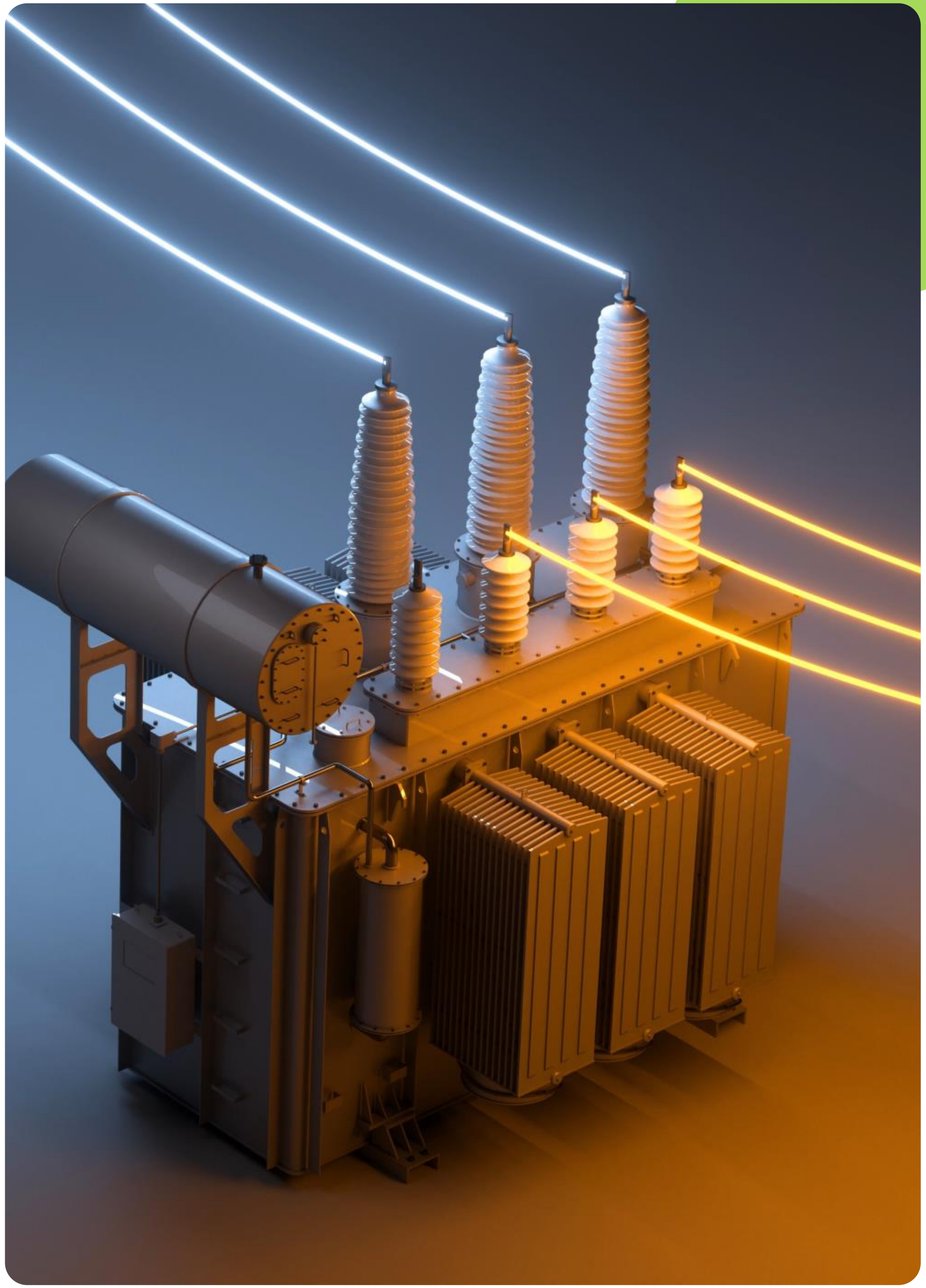
VulPro

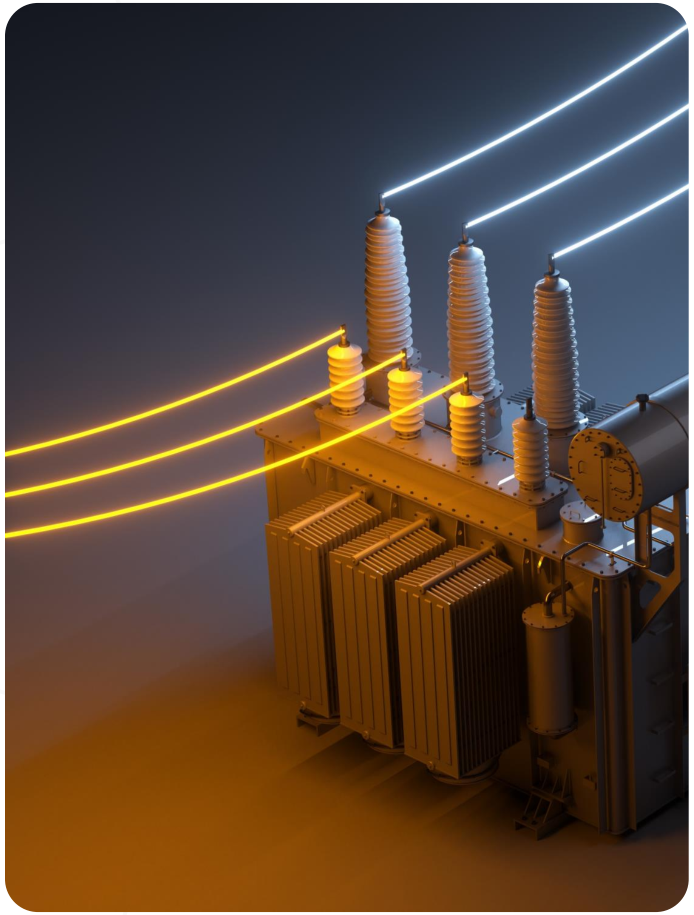
Risk and vulnerability prognosis for power system development and asset management

VulPro was a knowledge-building project for industry (KSP, 2020–2024), developing knowledge and methods for capturing the relationship between the technical condition of components and power system reliability.

This slide deck contains one-page summaries of the results from the VulPro project.

(See the project web page for a full overview of project results.)





Background

To be able to integrate new load demand and generation in an ageing power system, we need to better utilize the components of the power system, such as for example power transformers. At the same time, we also need to keep reliability of electricity supply at an acceptable level.

To utilize and manage components better, power system planners need better information on the actual risk exposure of the power system and how it is affected by different factors. The technical condition of power system components is an important risk-influencing factor.

Power system planning includes both long-term system development and mid-term asset management. Examples of decisions within power system development are where and when to reinforce or expand the grid, while mid-term asset management includes decisions about existing assets, such as when to renew or maintain power transformers.

SINTEF NVE LANDSNET Statnett NTNU

Funded by
The Research
Council of Norway

Overview of one-page summaries of project results (slides 1–4)

01

Summary of the results from the VulPro project

02

The impact of the technical condition of power transformers on the reliability of supply

03

Risk based asset management strategies

04

The combined impact of mid-term asset management and system development on reliability of supply

Overview of one-page summaries of project results (slides 5–8)

05

Modelling the outage duration of power transformers

06

Simulating rare interruption events in reliability of supply analysis

07

Capturing the relationship between component condition and power system reliability – transformers vs. circuit breakers

08

The impact of high-voltage circuit breaker condition on power system reliability

VulPro – Risk and vulnerability prognosis for power system development and asset management

Challenge and objective

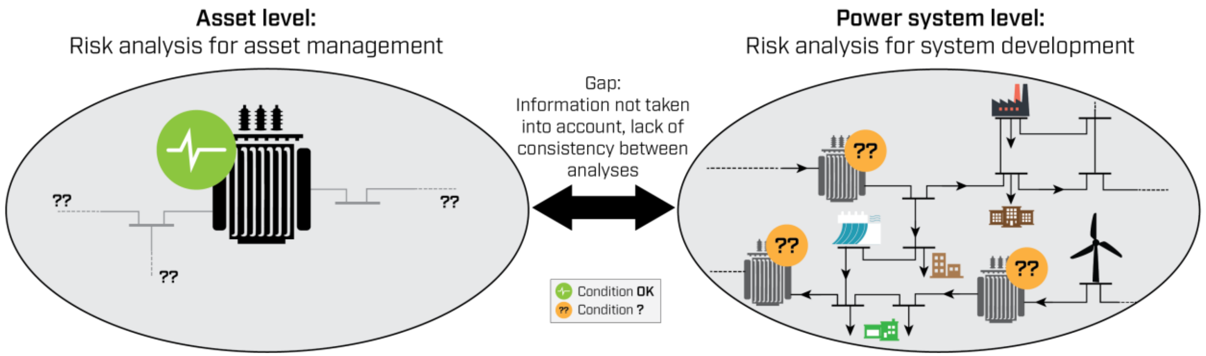
- Power system planners need information about the risk exposure of the system and how it may develop in the future, for informing decisions on both mid-term asset management (AM) and long-term power system development.
- AM decisions focus on single components in the power system but do not properly account for their importance for the reliability of supply. System development, on the other hand, does not account for component condition when analysing risk to reliability of supply.
- Primary objective of the VulPro project: Develop methodologies for risk prognosis that can be used to inform decisions in power system asset management and system development, accounting for the condition of power system components.

What have we learned? (new knowledge and methods)

- Methodologies for integrating component condition and component reliability models in reliability of supply analysis, demonstrated for SINTEFs transformer health index model.
- Methods for estimating how important individual components' condition is for the reliability of the power system.
- An open-source model for estimating the outage duration of transformers, its uncertainty, and how it depends on risk-influencing factors such as accessibility and spare strategies.
- Component reliability models (failure rate and outage duration models are compatible with existing analysis tools for reliability of supply (such as Statnett's MONSTER tool)
- Most components are well maintained and in good condition and have a low probability of wear-out failure. If condition deteriorates, however, the probability may increase.
- The impact of high-voltage circuit breaker condition on reliability of supply is investigated through the PhD study in the project.

Implications and recommendations

- Component age should not be primary basis for asset management decisions.
- Data can be used to estimate if condition deteriorates and the probability of failure increases.
- Grid owners should collect and manage relevant component condition and reliability data.
- Transformer condition data should be collected in a common data base both for operational transformers and scrapped transformers, together with historic load and temperature data.
- Risk-based asset management strategies can give considerable lifecycle savings on reinvestment and maintenance costs while keeping the reliability of supply at a satisfactory level.
- Mid-term asset management decisions should be made in accordance with the future system development alternatives. Correspondingly, system development plans should consider the needs of the existing assets and mid-term asset management decisions.
- Decision processes within the grid owners must be updated to better consider risk.
- Competence on risk-based and probabilistic approaches should be improved.



The impact of the technical condition of power transformers on the reliability of supply

Challenge and objective

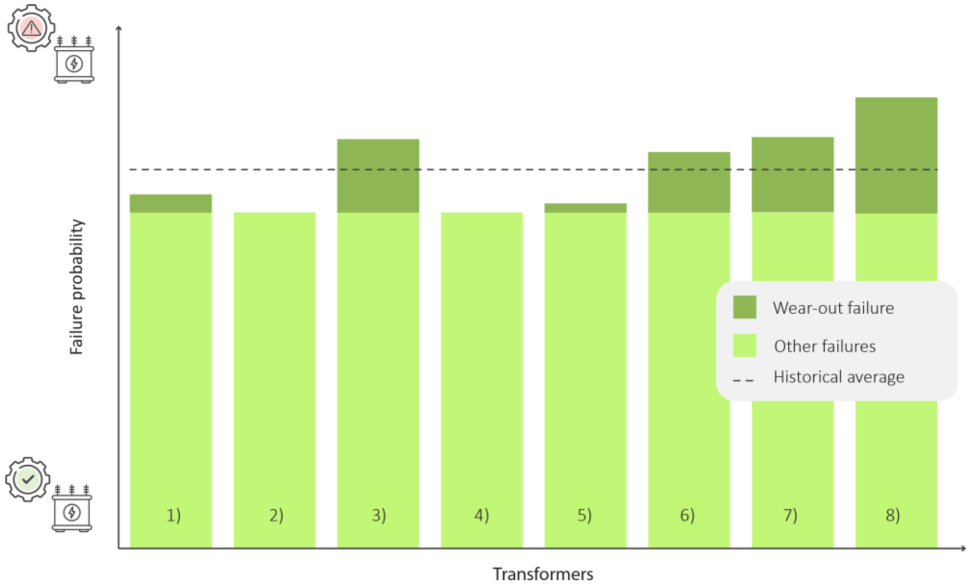
- Deteriorating technical condition will increase the probability of component failure, which in turn will weaken the reliability of supply.
- Power system reliability analysis traditionally does not consider that different components have different technical condition.
- The objective has been to develop methodologies for analysing reliability of supply that consider both the condition and location of power system components, focusing on power transformers

Implications and recommendations

- Component age should not be primary basis for asset management decisions
- Condition data should be collected in a common data base both for operational transformers (periodic oil test data) and scrapped transformers (age, degree of depolymerization), together with historic load and temperature data
- The development of technical condition of components and the consequent impact on the reliability of supply should be monitored over time
- Condition-dependent failure rate for individual transformers can be incorporated in both new and existing reliability analysis tools (e.g. Statnett's MONSTER tool).

What have we learned?

- The correlation between component age and condition is not particularly strong.
- In power systems where components are in a good condition, it is not very important for the reliability of supply in the short term to account for their technical condition.
- The technical condition becomes important for the reliability of supply depending on the criticality of the component in the power system.
- It becomes much more important to account for the technical condition of each component in reliability of supply analyses, if the technical condition is allowed to deteriorate.
- SINTEF's transformer health index model gives higher failure rates than historical failure frequencies. This can to some extent be explained by preventive replacements causing statistical censoring of wear-out failures. Depending on the purpose of the reliability analysis, it is important to consider the difference between the uncensored failure rate and the censored failure frequency.



[1] H. Toftaker, J. Foros, and I. B. Sperstad, 'Accounting for component condition and preventive retirement in power system reliability analyses', *IET Generation, Transmission & Distribution*, vol. 5, no. 1, 2023, doi: 10.1049/gtd2.12761.

Risk based asset management strategies

Challenge and objective

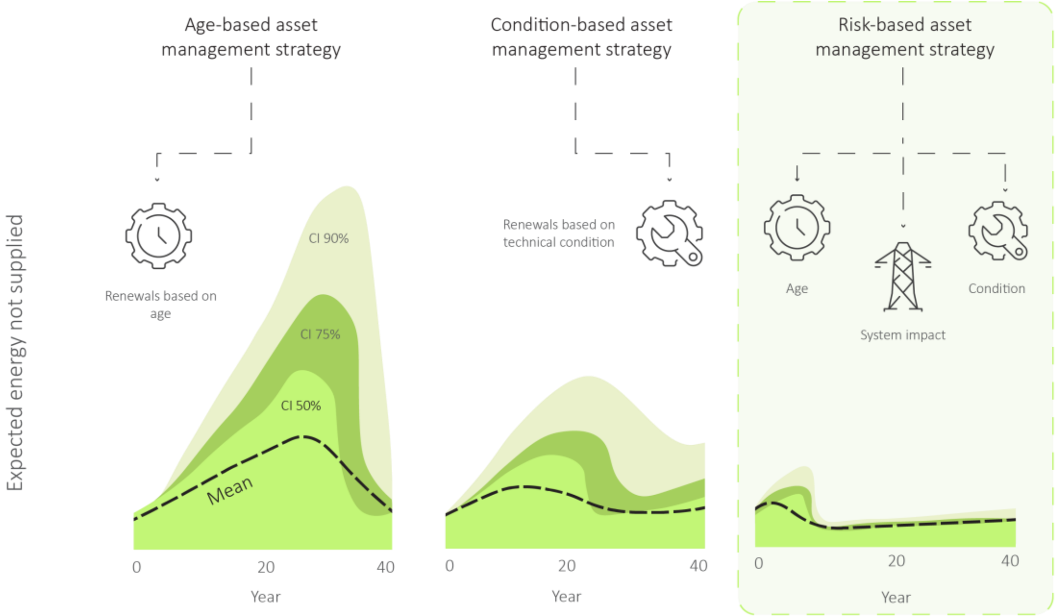
- Component degradation is a major risk to reliability of supply.
- This risk can be mitigated by risk-based asset management strategies.
- New methods are needed to 1) Assess the combined influence of degradation and asset management on reliability of supply 2) Provide decision support and evaluate the effectiveness of different asset management policies.
- The objective is to develop methods for simulating the effect of asset management strategies on reliability of supply.

Implications and recommendations

- Risk-based asset management strategies can give considerable lifecycle savings on reinvestment and maintenance costs while keeping the reliability of supply at a satisfactory level.
- Risk-based strategies should also consider the vulnerabilities with respect to long outage durations after component failures and poor technical condition of critical components.
- There is a great deal of uncertainty about how fast each component will degrade. Therefore, it is important to include this uncertainty in the risk prognoses.
- The risk prognosis is most useful for time horizons where the role and importance of the components in the system remain the same (typically up to around 5 years).

What have we learned?

- Risk based asset management strategies which consider both the structural importance and technical condition of individual components, can achieve acceptable reliability of supply at a lower cost than purely condition based strategies.
- Common methods for power system reliability analysis do not fully capture the risk of high impact, low probability events such as double outage of transformers. Therefore, reliability analysis should be combined with condition-based criteria.
- The impact on reliability of supply from individual components can be ranked and offers practical risk-based decision support for prioritizing asset management actions.
- Findings are based on two different case studies are performed [1, 2]: The first considers reinvestment and replacement of power transformers on a long-term planning scale of several decades. The latter considers inspection and maintenance of circuit breakers on an intermediate time scale of a few years.



[1] I. Bjerkebæk, I. B. Sperstad, H. Toftaker, and G. Kjølle, "Simulating the Long Term Effect of Asset Management Strategies on Reliability of Supply," 2024, *TechRxiv*. doi: 10.36227/techrxiv.172107759.95745501/v1.
[2] S. Perkin, "VulPro Work Package 4 - Landsnet Case Study," report, Landsnet, 2024.

The combined impact of mid-term asset management and system development on reliability of supply

Challenge and objective

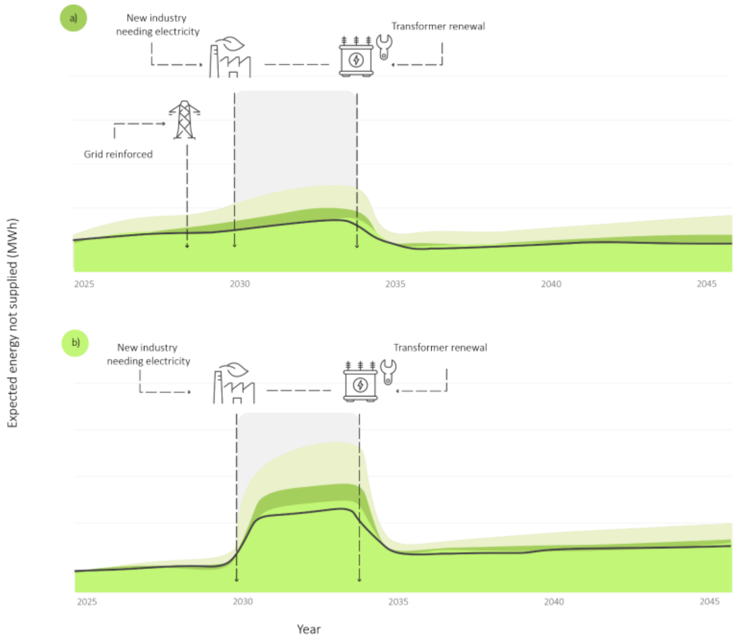
- Several things influence how the risk with respect to reliability of supply may develop over the next years and decades, for instance: 1) component ageing, 2) component renewal and other mid-term asset management measures, 3) load growth, and 4) grid development.
- How do these influence the risk prognosis?
- What is the combined effect of mid-term asset management and system development?
- How may system development decisions influence mid-term asset management decisions and vice versa? In other words, what are the interactions between these decision processes?

Implications and recommendations

- Mid-term asset management decisions should be made in accordance with the future system development alternatives. Correspondingly, system development plans should consider the needs of the existing assets and mid-term asset management decisions.
- In other words, it is beneficial to consider system development and mid-term asset management decisions together.
- Using common analysis methods and common sets of input data for the risk prognosis make decision making more consistent across mid-term asset management and system development

What have we learned?

- Allowing the load demand in the system to increase without/before reinforcing the grid makes the system more vulnerable to condition-dependent transformer failures.
- The system operator can combine the uncertainty information in the risk prognosis with its risk preferences.
- System development decisions such as increasing grid capacity and connecting new loads has a significant impact on the risk prognosis. This impact is more sudden and can be greater than the impact of degradation and mid-term asset management decisions.
- The choices made for system development decisions thus impact what is the best choice in asset management decisions.
- How long outage duration one expects greatly impacts the best time for replacing the transformer. A higher outage duration means that the transformer should be replaced earlier.



[1] I. Bjerkebæk, I. B. Sperstad, and G. Kjølle, "Long-term reliability of supply prognoses for decision support in asset management", manuscript to be submitted to a scientific conference, 2024.

Modelling the outage duration of power transformers

Challenge and objective

- Transformer failures can cause long power outages with high costs to society.
- Transformer failures are rare and there is limited available generalizable data on transformer outage durations.
- The objective of the work is to construct a transformer outage duration model which can be conditioned on relevant asset management input variables to support risk assessments and asset management decisions for these critical assets.

Implications and recommendations

- The model has application in risk assessments and as decision support and can be incorporated in both new and existing resilience and reliability analysis tools (e.g. Statnett's MONSTER tool).
- There are potential applications of the model within system development which could be explored further.
- The model construction approach is generalizable and can be applied to other power system components. It is recommended that similar models are developed where necessary.
- A functioning Python-code of the model is available as open-source code and can be used by potential users.

What have we learned?

- Information about transformers failures (time of failure, component technical condition, availability of spares, and accessibility to the fault site) influences the associated outage duration due to a permanent failure.
- It is possible to construct a logical model based on available data and expert judgements to alleviate challenges related to lack of data on transformer outages.
- The developed model was applied in an asset management decision context, which showed that the choice of spare strategy could have a significant impact on the expected- and tail-end risk of the system.
- Structured expert elicitations can help predict duration of outages in situations which has previously not been observed before.
- The Bayesian Network structure and elicitation process helps incorporate uncertainty in the analysis and communicate this to the decision maker.

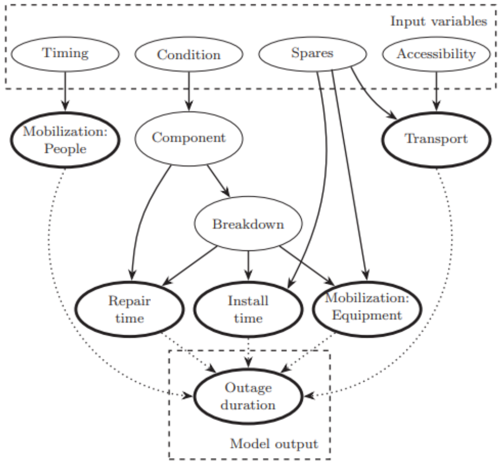


Fig. 1. Final model structure. Continuous variables illustrated by ellipses with a bold outline.

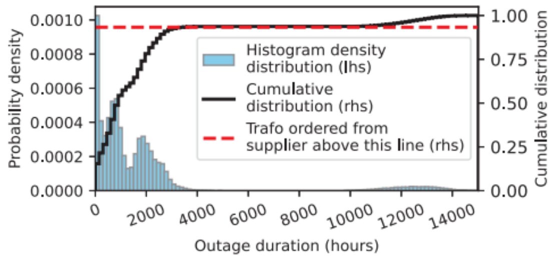


Fig. 4. Illustrative example of outage duration model output. 10 000 samples.

[1] Kiel, E. S., Catrinu-Renstrøm, M. D., & Kjølle, G. H. (2023). A transformer outage duration model with application to asset management decision support. In *The 33rd European Safety and Reliability Conference (ESREL)*, doi: 10.3850/978-981-18-8071-1_P078-cd
[2] Kiel, E. S. Transformer outage duration model (t_odm). Available: https://gitlab.sintef.no/power-system-asset-management/t_odm.

Simulating rare interruption events in reliability of supply analysis

Challenge and objective

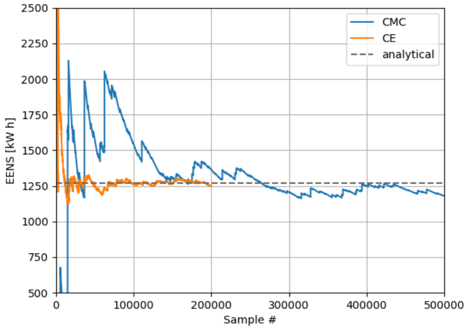
- Power interruptions due to wear-out failures of transformers are relatively rare.
- Assessing the risk of rare, overlapping events in MCS is computationally challenging since capturing these events requires many time-consuming simulations
- Monte Carlo simulation (MCS) is the natural tool to capture more complex behaviours in reliability of supply analysis, compared to analytical methods based on complicated Markov Models
- Modelling of component degradation and wear-out failures in reliability of supply analysis is of particular interest in our case

What have we learned?

- The computational cost of reliability assessment with MCS can be reduced by applying different Variance reduction (VR) techniques, such as
  - Importance sampling using the Cross Entropy method (CE) [1]
  - Conditional / Semi Analytical Monte Carlo (SAMC) conditional on a rare event occurring [2]
- The techniques have in common that they exploit prior knowledge of the system to obtain the same level of accuracy with fewer simulations
- Both methods achieved substantially lower run time when estimating EENS on test systems
- We found that the CE method encounter challenges on large power systems with many components
- The SAMC method requires thought into how historical behaviour of components (before the event occurring) is modelled

Implications and recommendations

- The developed rare event MCS methods can be used to give significant improvements in the run time of reliability assessments, especially when considering rare events
- The CE method that was developed is most useful when analysing smaller systems or sections of a large system
- The SAMC method is scalable to larger grids
- Efficient code is important in all reliability analysis whether VR techniques are applied or not, and is also highly dependent on the power system optimization solver
- Further development and testing of the methods can be useful for activities post-VulPro



Comparison of CE-method convergence for reliability evaluation with (orange) and without (blue) variance reduction [1]

TABLE I
COMPARISON OF PERFORMANCE: SMC AND SAMC PROCEDURES [a]

Method	Iterations	Realizations of contingencies			Computation time (seconds)
		Line 2, Line 3	Line 2, Line 4	Line 3, Line 4	
SMC	10 000	359	385	486	4.163
SAMC	10 000	10 000	10 000	10 000	0.256

[a] Python implementations using Numba [29]. CPU parallel processing of algorithm iterations. Computation time includes summation and parsing of results.

Comparison of simulation iterations, realizations of "rare" contingencies, and computation times, when using traditional MCS (SMC in the table), and the SAMC method developed in [2].

[1] I. Bjerkebæk and H. Toftaker, "Reliability assessment combining importance resampling and the cross entropy method," *Electric Power Systems Research*, vol. 234, p. 110722, Sep. 2024, doi: 10.1016/j.epsr.2024.110722.

[2] E. S. Kiel and G. H. Kjølle, "A Monte Carlo sampling procedure for rare events applied to power system reliability analysis," in *ISGT EUROPE 2023 Proceedings*, Oct. 2023, pp. 1–5. doi: 10.1109/ISGTEUROPE56780.2023.10407144.

Capturing the relationship between component condition and power system reliability – transformers vs. circuit breakers

Challenge and objective

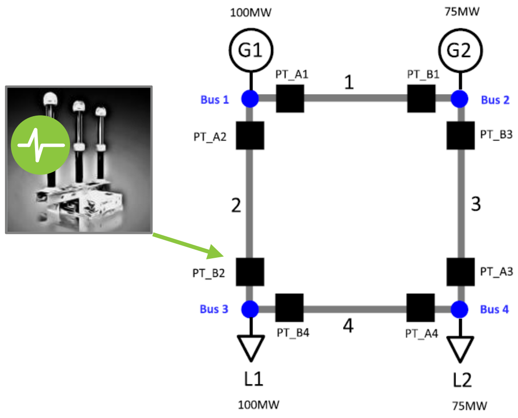
- The VulPro project has developed methodologies for analysing reliability of supply that take into account the technical condition of power system components. Initial work considered power transformers, building on an existing health index model.
- To complement the work on transformers, the PhD study in the project has focused on high-voltage circuit breakers (HVCBs) and on how their technical condition impact reliability of supply.
- An important question then raised was: How should the technical condition of circuit breakers accounted for in reliability of supply analysis? Can other component types be treated in a similar way as power transformers?

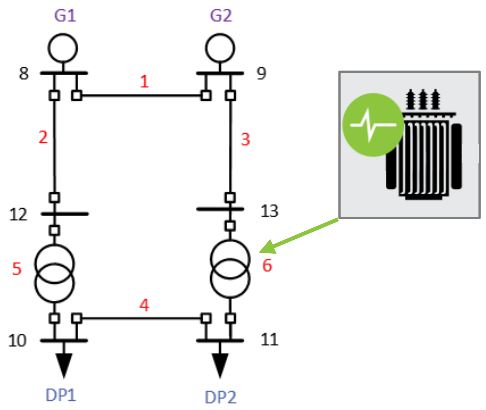
Implications and recommendations

- The VulPro methodology for integrating component condition and component reliability models in reliability of supply analysis can be applied to different types of components.
- However, it must be considered how different types of components have different roles in the power system (e.g., power transformers vs. high-voltage circuit breakers (HVCB)).
- For HVCBs, the influence of substation topology should be considered in future work.
- A database of scrapped HVCBs and/or time stamps on exactly when outages occurred would have improved the accuracy of component reliability models for HVCBs.
- Degradation models for transformers and HVCBs should be further improved.
- There is a great need to develop degradation and reliability models for other components such as power cables and overhead power lines, for which few models are available today.

What have we learned?

- HVCBs have different failure mechanisms from power transformers and have two distinct failure modes that are related to their technical condition:
  i) failure to trip on command and ii) tripping without a command.
- How probabilities of such failures depend on condition can be estimated using existing data.
- The fault statistics available for calibrating CBs probability to fail to trip on command is particularly scarce, making this estimate relatively uncertain.
- Compared to transformers, circuit breakers have a different role in the power system as part of protection systems for transmission lines. This means that some HVCB failures (not tripping on command) lead to the simultaneous occurrence of two or more outages.
- For HVCBs, no failure database of scrapped components could be used to translate health indices to failure rates, and the HVCB failure method instead had to rely on a database of planned and unplanned outages (with a flag that an outage had occurred but no time stamp).





[1] J. A. Grant, I. B. Sperstad, J. Foros, and V. V. Vadlamudi, "Health index calculation using failure modes, effects, and criticality analysis for high-voltage circuit breakers," *in ESREL 2023*, 2023, doi: 10.3850/978-981-18-8071-1_P128-cd.
[2] J. A. Grant, H. Toftaker, S. Perkin, I. B. Sperstad, and V. V. Vadlamudi, "High-voltage circuit breaker condition-dependent failure rate with covariates," *in 2024 Annual Reliability and Maintainability Symposium (RAMS)*. IEEE, 2024, doi: 10.1109/RAMS51492.2024.10457806.
[3] J. A. Grant, I. B. Sperstad, V. V. Vadlamudi, S. Perkin and E. S. Kiel, "The impact of high-voltage circuit breaker condition on power system reliability indices", *IET Generation, Transmission & Distribution*, vol. 18, no. 23, pp. 3980–3994, 2024. doi: 10.1049/gtd2.13333.

The impact of high-voltage circuit breaker condition on power system reliability

Challenge and objective

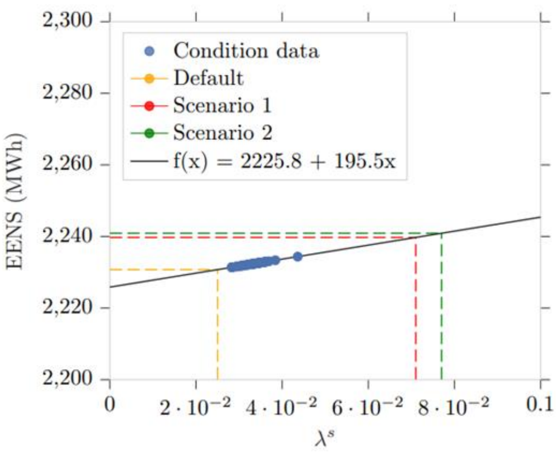
- How can high-voltage circuit breaker (HVCB) condition data be integrated into power system reliability analysis?
- How does the condition of an HVCB influence the likelihood of the HVCB tripping without a command or failing to trip on command?
- What are the effects of unwanted and missing HVCB operation on the system-level reliability indices?
- What are the sensitivities between the reliability indices and the HVCB condition parameters?

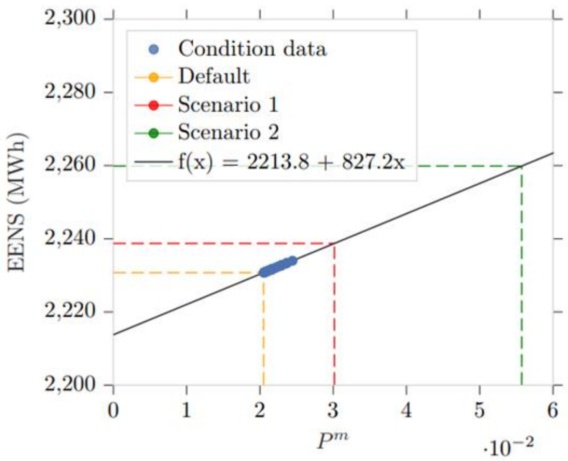
Implications and recommendations

- The methods enable the assessment of how the condition of high-voltage circuit breakers affects the reliability of a system.
- This can be used for decision support to enable condition-based and risk-based maintenance and renewal of high-voltage circuit breakers.
- The failure mechanism of failure to trip on command has a stronger influence on reliability of supply due to common-mode failures (multiple outages from a single line fault).
- Collecting data for HVCBs' failure to trip on command is therefore more important to assess how the reliability (and vulnerability) of a power system depends on HVCB condition.

What have we learned?

- The condition data of HVCBs can be utilised to assess the deterioration of failure mechanisms. The weight that these failure mechanisms contribute to the health index can be justified through a framework employing failure modes, effects, and criticality analysis.
- The Cox Proportional Hazards Model can be used to facilitate the transformation of health indices into the HVCB condition-dependent reliability parameters of Pm (probability of failure to trip) and λs (trip without a command rate) while considering the effect of covariates.
- Trip coil current measurements can account for a higher fraction of the weight of the failure mechanisms that contribute towards λs (92\%) than Pm (39\%). As a result, λs could potentially vary by 184.07% compared to default values found in the literature that do not account for the HVCB condition, while Pm could potentially vary by 47.13%.
- In a study using a 4-bus test system, it was found that λs had minimal impact on reliability indices despite its high variability, while Pm had a significant effect on reliability indices despite being less variable.





[1] J. A. Grant, I. B. Sperstad, V. V. Vadlamudi, S. Perkin and E. S. Kiel, "The impact of high-voltage circuit breaker condition on power system reliability indices", *IET Generation, Transmission & Distribution*, vol. 18, no. 23, pp. 3980–3994, 2024. doi: 10.1049/gtd2.13333.