Probabilistic security management for power system operations with wind power

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24/10/2016

Outline

Outline

N-1 criterion

- The N-1 criterion captures the security of the system in terms of its robustness against contingencies.
- System operators identify a list of contingencies against which the system must be secured.
- Contingencies = loss of generation units, faults on transmission lines, . . .

### Security according to the N-1 criterion

The power system is secure = the operational security limits are fulfilled after any contingency in the contingency list occurs.

Security limits

- If the system becomes too loaded, instability issues can occur or operational security constraints can be violated.
- Example:
  - Voltage stability
  - Small-signal stability
  - Thermal limits of transmission lines

Stability limits can be defined as operating conditions beyond which the system becomes unstable or operational security constraints are violated.

Example of voltage instability - 1
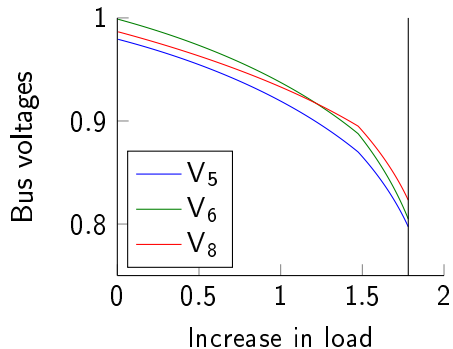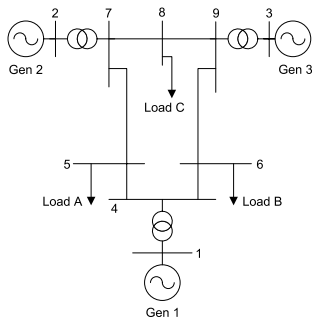
Example of voltage instability - 2
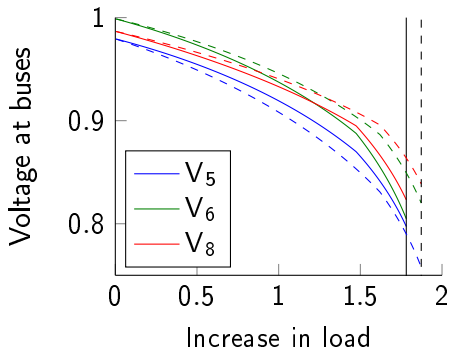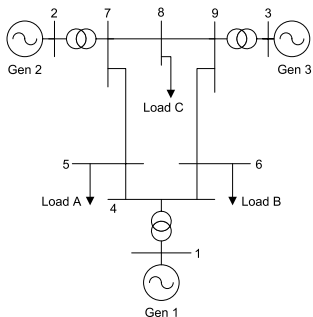
Solid=All loads increase by the same amount
Dashed=Load A increases double as much as the other two.

Example of voltage instability - 3
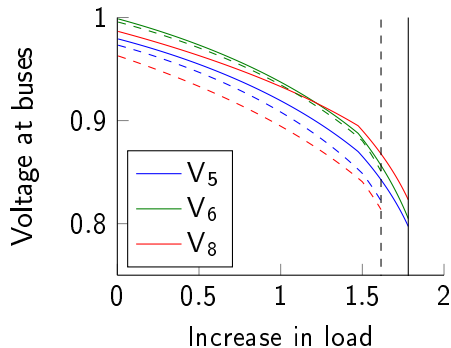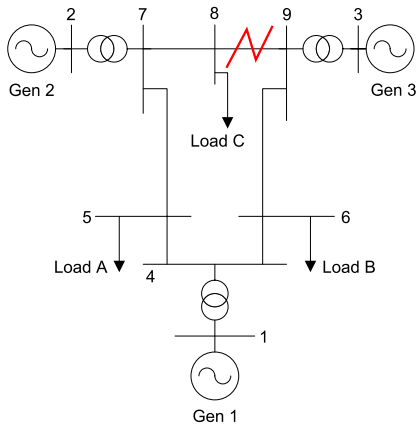
Solid=System intact
Dashed=Fault on line between
buses 8 and 9.

Stability boundary
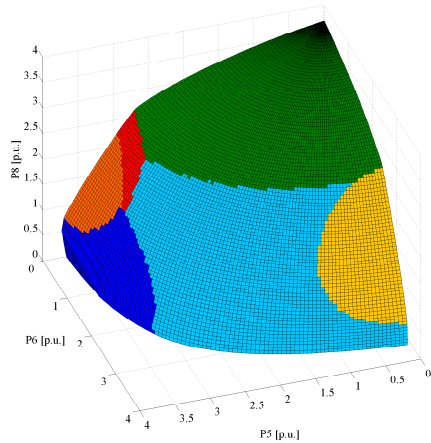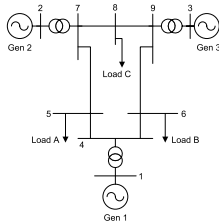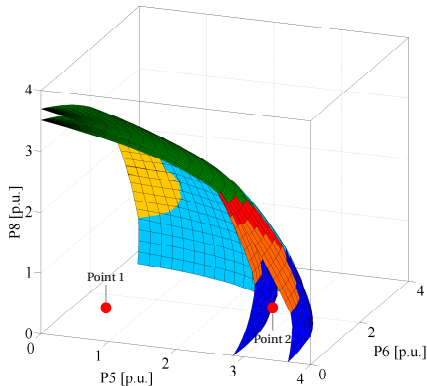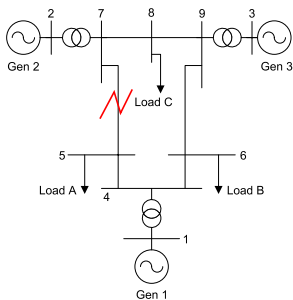
Stability boundary

Stability boundary

Security according to the N-1 criterion

The operating conditions must be within the pre- and post-contingency stability boundaries

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Security and uncertainty
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Proposed methods
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Conclusions
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Security management

Two aspects:

Security assessment Monitor the system and evaluate whether the N-1 criterion holds.

Security enhancement Automatic or manual actions to improve the security.

Security management in Sweden

- Four price areas separated by bottlenecks (=critical transmission corridors).

- **Security assessment** The TSO monitors the power transfers across the bottlenecks.

- **Security enhancement** The TSO sends re-dispatch orders (increase/decrease production) if necessary.

Price area SE1

Price area SE2

Price area SE3

Price area SE4

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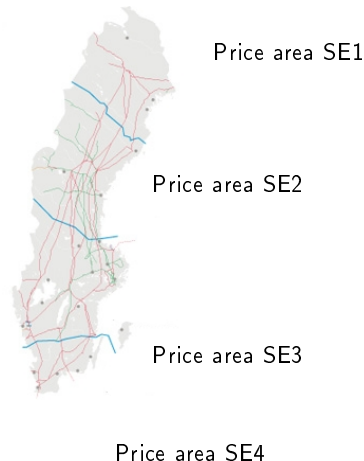
Security management in Sweden - 2

Security assessment:

1. A list of contingencies is defined.
2. Every 15 minutes, for each contingency and each bottleneck, transmission limits are computed.
3. The power transfers are monitored and checked against all computed transmission limits.

Security enhancement:

4. If the power transfers come close to one of the computed limits, re-dispatch the generation to decrease the power transfers.

Production area

ΔPGa ΔPGb ΔPGc

ΔPGe ΔPGd

P   Network bottleneck

Load area

ΔPLa ΔPLb

ΔPLd ΔPLc

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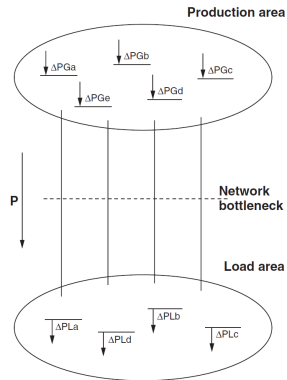
Security management in Sweden - 3
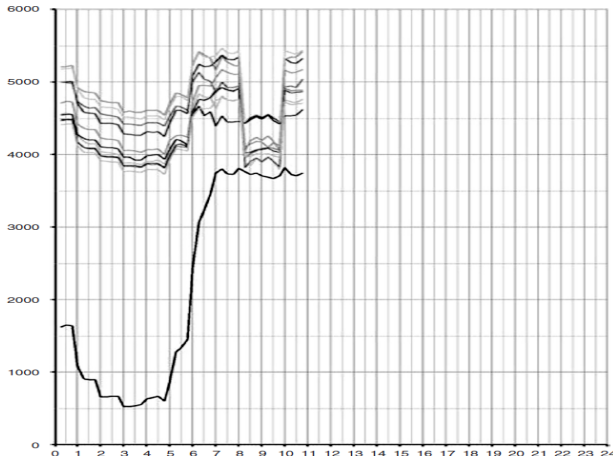
Source: Sandberg, L., & Roudén, K. (1992). *The real-time supervision of transmission capacity in the swedish grid*. In S. C. Savulescu (Ed.), *Real-time stability assessment in modern power system control centers*.

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N-1 criterion

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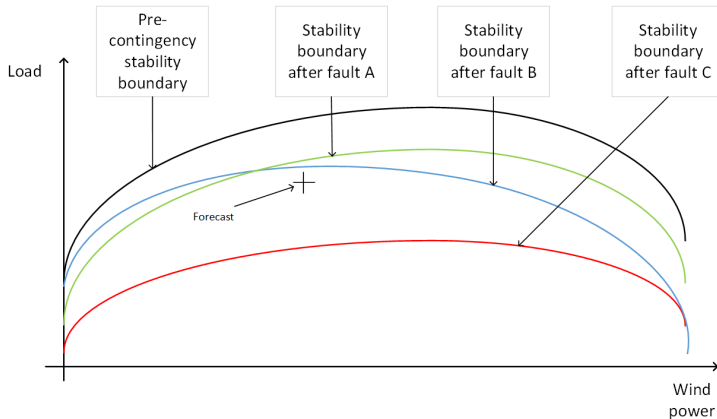
Uncertainty - 1

First source of uncertainty: Load and wind power forecast errors.
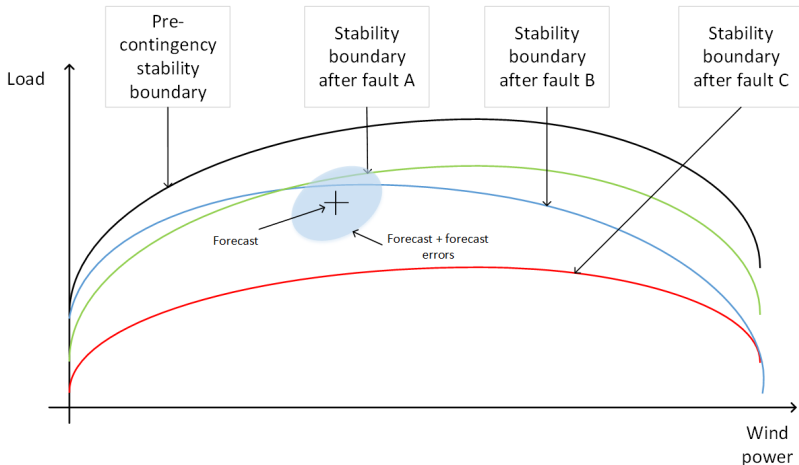
Probabilistic forecasts

Probabilistic forecasts give a joint probability distribution for the future net power injections, i.e.:

1. A set of possible future net power injections
2. A probability density function
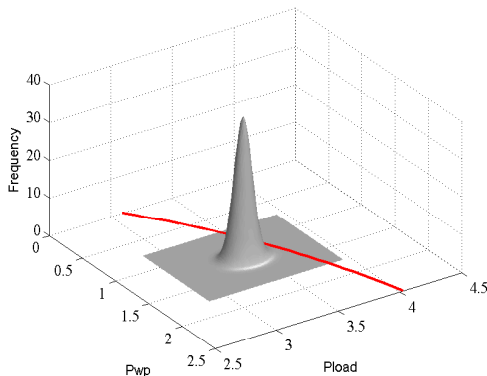
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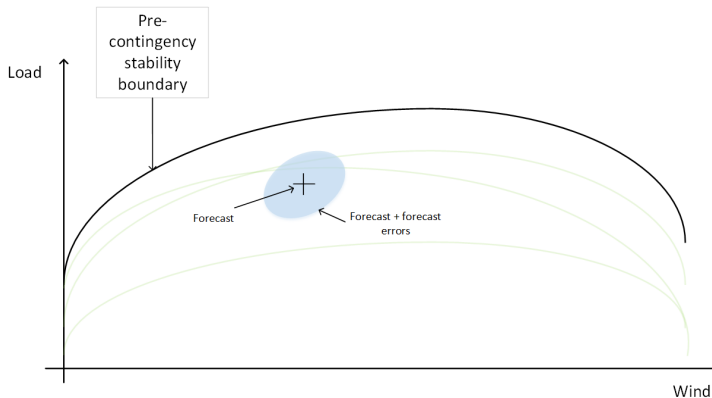
Uncertainty - 2

Second source of uncertainty: Contingencies occur randomly.

Fault	No fault	Fault A	Fault B	Fault C
Probability	**0.999**	0.0005	0.0003	0.0002

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N-1 criterion and uncertainty

Security according to the N-1 criterion

The **operating conditions** must be within the pre- and post-contingency stability boundaries.

What does it mean when there is uncertainty on the operating conditions / occurrence of contingencies?

Shortcomings of N-1 criterion:

1. Does not consider the uncertainty.
   - Probability of occurrence of contingencies.
   - Probabilistic forecasts.
2. Does not consider the extent of the violations.

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Security and uncertainty
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Changes to today's approach

Furthermore, and most relevant, the increase in penetration of variable generation further undermines the value of deterministic snapshot analysis. To give a specific example: while the critical operating points of bulk power systems have traditionally been known, with the advent of wind and solar generation, these points are difficult to find, and require analysis of many more points. Hence, there is a need to study multiple scenarios, a process that is largely deterministic but could become computationally intractable. *Probabilistic techniques are developed by studying the underlying distribution of scenarios rather than a specific set of points that make up the distribution*.

Lauby, M. et al. (2011). Balancing Act. IEEE Power and Energy Magazine

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Security and uncertainty
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Proposed methods
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Proposed approach

Inputs: list of contingencies and their probability of occurrence, probabilistic forecasts for wind power and load.

Today: N-1 criterion

The power system must remain stable after any contingency in the pre-defined list occurs.

Proposed: probabilistic approach

1. Define the operating risk = probability of the system to be unstable / operational security limits to be violated.
2. "Probabilistic N-1 criterion": Operating risk $\leq \alpha$.

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Security and uncertainty
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Proposed methods
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Operating risk

Operating risk

$=$ Probability of the system to be unstable

$$= \sum_{\text{contingencies}} (\text{ Prob. contingency } \times \text{Prob. unstable after contingency})$$

- New probabilistic criterion: Operating risk $\leq \alpha$.
- The operating risk is in general never zero. What we propose is to make this probability visible.
- $1 - \alpha =$ level of system security.

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Proposed methods
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Operating risk - illustration

$$\text{Operating risk} = \sum_{\text{cont.}} (\text{ Prob. cont. } \times \text{Prob. unstable after cont.})$$

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Proposed methods
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Operating risk - illustration

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Operating risk - illustration

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Security and uncertainty
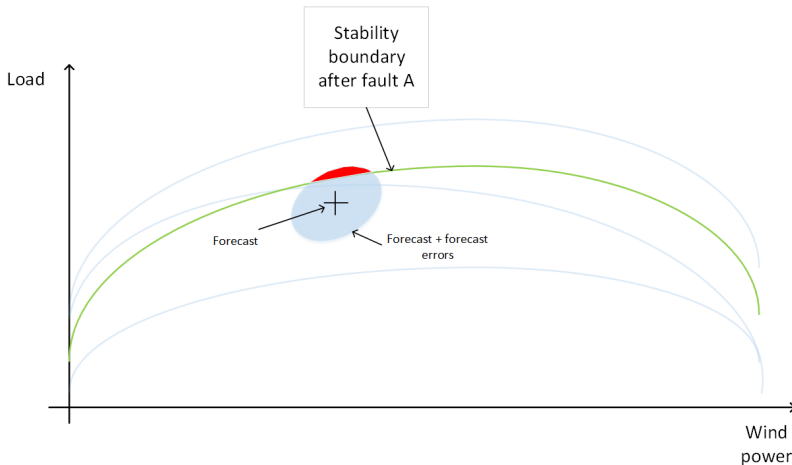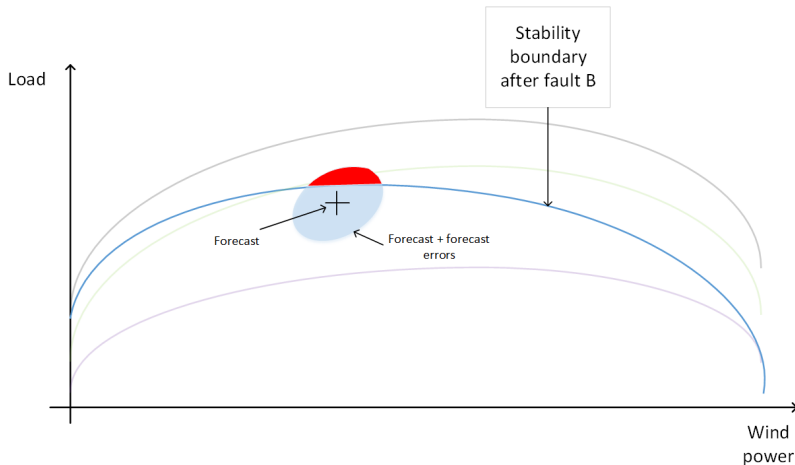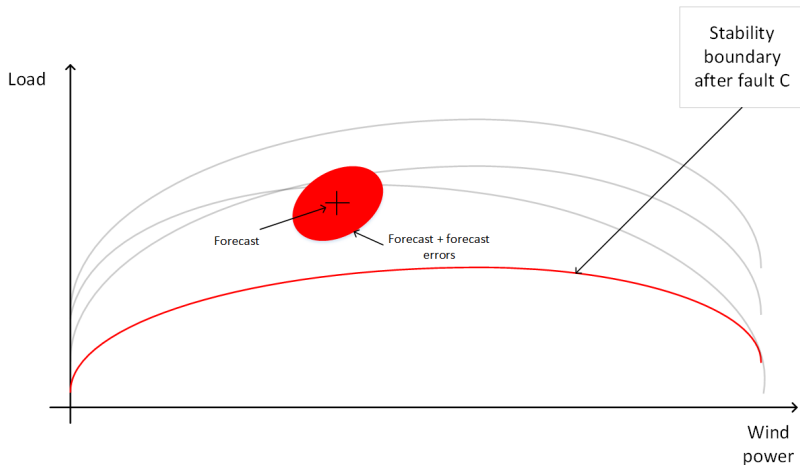○○○○○○○○○○●○○○

Proposed methods
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Conclusions
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Operating risk - illustration

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Security and uncertainty
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Proposed methods
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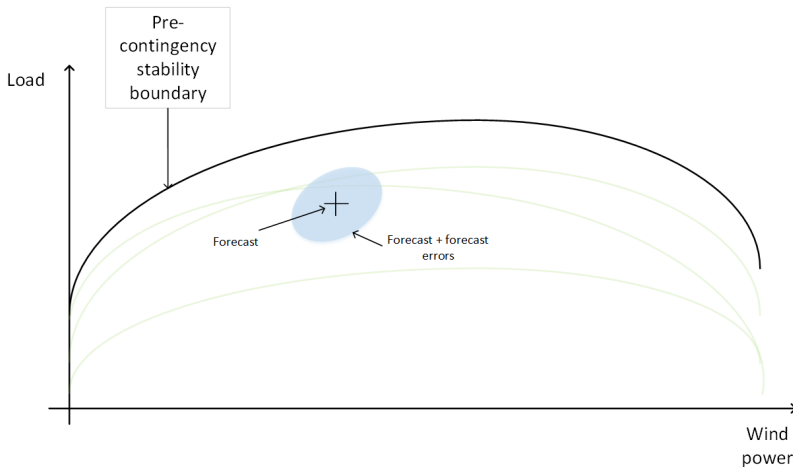
Probabilistic security management

Given the definition of the operating risk, the proposed framework
for probabilistic security management has two aspects:

Security assessment Given probabilistic forecasts for a time ahead
in the future, a list of contingencies and their
probability of occurrence, evaluate the operating risk.

Security enhancement Given some controllable parameters in the
system, find the most economical way of ensuring that
the operating risk remains below a certain threshold.

$$\begin{aligned} &\min & &\text{Re-dispatch cost} \\ &\text{such that} & &\text{Operating risk} \leq \alpha \end{aligned}$$

Challenges

1. The stability boundaries are not known. We can obtain points on them (continuation power flows) but it is time consuming.

2. Security assessment: the operating risk is very low $\Rightarrow$ challenging to estimate it by naïve Monte-Carlo simulations (required number of samples $\propto \frac{1}{\text{prob}}$).

3. Security enhancement: control actions change the stability boundary and, hence, the operating risk. However, the impact of control actions on the stability boundaries is difficult to capture.

4. Modelling: we need probabilistic forecasts for net power injections (load and wind power) and models for the contingency probabilities.

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Security and uncertainty
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Proposed methods
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Conclusions
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Modelling

1. We used existing research for the probabilistic forecasts: joint normal transform (which fits a Gaussian copula to model the correlation between forecast errors).

2. We assumed arbitrary values for the contingency probabilities. In reality, one can use threat-based models to get more accurate contingency probabilities for the system of interest.

A lot of ongoing research for both modelling issues.

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Security and uncertainty
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Proposed methods
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Security and uncertainty
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Proposed methods
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Conclusions
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Contributions

Contributions to three problems:

Problem 1 Parametrized approximation of the stability boundary.

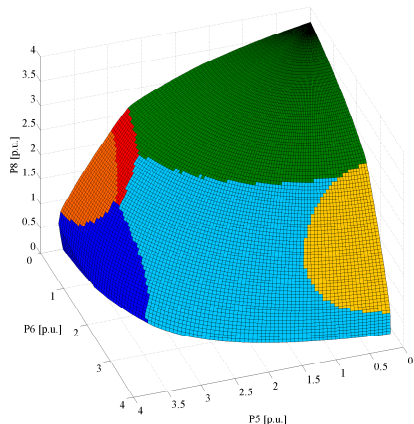Problem 2 Security assessment: Evaluation of the operating risk.

Problem 3 Security enhancement: Determine the optimal re-dispatch.
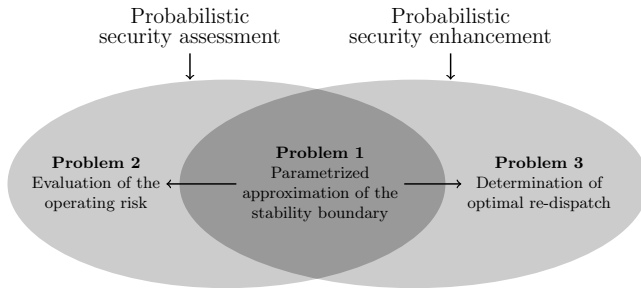
Problem 1: Parametrized approximation of the stability boundary

Challenges:

- There does not exist any known parametrization of the stability boundary.

- The stability boundary is made of different parts.

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Proposed methods
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Conclusions
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Problem 1: Parametrized approximation of the stability boundary

Contribution:

- Second-order approximations of the stability boundary are developed.

- They are based on second-order sensitivities of the margin to the most likely points on different parts of the stability boundary.

- Voltage stability, small-signal stability and line thermal limits are considered.

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Security and uncertainty
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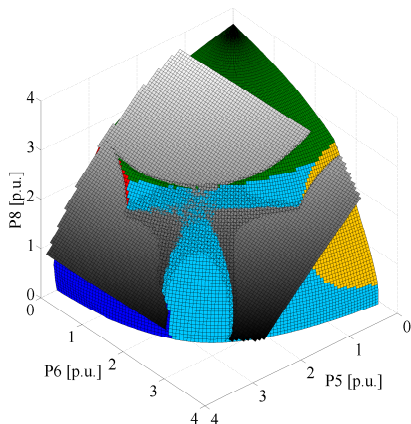
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Security and uncertainty
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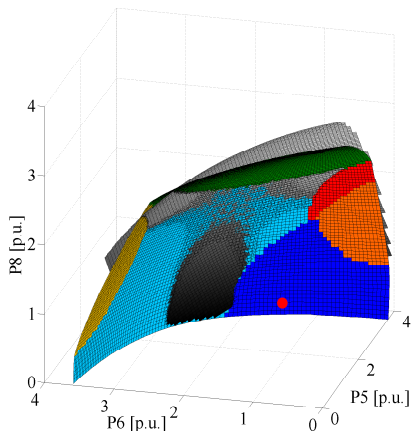
Problem 2: Tools for probabilistic security assessment

Challenges:

- The operating risk is a probability that must be kept very small during normal operations of power systems.

- Estimating such probabilities is usually done by Monte-Carlo simulations.

- For such small probabilities, Monte-Carlo simulations are computationally demanding.
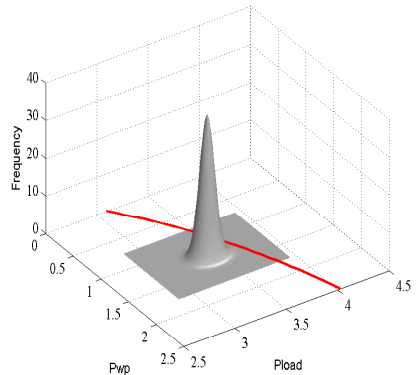
Problem 2: Tools for probabilistic security assessment

Contributions:

- Method 1: Analytical approximations of the operating risk are developed. Technical details:
    1. Second-order approximations of the parts of the stability boundary.
    2. Hunter-Worsley bound as approximation of the probability of the intersection of events
    3. Edgeworth approximations to approximate the probability of being beyond each part of the stability boundary.

- Method 2: Speed-up methods based on importance sampling for Monte-Carlo simulations are developed. Technical details:
    - Second-order approximation of the stability boundary.
    - Optimal exponential twisting of the original distribution (adapted from application in finance, from large deviation theory).

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Security and uncertainty
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Proposed methods
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Analytical approximation

Comparison between the estimate of the operating risk by crude Monte-Carlo simulations (CMC) and the analytical approximation in different cases (different productions at the controllable generators)
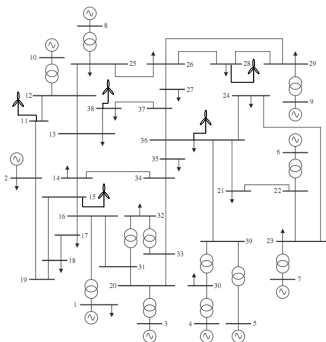
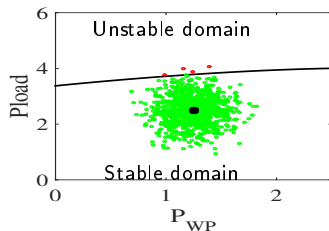| Operating risk (CMC)	Operating risk (approx)
7.7e-03	7.4e-03
8.2e-05	9.0e-05
1.1e-04	1.3e-04
1.7e-04	2.6e-04
2.0e-03	1.8e-03

Computational time:

- CMC: 130-280 seconds.
- Our approximation: 0.05-0.5 second.

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Conclusions
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Importance sampling method

Crude Monte-Carlo

With importance sampling
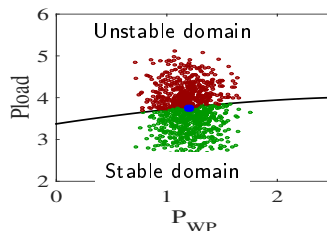
Key ideas:

1. we want to sample around the stability boundary Σ_i.
2. we can get points on Σ_i (continuation power flow).
3. we can move the sampling distribution to these points $\Leftrightarrow$ Efficient IS distribution for the first-order approximation of the stability boundary.
4. Not good in some cases $\rightarrow$ Instead, we use a IS distribution efficient for for the second-order approximation.

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Proposed methods
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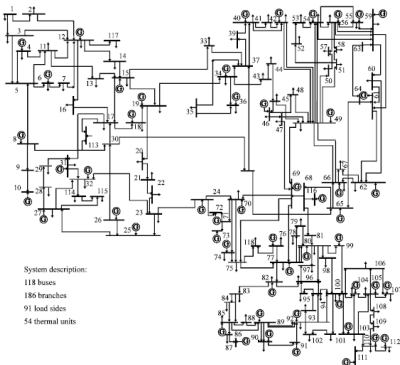Conclusions
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Importance sampling - results

Comparison between crude Monte-Carlo simulations (MCS) and MCS with importance sampling for different cases (different production levels in the controllable generators)

System description:
118 buses
186 branches
91 load sides
54 thermal units

Operating risk	Speed-up factor
$7.3 \cdot 10^{-4}$	176
$3.4 \cdot 10^{-5}$	1750
$1 \cdot 10^{-6}$	18 000

Security
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Security and uncertainty
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Problem 3: Tools for probabilistic security enhancement

Challenges:

- The operating risk must be embedded in the following optimization problem (chance-constrained optimal power flow CCOPF)

$$\text{min Re-dispatch cost}$$
$$\text{such that Operating risk } \leq \alpha$$

- Operating risk must be expressed as a function of the production in the re-dispatchable generators.

Contributions

- The analytical approximations developed for probabilistic security assessment are used to get a tractable approximation of the CCOPF above.

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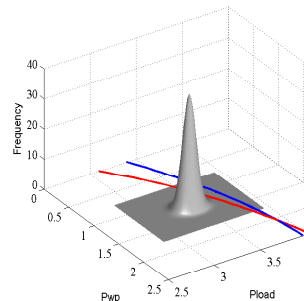
Chance-constrained optimal power flow: results

Chance-constrained optimal power flow:

$$
\begin{array}{rl}
\min & \text{Re-dispatch cost} \\
\text{s.t.} & \text{Operating risk} \leq \alpha\%
\end{array}
$$

α	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
Re-dispatch cost	1.15	2.28	3.25	4.19	5.05
Relative error due to approximations	1 %	1 %	2 %	2 %	2 %

<u>Note</u>: there is a lot of ongoing research on CC-OPF now.

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Outline

1. Security

2. Security and uncertainty

3. Proposed methods

4. Conclusions

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Conclusion

- Wind power poses new challenges for power system operation since it introduces more uncertainty.
- Today's way of operating power systems is very deterministic (N-1 criterion).
- New methods needed to account for the stochastic properties of wind power.
- Proposed solution: switch to probabilistic framework by assessing the probability of violation of operating constraints.
- Methods developed for security assessment = how to evaluate the probability of violation of operating constraints (approximation, estimation).
- Methods developed for security enhancement = how to control this probability ⇒ Chance-constrained optimal power flow.

Thank you!