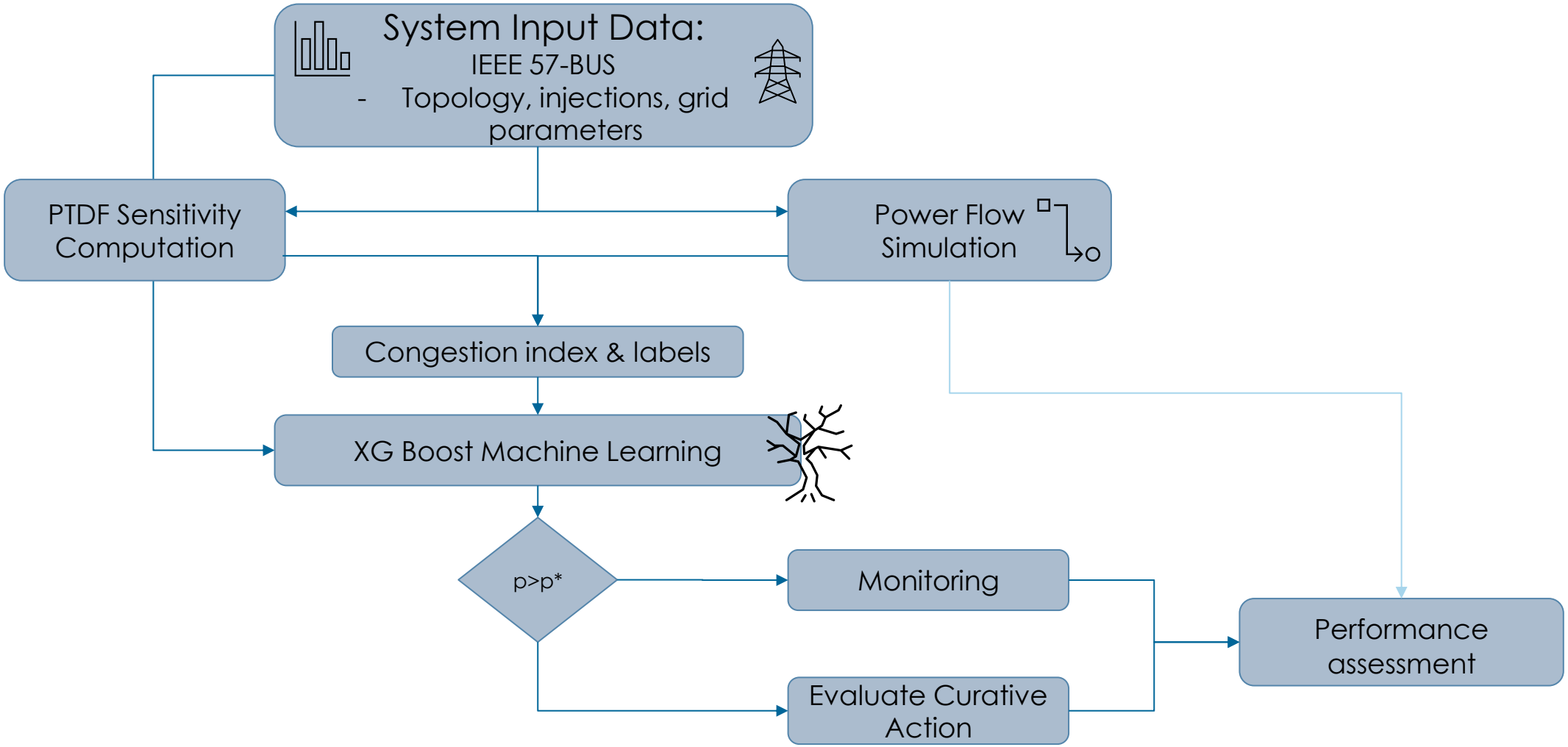

Simulation Setup

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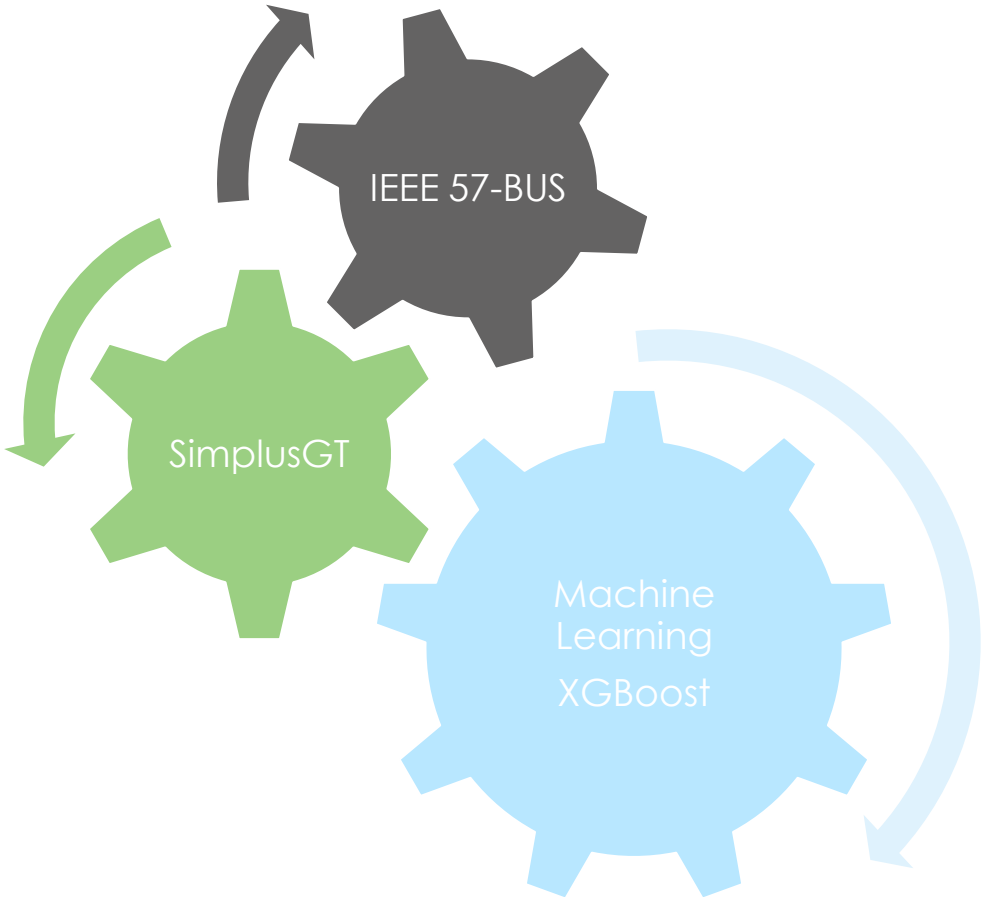
- transmission system benchmark
- n–0 and selective n–1 contingency scenarios
- Stressed load and generation operating points
- Line thermal limits - congestion definition
- power flow and sensitivity analysis



Probabilistic Congestion Forecasting

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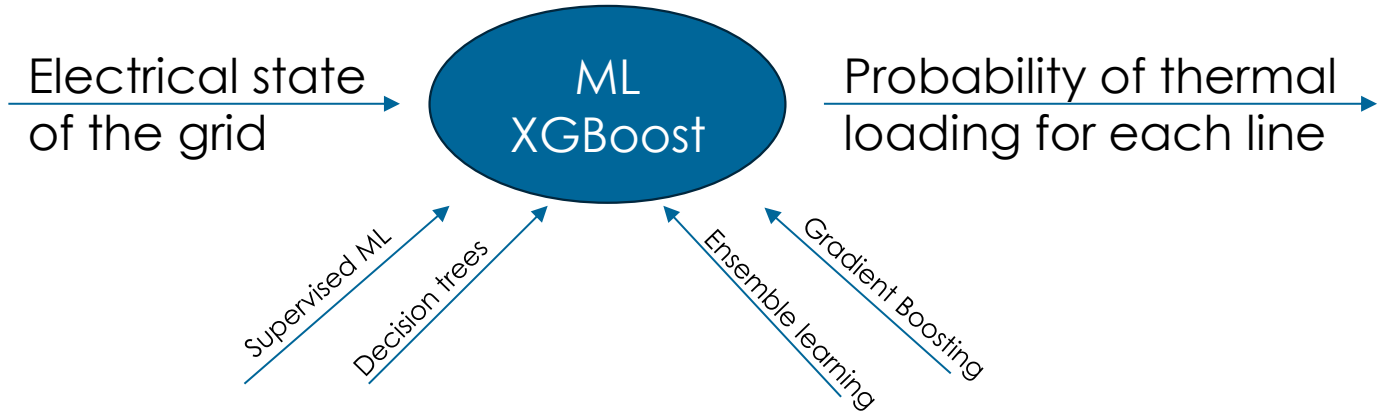
- Objective: early identification of congestion risk under uncertain operating conditions
- Line-level forecasting based on power-flow information

Input features:

- load and generation injections
- Network topology and contingency state
- PTDF-based indicators

XGBoost ML model

Output: probabilistic estimate of thermal limit exceedance per line



From Probability to Action

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- Probabilistic congestion risk as early-warning signal
- Identification of high-risk operating conditions
- Line-level risk assessment under contingencies
- Power flow used for results evaluation

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Preliminary Results - Performance metrics

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Category	*Metric*	*Value*	*Interpretation*
Congestion detection	ROC–AUC	0.992	Effective separation
	Brier score	0.0156	Well-calibrated probabilities
Severity estimation	RMSE	0.093	Low severity error
	MAE	0.031	Small average deviation
	R^2	0.931	High explained variance
Uncertainty	σ	0.029	Stable prediction spread

Prediction Results

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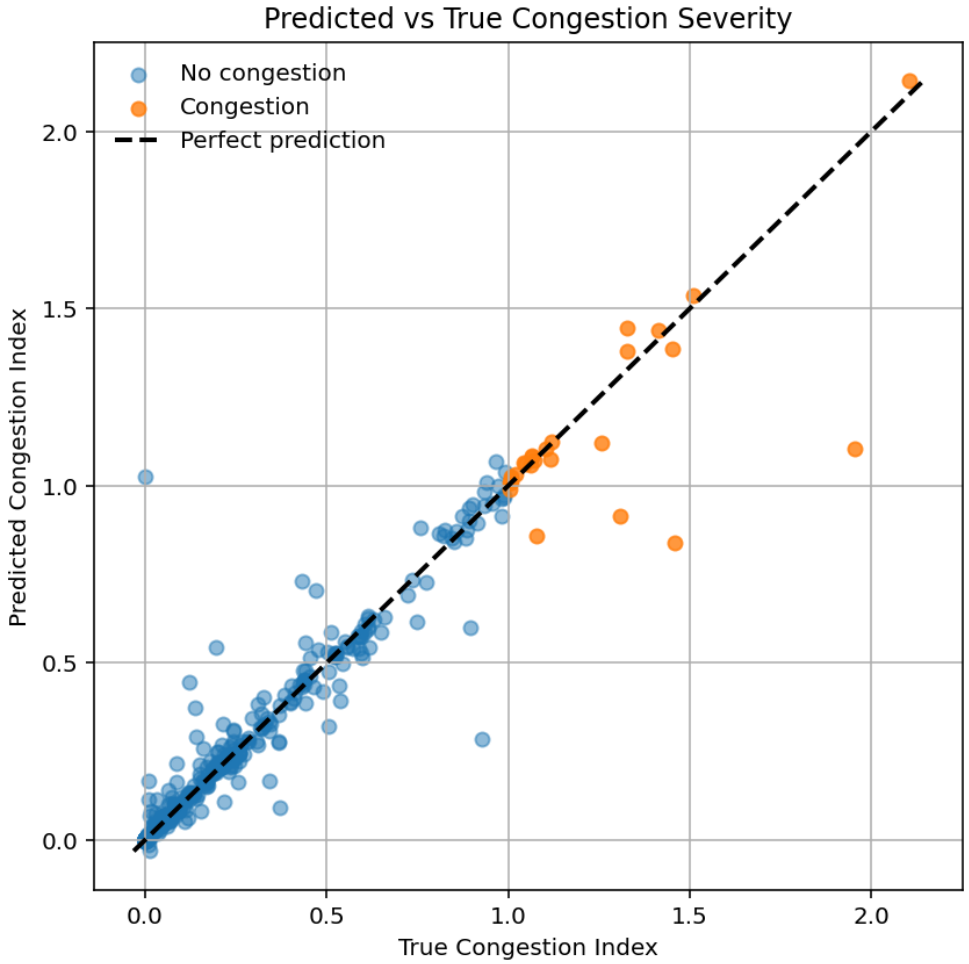

- Prediction of congestion severity across operating conditions
- Agreement between predicted and true congestion index

ML Parameters variations

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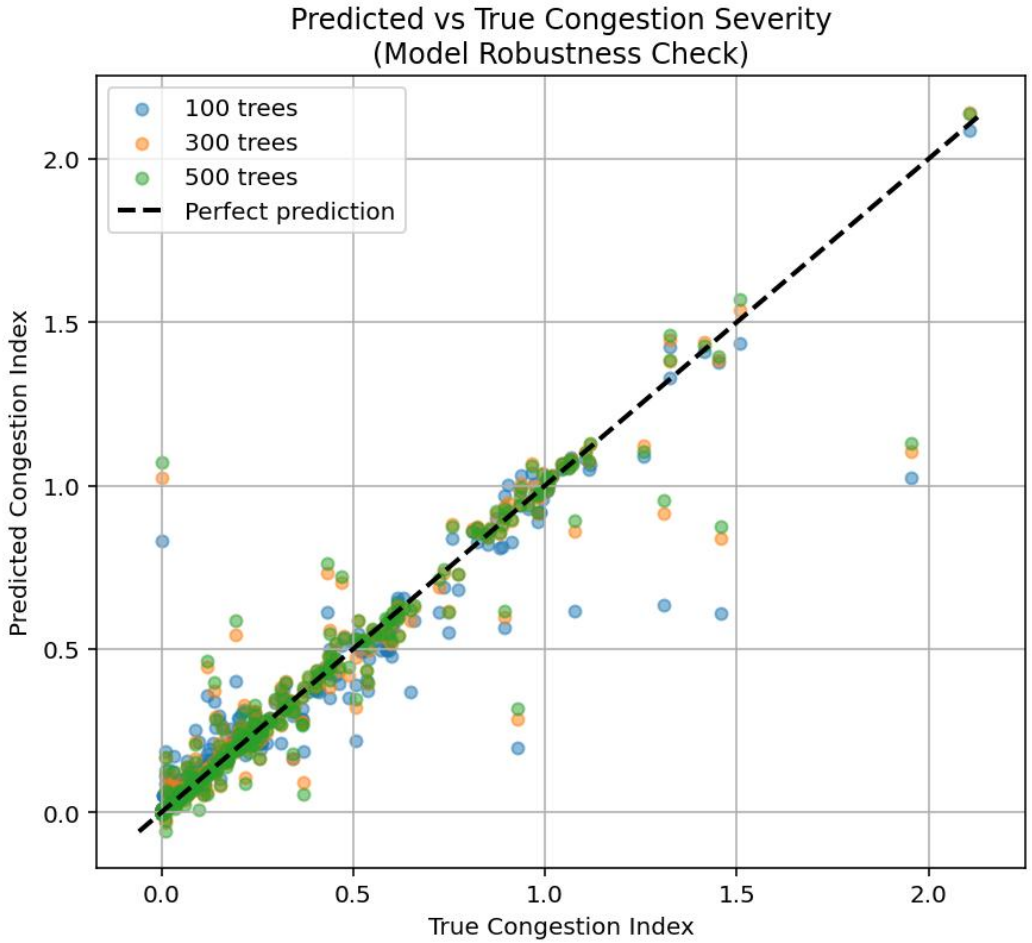

- Variation of number of estimators (decision trees) and tree depth (decisions per tree)

N estimators	max. depth	ROC-AUC	Brier Score	RMSE
100	6	0.9892	0.020	0.104
300	6	0.9924	0.016	0.093
500	6	0.9936	0.015	0.093
300	4	0.9905	0.020	0.101
300	6	0.9924	0.016	0.093
300	8	0.9915	0.018	0.099

Preliminary Results

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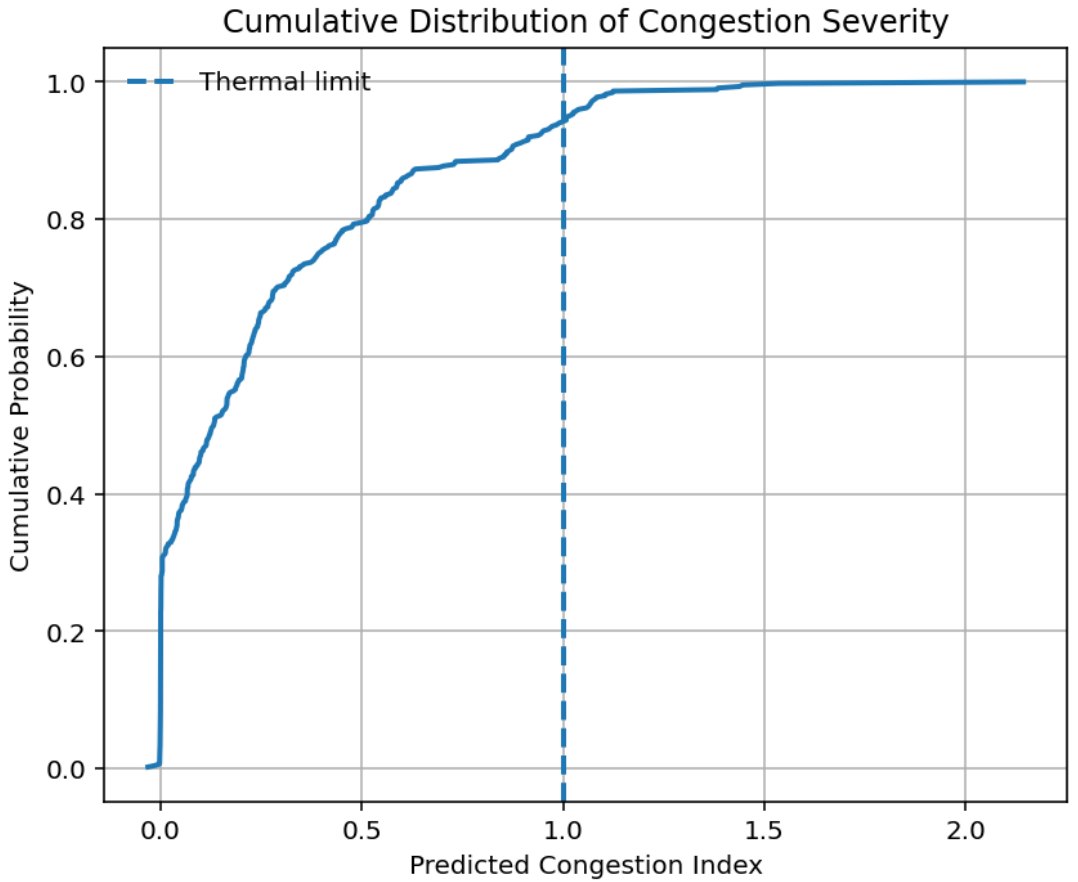
- Congestion - high-impact operating condition
- Most predicted congestion indices below thermal limits
- Tail behavior motivates probabilistic rather than deterministic assessment



Preliminary Results

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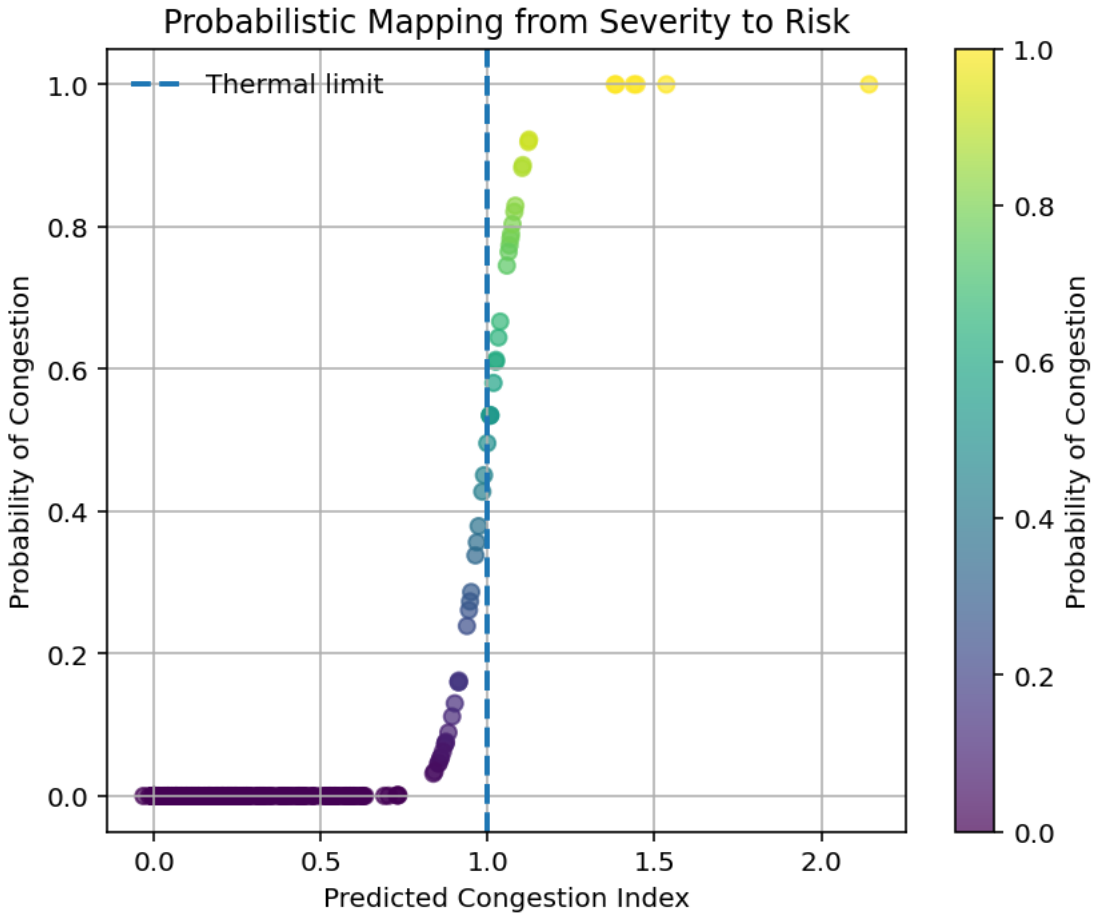
- Mapping from congestion severity to congestion probability
- Uncertainty explicitly represented near the thermal limit



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Limitations:

- *Static power flow formulation*
- *Simplifications – line limits*
- *No real operator data*

Challenges:

- *Computational scalability for large SimplusGT studies*
- *Model and uncertainty parameter tuning*
- *Simulation of time horizons with high temporal resolution*

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INCLUDE TEMPORAL INFORMATION &TIME STAMP

INCLUDE RISK-BASED CURATIVE ACTIONS SENSITIVITY ANALYSIS OF PROBABILITY THRESHOLD

EXTENSION TO:

- LARGER/REAL GRIDS
- ADDITIONAL CURATIVE ACTIONS

APPLICATION:

REAL-TIME DECISION SUPPORT IN TSO CONTROL ROOMS

Thank you for your attention!

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pss2030plus.eu