DOCTORAL THESIS

Development of a Substation Risk-Based Asset Management Decision-Making Process in the Case of Insuffcient Information

Guido Andreesen

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted for any academic degree elsewhere.

Guido Andreesen

signature

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Alajaama riskipõhise varahalduse otsustusprotsessi arendamine ebapiisava sisendteabe tingimustes

GUIDO ANDREESEN

KIRJASTUS

Contents

List of Publications

The present Ph.D. thesis is based on the following publications that are referred to in the text by Roman numbers.

I Guido Andreesen, Madis Leinakse, Jako Kilter and Mart Landsberg, "Maximum Risk Calculation Process for Individual Substation Equipment in Primary Side", in *ISGT Europe 2024*, October 2024, pp. 1-5

II Guido Andreesen, Madis Leinakse, Jako Kilter and Mart Landsberg, "Determining Cost-Efficient Sequence of Condition Inspection Based on Estimated Condition Data", in *ISGT Europe 2024*, October 2024, pp. 1-5

III Guido Andreesen, Madis Leinakse, Jako Kilter and Mart Landsberg, "Cost-Efficient Improvement of Power System's Reliability within Limited Funds", in *RTUCON 2024*, October 2024, pp. 1-6

IV Guido Andreesen, Madis Leinakse, Jako Kilter and Mart Landsberg, "Methodology for Forecasting the Cost of Substation Asset Management in Upcoming Future", in *PECON 2024*, November 2024, pp. 1-5

Author's Contributions to the Publications

I In I, Guido Andreesen was the main author, proposed the idea, wrote the simulation program, carried out the simulations and the analysis of the results, prepared the figures, wrote the manuscript, and presented the results in ISGT Europe 2024.

II In II, Guido Andreesen was the main author, proposed the idea, wrote the simulation program, carried out the simulations and the analysis of the results, prepared the figures, wrote the manuscript, and presented the results in ISGT Europe 2024.

III In III, Guido Andreesen was the main author, proposed the idea, wrote the simulation program, carried out the simulations and the analysis of the results, prepared the figures, wrote the manuscript, and presented the results in RTUCON 2024.

IV In IV, Guido Andreesen was the main author, proposed the idea, wrote the simulation program, carried out the simulations and the analysis of the results, prepared the figures, and wrote the manuscript.

Abbreviations and Symbols

$CAPEX$	Capital expenses
CBM	Condition-based method
$CoCBM$	Cost of condition-based method
$CENS$	Cost of energy not served
CoF	Cost of failure
CoI	Cost of inspections
$CoLC$	Cost of load curtailment
$CoMA$	Cost of maintenance
$CoMM$	Cost of management method
$CoMS$	Cost of measurement solutions
CoR	Cost of repair
$CoRBM$	Cost of risk-based method
$CoRR$	Cost of risk reduction
$CoRtF$	Cost of run-to-failure approach
$CoTBM$	Cost of time-based method
DSO	Distribution system operator
ENS	Energy not served
$EoRR$	Efficiency of risk reduction
LC	Load curtailment
$MTTR$	Mean time to repair
$OPEX$	Operational expenses
PoF	Probability of failure
RoF	Risk of failure
RBM	Risk-based method
t	Time step
T	Time period
TBM	Time-based method
TSO	Transmission system operator
$VoLL$	Value of lost load
z	Threshold parameter

Introduction

Background Overview

Access to electricity is the main cornerstone of modern society. It is essential for industries, research, healthcare, our daily tasks, and many other purposes. It propels the development of countries and regions and improves life-standards. Nevertheless, the electricity needs to be generated first and made available on-demand. In order to distribute the electricity to different areas, population centers, and people, a power system is used. In other words, the power system is the link between the electrical energy producers and the consumers.

The power system is a complicated structure, made up of numerous transmission lines and their connecting points. These connection points, called substations, tie together all the various lines and other connections. The distribution of electricity is controlled and regulated through substations. They also have a protective purpose in case of failures in the power system. If a failure occurs, then the area with the fault is disconnected from the rest of the grid via substations. It is not an overstatement to say, that without substations, electricity distribution could not be operated.

As with society, the power system is always evolving. New directives, regulations, and rules implemented by the government change the energy sector. This has an impact on electricity distribution as well, creating many challenges to tackle [1]. For example, traditional power generation units in coal-based power plants are being gradually replaced by renewable energy-based solutions. This subsequently alters the locations of electricity generation and demand centers. As a result, the load on some transmission lines increases, while it decreases on others. Similarly, the power system's electrical strength and transmitted energy change at specific substations. Thus, these changes have an impact on the overall planning and management of the power system and substations.

The functionality of the substations itself depends on the functionality of their individual equipment and elements. If the equipment is not capable of operating within the required limits, then the part of the power system with that specific equipment can become disabled. This has an impact on the transmission capability of electricity between generation and demand, causing failure consequences measured mainly by the value of undelivered energy. These situations need to be avoided by focusing on equipment with higher risk of failure. Therefore, the risk of equipment failures needs to be assessed as stated in the ENTSO-E regulations [2, 3]. Mainly, it is essential to map the power system's elements, that can cause disruptions in energy distributions.

The risk of failure itself includes in most cases financial and probabilistic factors. Therefore, the risk of failure indicates the combination between the likelihood of occurrence of a specific failure event and its related economic consequences. The obtained value makes it possible to evaluate the degree of failure significance of various power system equipment on the common scale. Higher risk of failure indicates the importance of that equipment in terms of overall reliability and the redundancy of the power system. In order to decrease the risk of failure, appropriate solutions are needed.

An option for decreasing risk of failure is to keep the condition of the power system equipment as good as possible. However, this can have a relatively high associated cost, which may exceed the available resources dedicated for maintaining proper power system functionality. Thus, it is necessary to develop new approaches for decreasing failure risk more optimally. As in every sector in society, cost-efficiency has become one of the main factors in the operation of the modern power systems. Continuing as usual might not be enough to adapt to the changing energy sector and deal with various challenges related to substation asset management. Mainly, it is important to predict and avoid equipment failures that have extensive consequences, such as a disconnection of larger areas or crucial facilities. In addition, it is necessary to improve awareness of the condition of the equipment and allocate the available funds to equipment with a higher likelihood and cost of failure.

Maintaining the functionality of the power system is the responsibility of transmission system operators (TSOs) or distribution system operators (DSOs). They also need to take necessary actions to prevent potential failures in the grid and keep its reliability at a socially acceptable level. This means having awareness about the failure risk and the condition of the equipment in the system. Asset management is used in order to gather necessary data and justify various decisions related with power system equipment and reliability. It requires the assessment of the condition of equipment in a regular basis to detect occurring degradations. If the condition of equipment has started to degrade, maintenance procedures are carried out. Through frequent condition inspections, equipment-related data is improved. Having awareness of the condition of equipment also makes it possible to prevent potential failures with higher and more serious consequences.

Asset management itself consist of different methods and principles. It has evolved over the decades and is constantly improving. Nevertheless, multiple aspects are still inefficient and not optimal. These are mainly related to reliability issues and statistics describing equipment condition data. Changes in the power system alter demand, load, and the and transmitted power in lines. This has an impact on reliability as well. As a result, the risk of some equipment failure increases and maintaining their proper functionality becomes a priority. Another important factor in the power system's reliability is the aging of its equipment. The majority of the substations were constructed more than 30 years ago, meaning that the equipment has already reached its life expectancy or is about to reach it [4]. Due to aging, their overall reliability starts to decrease.

This requires power system operators to replace the aged equipment in order to increase reliability, but it has a high cost and also requires available funds. Instead, it is possible to maximize equipment operational time by implementing dedicated approaches in asset management. This makes it possible to decrease the total replacement cost and use the remaining funds for other things, such as improving the power system's reliability. Thus, equipment replacement should be done based on the actual condition of equipment, not on statistical estimates. In order to make decisions on more optimal and cost-efficient options regarding aging assets, research is needed to develop the necessary methodologies to justify these choices.

The lack or absence of statistical data on equipment condition decreases the efficiency of asset management as well. It is necessary to know the actual condition of equipment in order to determine the accurate failure risk or to justify its replacement. Due to the large amount of equipment in the power system and the previously implemented asset management methods, statistical information can be limited for some equipment types. As a result, the partial information related to equipment condition alters their importance in the power system and makes determining their failure risk complicated. Thus, obtaining equipment failure risk in the case of data uncertainty is a crucial factor. This additionally requires the development of dedicated approaches improving asset management decision-making.

After determining the failure risk of equipment, it is necessary to reduce it by implementing the corresponding methods. Different risk reduction methods can be used within the asset management decision-making procedure. Nevertheless, each of them has a specific associated cost. Therefore, determining cost-efficient way to increase power system reliability requires the consideration of various cost-related components of risk reduction. For that purpose, the costs of multiple asset management methods need to be evaluated. In order to optimize asset management at a larger scale and improve its cost-efficiency, it is important to include all substation equipment in the process. This requires the determination of individual failure risks for "smaller" and less expensive pieces of equipment in addition to the "larger" and more expensive ones, especially if they can similarly cause extensive failures in the power system. Their condition data, either statistical or estimated, is also needed.

Therefore, in order to increase the cost-efficiency of asset management, it is necessary to take into account its multiple domains. These domains are related to each other and can be determined using dedicated methods. Combined, they create a structure of modern day asset management and describe the various challenges in asset management decision-making. These domains are also illustratively depicted in Fig. 1. Firstly, in order to increase the efficiency of asset management, it is necessary to determine optimal management strategies. For that, the cost-efficiency of different management methods needs to be analyzed. Secondly, optimal decision-making is related to the availability of equipment-related condition data. Having high-quality statistical data is an important factor in improving asset management. In the case of limited or absent data, data estimation is necessary. Thirdly, failure risk of equipment needs to be decreased cost-efficiently. This is achieved by analyzing potential risk reduction methods and using the proper methodology for risk assessment. In addition, for calculating failure risk values, it is initially important to determine equipment failure probability and its condition.

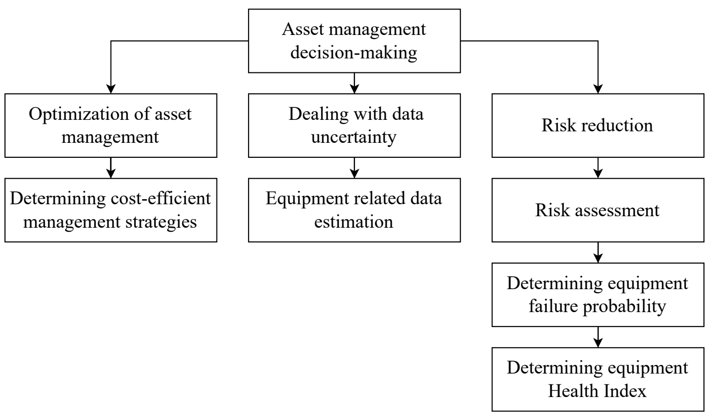

Figure 1: Main domains related with asset management decision-making

Thus, all of these domains are crucial for optimizing asset management decision-making. In a modern power system, one option for overcoming the challenges related to this is to develop suitable solutions, as stated in ENTSO-E future goals for 2030 [5]. Therefore, it is necessary to: i) maintain the reliability of the power system in the case of aging substations; ii) determine the failure risk of each individual component or piece of equipment in the power system; iii) prevent potentially occurring equipment failures with higher consequences in a more cost-efficient manner; iv) obtain equipment-related data in the case of data uncertainty; v) decrease the failure risk of equipment in a more cost-efficient manner. Therefore, developing methodology to improve the reliability of the power system and increase the cost-efficiency of asset management in the case of limited funds and uncertainty in condition data is crucial. This thesis focuses on the challenges listed above and describes corresponding methods with appropriate solutions to overcome them.

Hypotheses

In accordance with the selected domains of asset management decision-making and their related challenges, the hypotheses in this thesis are presented in the following.

- **Hs1** - Failure risk assessments with a focus on high-cost equipment can leave low-cost equipment with significant failure risks unnoticed
- **Hs2** - Failure risk of equipment could be cost-efficiently reduced in the case of unknown condition data
- **Hs3** - Failure risk reduction cost-efficiency could be used to determine the optimal risk reduction methods for individual equipment

Research Questions

In accordance with the hypotheses, the following research questions are addressed.

- **RQ1** - Is it possible to calculate the maximum failure risk of equipment including all substation equipment on the primary side?
- **RQ2** - Is it possible to estimate equipment failure risk in the case of condition data uncertainty?
- **RQ3** - Is it possible to determine a cost-efficient failure risk reduction sequence (process) to distribute equipment between preventive and corrective asset management including all substation equipment on the primary side?
- **RQ4 -** Is it possible to increase asset management cost-efficiency in the case of condition data uncertainty?

RQ1 corresponds to **Hs1**. **RQ2** and **RQ4** corresponds to **Hs2**. **RQ3** corresponds to **Hs3**.

Objectives of the Thesis

- In accordance with **RQ1**, the first objective of the thesis is to develop a failure risk calculation method for all equipment on the substation's primary side. It is intended for the calculation of equipment maximum risk based on its failure probability and cost-related parameters, such as cost of load curtailment and repair. The calculation process takes also into consideration the single failure and combined failure events from the perspective of individual equipment and its related failure impact to the power system.
- In accordance with **RQ2** and **RQ4**, the second objective of the thesis is to develop methods for equipment failure risk assessment and reduction in the case of uncertainty in equipment condition data or lack of a sufficient level of data. The methods incorporates data or cost estimation in the process for determining a cost-efficient sequence of equipment inclusion into the preventive asset management method. They also indicate the justification for using preventive or corrective management methods in the case of limited condition data.

- In accordance with **RQ3**, the third objective of the thesis is to develop a method for cost-efficient reduction of equipment failure risk. It determines the individual equipment risk reduction efficiency according to the achievable decrease in risk and its cost. The method makes it possible to evaluate the justification of decreasing failure risk by implementing measurement solutions or arranging spare equipment in the same or a nearby substation.

The links between publications, the factors and domains of asset management decision-making, and the research questions of the thesis are depicted in Fig. 2. Publication I addresses **RQ1** and focuses on the failure risk calculation method of individual pieces of substation equipment. Publication II addresses **RQ2** by proposing a process for the estimation of equipment condition-related data and uses the results to distribute equipment between the different management methods from a management cost perspective, therefore addressing **RQ4**. Publication III addresses **RQ3** and proposes a procedure for determining a sequence (process) for equipment failure risk reduction and their distribution between management methods by considering management costs. Publication IV addresses **RQ4** and describes a method for evaluating the asset management costs of different approaches during a specified time period.

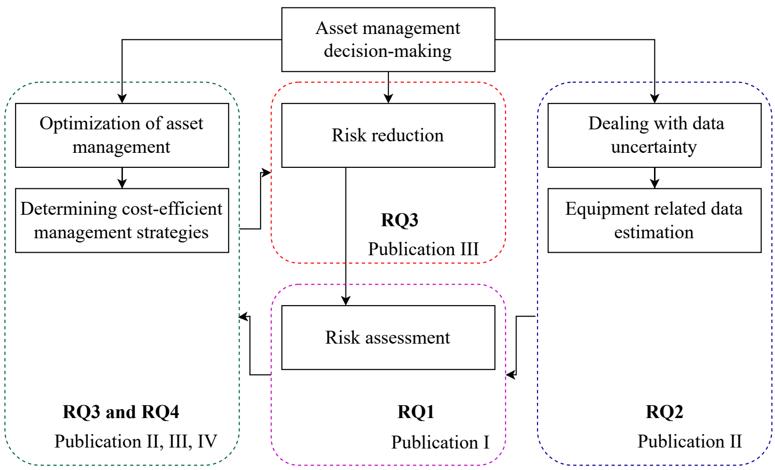

Figure 2: Links between main domains of asset management decision-making, research questions, and publications used in thesis

Contribution of the Thesis

Scientific Novelty

- A hybrid calculation process of equipment failure risk is developed to determine its maximum value for all equipment types in substation's primary side from the individual equipment perspective.

- A condition Assessment process of substation equipment is proposed in the case of limited condition data by incorporating data estimation and cost components related to asset management methods.

- A reduction process of equipment failure risk is proposed by incorporating preventive and corrective asset management methods for all substation equipment types within the available risk reduction funds.

Practical Novelty

- The process failure risk calculation makes it possible to obtain a full overview of substation equipment with higher failure risk by including "smaller" and less expensive equipment types in addition to "bigger" and more expensive ones.

- The procedure for determining the process of assessing equipment condition inspections makes it possible to justify using preventive or corrective asset management methods for all substation equipment types in the case of limited condition data.

- The process for failure risk reduction makes it possible to determine a procedure of including individual equipment or equipment types in preventive or corrective asset management methods from a cost and reliability perspective.

Thesis Structure

This thesis is divided into three chapters. In the first chapter, an overview of the substation asset management and the importance of equipment failure risk is given. In the second Chapter, the calculation process of determining the maximum failure risk from equipment perspective is explained. In the third chapter, the obtainment of estimated failure risk and probabilistic state of equipment condition in the case of data uncertainty is analyzed. In addition, an equipment failure risk reduction process considering the related asset management costs is presented.

1 Substation Asset Management

Substation asset management contains various guidelines for maintaining the proper functionality of a power system's equipment. It includes different management methods, such as preventive and corrective, with specific cost components. Another key factor in asset management is equipment failure risk (RoF). It is possible to optimize asset management procedures according to the cost components and RoF values. In the case of input data uncertainty, as RoF estimation is also needed. Based on the management decisions and corresponding procedures, the RoF of substation equipment can be reduced. This is the main factor in increasing management cost-efficiency.

This chapter will provide background information on substation asset management. Initially, a brief overview of substation asset management methods and their cost components is given. This is followed by a description of the risk of failure, its use in asset management, and a discussion on the necessity of asset management cost optimization. Next, it analyses the impact of inaccuracy on the risk of failure and potential options for reducing it. The chapter ends with a description of RoF reduction methods for increasing asset management cost-efficiency.

1.1 Methods of Substation Asset Management

Substation asset management is used to maintain the good condition and proper functionality of substation equipment. Its objective is to evaluate the condition of the equipment and take necessary action, if a change in its condition has been detected. Usually, these actions involve equipment maintenance or replacement. The efficiency of asset management depends on the efficiency of avoiding equipment failures. If the condition of the equipment begins to deteriorate, its operational capabilities decrease. Without timely interference, the deterioration of its condition leads to equipment failure. The latter can cause a disruption in energy supply and leave part of the grid without electricity. These situations could have serious and significant consequences. Therefore, to avoid equipment failures, their condition needs to be evaluated or inspected regularly.

Another objective of asset management is to reduce the operational expenses ($OPEX$) of the power system. This foremost requires avoiding equipment failures with higher costs and decreasing the failure probability of equipment. As such, it depends on the equipment condition evaluation methods and its inspection frequency. On the other hand, these actions can increase the $OPEX$. An option is to increase the capital expenses ($CAPEX$) in order to lower overall management costs. Mainly, the $CAPEX$ can be used to obtain condition measurement solutions that allow for the prevention of equipment failures and reduce the need for time-based condition inspections of equipment.

The main principles of asset management are described in the ISO 55000 [6–8] and PAS 55 [9, 10] standards. In these, overall guidelines for implementing asset management in various companies are provided. However, there is a lack of more detailed descriptions related with asset management optimization and cost-efficiency. Therefore, these standards only give more generalized instructions and approaches rather than solving specific management-related issues. Thus, research done is this field could provide more accurate and directly focused potential solutions and highlight efficient approaches. In this regard, various aspects of substation asset management are covered in the literature.

An overview of asset management methods and their principles of use is provided in [11]. These are compared based on their impact on power system reliability and associated costs. In addition, an analysis of advantages and disadvantages of management methods are given in [12]. Accordingly, the chosen asset management approach depends on the preset objectives and the justification of the increase in $OPEX$ and $CAPEX$. Therefore, the asset management methods can be divided into the following categories:

- Preventive
- Predictive
- Corrective

In preventive methods, various approaches and solutions, such as equipment condition inspections and measurement sensors, are used to detect changes in equipment condition. If significant changes are detected, preventive actions are implemented. These may be equipment maintenance or even replacement. Preventive methods could also include replacing still functional equipment before the end of its life expectancy. The predictive method has common aspects with the preventive method. Its main essence is to predict changes in equipment condition. Similarly, equipment condition inspections and measurement solutions are used for that. In addition, it includes statistical analysis to estimate the time frame where the degradation the condition is most likely to occur. Based on analysis, it is also possible to estimate the life expectancy of equipment.

The preventive and predictive methods can also be described as reliability-focused methods. Nowadays, the aim is to transition towards methods, that increase the power system's reliability. Examples of reliability focused asset management methodologies are presented in [13–15]. The key component in these approaches is statistical or measured data representing equipment condition. In accordance with that, the equipment importance in the power system is obtained and expressed by failure probability. Next, equipment with higher failure risk is focused on and more frequent condition assessments are used. The majority of relevant reliability-based methods require relatively accurate input data. This makes them less efficient in the presence of condition-related data uncertainty. In addition, they focus on specific substation equipment type, which also limits their functionality.

The corrective method is the opposite of the previous two. It means that no direct actions are implemented beforehand to prevent or predict equipment failures due to changes in their condition. Asset management-related actions are taken mainly after failures. Therefore, using the corrective method has an impact on overall power system reliability and cost-efficiency. Nevertheless, it can be a justified option with low cost-equipment, whose failures do not cause significant consequences.

It is also possible to divide asset management methods into:

- Time-based
- Condition-based
- Risk-based
- Run-to-failure

Both categorizations of asset management methods are used in parallel. The latter distribution also specifies the parameter considered in management decision-making. For example, in the risk-based method, the failure risk of equipment is the main parameter for choosing appropriate management decisions. Fig. 3 shows an overview of the asset management methods from risk-based method perspective. It is possible to use the time-based, condition-based, and run-to-failure approaches individually and in accordance with previous practices. Nevertheless, to optimize asset management cost and

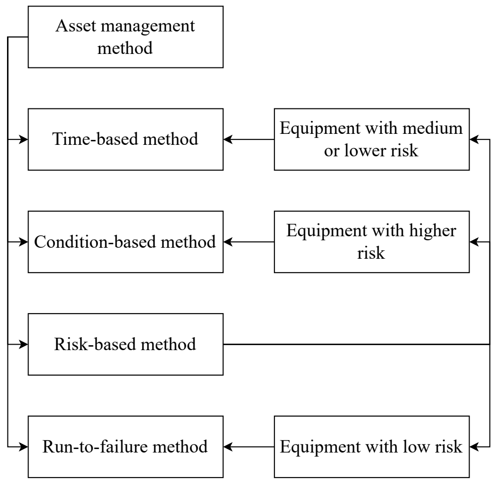

Figure 3: The overview of the asset management methods and the principle of the risk-based distribution of the equipment between these methods

increase the power system's reliability, the risk-based method is preferred. Thus, equipment is distributed between various management methods based on failure risk value.

The time-based method (TBM) shares aspects with the preventive and predictive methods, as they all involve periodic condition inspections. It is also a corrective method for the same reason. Nevertheless, the periodic inspections can not avoid equipment failures, if the deterioration of the condition has a faster pace and reaches equipment failure before the next inspection. Still, it can be an adequate option for equipment with lower failure cost.

The condition-based method (CBM) can be considered preventive and predictive, as it makes it possible to obtain a relatively accurate overview of the assets' conditions. This is achieved by relatively frequent condition inspections or by using condition measurement solutions. Therefore, the likelihood of equipment failures is decreased. On the other hand, it can also be a more expensive method than TBM due to the more frequent condition evaluation.

Opposite of the CBM is the run-to-failure method, where condition inspections and measurement solutions are not used. Subsequently, it can not prevent or avoid equipment failures. Therefore, it is a purely corrective approach. It may be an option to consider, if the cost of equipment failures and their likelihood are relatively low and the cost of condition inspection is not justified.

The risk-based method (RBM) combines aspects from TBM and CBM. According to this method, equipment with a higher RoF is managed in accordance with the principles of CBM, while equipment with a medium or lower RoF is managed in accordance with the TBM. Another option is to use the run-to-failure method for equipment with a relatively low RoF. The RoF is calculated based on the consequences and the probability of the equipment's failure. The threshold values determining the distribution of the equipment between each method can be obtained according to the optimization of asset management cost-efficiency.

The chosen asset management methods depend also on the functionality and complexity of the equipment, as well as the cost of replacing the equipment after failure. If the equipment has less complexity and lower cost, different management methods may be preferred to the ones used on bigger equipment with higher costs. Therefore, equipment type is a major factor determining the optimal asset management method. Similar types of equipment based on their functionality, complexity, degradation or aging characteristics, and cost can be represented by equipment groups. The equipment types on the substation's primary side are:

- Power transformers
- Circuit breakers
- Disconnectors
- Current transformers
- Voltage transformers
- Earthing switches
- Surge arresters
- Insulators
- Inductive reactors, capacitor banks, and voltage controllers

With power transformers, the CBM is preferred, because more frequent data on equipment condition allows for a decrease in the likelihood of expensive failures. With other primary equipment, the TBM is widely used. The frequency of periodic inspections varies based on the equipment type, its complexity, and its functionality. As stated in [16], the methods used in substation asset management are chosen based on common practices, traditional approaches, available knowledge and statistics, and field experience. Nevertheless, it can also mean continuing as usual, which might be inefficient and decrease the power system's reliability in the long run. Therefore, to avoid and prevent equipment failures and increase the cost-efficiency of asset management, the optimal management method needs to be chosen for each equipment group. Mainly, this depends on management method cost components. Thus, it is necessary to compare the costs of the different asset management methods.

1.2 Cost of Asset Management

Asset management methods can be linked to specific cost components, which determines their overall cost during a specific time period. Fig. 4 gives an overview of the principal links between asset management methods, management decisions, and cost components. Depending on the management method, either preventive or corrective measures are used. These are either implemented in the condition assessment of equipment for degradation prevention or for correcting consequences after equipment failure. If a preventive approach is followed, management decisions are taken in accordance with equipment condition. In the case of condition degradation, equipment maintenance or replacement is used. Subsequently, these actions are related to specific cost components. Using the preventive approach itself for determining equipment condition has a specific cost due to condition inspection or monitoring. The corrective approach is similar, as it is linked to the cost of equipment failure. After obtaining asset management cost components, overall management cost is calculated.

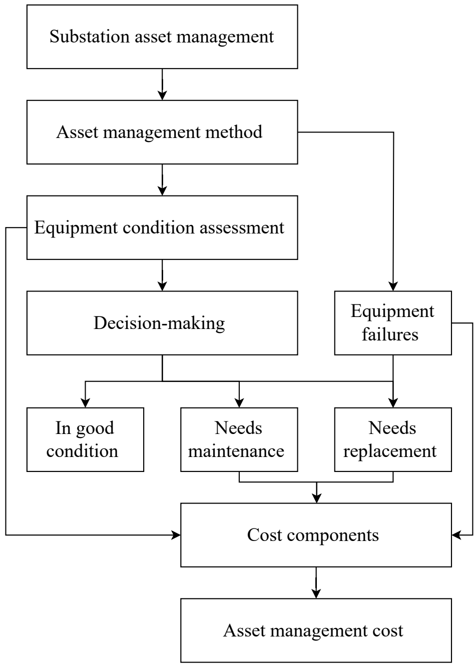

Figure 4: Principle overview of the relations between the asset management methods, management decisions and the related cost components

The TBM includes multiple cost components. Its first cost component is the cost of condition inspections (CoI), which depends on the inspection frequency. Therefore, more frequent condition inspections also mean an increase in the total CoI. A second important cost component of the TBM is the cost of failure (CoF). This combines the cost of the equipment repair (CoR), including replacement if needed, and the cost of the load curtailment ($CoLC$) that occur with equipment failure. The $CoLC$ represents the total value of the energy not supplied (ENS) as a result of the equipment failure. It can also be indicated by the summarized value of the lost load ($VoLL$) at the period of failure.

Similarly, the CoF depends on the frequency of the condition inspections. Due the gaps between inspections, the TBM can be inefficient for avoiding failures with larger consequences (higher ENS and $VoLL$) and detecting the degradation of equipment on time. Due to the less frequent inspections, the condition of equipment degrades further without interference. As a result, the likelihood of having a higher CoF component in that time period increases.

Usually, the CoR is the same within the equipment group. However, the $CoLC$ can vary significantly. It is determined by two factors after equipment failure [17]. The first factor is the redundancy of the connection between the load (demand or supply) and the power system. The load curtailment is higher, if there are few or no alternative paths to power system connections, that lead to substations. The load curtailment is lower or absent, if multiple paths exist. The second factor is the electrical strength and capability of the power system. This is measured by the voltage values at the substations, and the current values in the connection lines and power transformers. After equipment failure, the voltage could be below the allowed minimum limit. Similarly, the current in nearby connections or power transformers could surpass the allowed maximum limit. To increase the voltage and decrease the current, load curtailment is used. In accordance with these factors, the total value of load curtailment and the $CoLC$ can be obtained.

the third cost component of the TBM is the cost of equipment maintenance ($CoMA$). This depends on the amount of equipment with the detected condition degradation at the time of the condition inspections, as well as the scale of the condition degradation. Due to the periodic condition inspections, the condition degradation might not be detected in its earlier stages. This means, that the $CoMA$ will be higher compared to if defects are detected in an earlier stage. In addition, the condition degradation can progress between inspections. This means, that it could be more reasonable to replace equipment than to use maintenance, if the CoR and the $CoMA$ are relatively similar.

Overall, the cost of the time-based management method ($CoTBM$) in time period t (1) depends on the condition inspection frequency, the CoI and the CoF_i. Due to that, it is not optimal or cost-efficient. To increase its efficiency, evaluation of the inspection frequency is necessary.

$$CoTBM(t) = \sum_{i=1}^{n} (CoI_i + CoMA_i + CoF_i) \tag{1}$$

In order to prevent potential failures due to the degradation of equipment condition and detect the occurred defects on time, the CBM can be used. This means, that the condition of equipment is assessed based on relatively frequent inspections or measurement solutions. Therefore, the CoI is higher in the CBM compared the TBM, if using condition inspections. The cost of measurement solutions ($CoMS$) is added, if measurement solutions are used instead or with condition inspections. Usually, though, the inspections are replaced by measurement solutions. As a result, the degradation of equipment has higher probability of being detected in its earlier stages. In addition, equipment maintenance is implemented without significant delays. Subsequently, this decreases the $CoMA$. On the other hand, frequent condition inspections or measurement solutions increase the overall cost of the condition-based management method ($CoCBM$) in a time period t (2) compared to $CoTBM$, without considering the CoF.

$$CoCBM(t) = \sum_{i=1}^{n} (CoMS_i + CoMA_i) \tag{2}$$

If including the CoF, the $CoCBM$ can be lower than the $CoTBM$. It depends on the number of prevented equipment failures and the scale of the analyzed time period. In accordance with the CBM and its outcome, the failure probability (PoF) of the equipment is decreased. This subsequently reduces the potential failures with extensive consequences, as indicated by the $CoLC$. Therefore, it is possible to minimize or discard the component of the CoF. Overall, the $CoCBM$ depends on the condition inspection frequency, or the $CoMS$, and the $CoMA$.

Another important factor in the CBM is the amount of equipment with added measurement solutions. To optimize the cost of asset management and avoid the extensive increase of $CAPEX$, the optimal amount of equipment with measurement solutions is necessary to determine. In that, the $CoMS$ is an important factor as well. If it decreases, more equipment can be included in the CBM without exceeding $CAPEX$ significantly. In addition, the avoided $CoLC$ makes it possible to reduce the $OPEX$. Therefore, it is necessary to compare the change in $CAPEX$ and $OPEX$ based on the usage of the TBM and the CBM. Based on the results, the equipment can be divided between different management methods in accordance with the RBM.

The use of the run-to-failure approach may be preferable from a cost-efficiency perspective, if the potential CoF_i is lower than the total CoI_i or the $CoMS_i$ of equipment in the specific time-frame. It is still an alternative option, though, and not suitable for preventing equipment failures. In addition, the overall cost of the run-to-failure approach ($CoRtF$) in a time period t (3) can be higher compared to the TBM due to the condition deterioration of equipment without interference.

$$CoRtF(t) = \sum_{i=1}^{n} CoF_i \tag{3}$$

The cost of risk-based asset management ($CoRBM$) in time period t (4) depends on the amount of equipment k added into the CBM, m added into the TBM and p added into the run-to-failure approach. Subsequently, each equipment added to the CBM can increase the $CoRBM$. On the other hand, it decreases the likelihood of equipment failures, and therefore, can decrease the total CoF and the $CoRBM$. A dedicated analysis is needed to determine the efficient balance of the amount of equipment in different management methods. Still, because of the higher probability of avoiding failures, the CBM is preferred in the case of equipment with a higher risk.

$$CoRBM(t) = \sum_{i=1}^{k} CoCBM_i + \sum_{i=1}^{m} CoTBM_i + \sum_{i=1}^{p} CoRtF_i \tag{4}$$

The main objective of using the RBM is to optimize the cost of asset management. For that, it is necessary to analyze multiple cost components, which are linked with a relatively frequent condition inspections, the number of measurement solutions added, and the potentially avoided equipment failures. This makes it possible to determine the optimal amount of equipment to include in the CBM. The remaining equipment is divided between the TBM and the run-to-failure approach.

1.3 Risk of Failure

The risk of failure incorporates the likelihood of a failure event and its related economic consequences. Combined, the calculated value indicates the financial risk of the failure event on the probabilistic scale. The financial risk is higher if the failure event has significant economic consequences in addition to a relatively high probability. On the other hand, it is lower if the consequences of a failure event do not cause economically serious enough limitations. Mainly, the financial aspect is related to the amount of undelivered energy to demand and restrictions implied to generation. Therefore, it can be described as load shedding (curtailment). An additional part in that is also the cost of equipment repair or replacement after the failure. The probabilistic aspect is related to equipment condition and its worsening over time. Equipment with a more deteriorated condition and higher likelihood for that has also a higher risk of failure. The risk calculation is used to combine these aspects in the same process.

The substations of a power system can include over tens of thousands of units of equipment. Their overall functionality and the CoR_i are the same within the equipment type. On the other hand, their failure consequences and related costs can be different. These depend mainly on the $CoLC$. To decrease the $OPEX$ and increase the cost-efficiency of asset management, it is necessary to focus on equipment with higher CoF_i. Another related parameter is the PoF_i, indicating the likelihood of equipment failure in the specific time-frame. By combining the CoF_i and the PoF_i, the risk of failure (RoF_i) (5) can be obtained.

$$RoF_i = CoF_i \cdot PoF_i \tag{5}$$

If the RoF_i of equipment is higher, it might be caused by a higher CoF_i or a higher PoF_i. Very high RoF_i occurs in the case of higher values of both parameters. If the CoF_i or the PoF_i is lower, the RoF_i of equipment is also lower. In the case of lower values of both parameters, the RoF_i is relatively low. These relationships can also be used in asset management decision-making. A more detailed description of the risk calculation equations implemented in the scope of the thesis is available in Chapter 2.

The RoF_i value is mainly used to highlight the importance of the equipment in the power system and, subsequently, to direct the focus of asset management towards these pieces of equipment. This is also the main essence of the RBM. Its principle structure is provided in Fig. 5. Initially, the equipment included in the RBM is chosen. Next, the corresponding risk components are obtained and equipment RoF_i is calculated. The latter is used to determine the equipment's importance in the power system. This makes it possible to improve asset management decision-making.

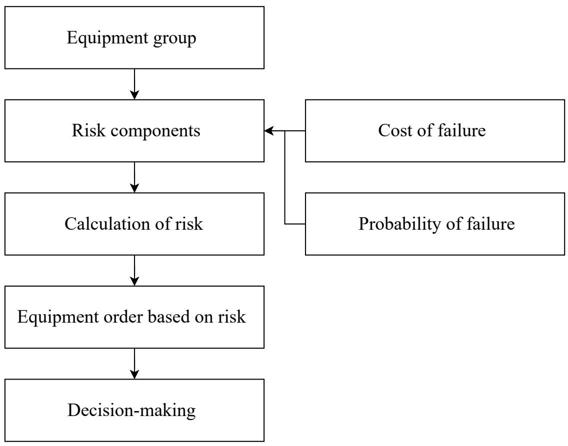

Figure 5: Principle overview of the risk-based asset management structure

The failure risk of the equipment has a direct link to substation and power system reliability. Mainly, if the RoF_i is higher, then the reliability is lower. The usage of reliability assessment in the power system is analyzed in [18], with an included overview of key terms and usual approaches in the field. Commonly, overall reliability is assessed based on the available statistics describing equipment condition. The latter is converted to element failure rate or failure probability. The obtained failure probability of an element is used to calculate its reliability. Next, a specific power system example is implemented to determine element failure consequences, indicated usually by CoF. This makes it possible to analyze the failure consequences from the perspective of power system reliability. Nevertheless, as stated in [19], common methods of failure risk assessment need to be modified in order to obtain the required inputs for management decision-making. These modifications can be related to the calculation of load curtailment in the power system based on its topology, evaluating the equipment failure impact in accordance with substation configuration, or incorporating recently developed elements in the power grid.

The impact of different substation configurations with circuit breakers and disconnectors on reliability and risk is discussed in [20–24]. The common conclusion is, that the availability of alternative paths between transmission or distribution lines increases the overall reliability of the power grid. The main factor in choosing substation topology depends on the CoF values and equipment failure probability. If the highest power system reliability is required, then it is necessary to consider with a double-bus double-breaker substation configuration instead of a single-breaker single-disconnector configuration. Its impact is also analyzed in [25] by using the failure tree method to determine the equipment failure consequences in the power system substation.

Commonly, though, the risk values are calculated for specific equipment types. These are either power transformers, with examples in [26–29], and circuit breakers, with examples in [30–33] . The reason for choosing power transformers and circuit breakers is their higher CoR_i compared to other substation equipment. In addition, there are more available statistical data for these equipment types. It is less common to calculate the risk for cables and joints, with examples in [34,35]. The risk calculation of other equipment types is largely discarded. Similarly, part of that reason is related to their lower CoR_i. Another cause is the lack of data for the PoF_i.

Nevertheless, in order to assess the RoF of the overall power system and its substations, it is necessary to calculate the RoF for all of the equipment. This is an important and mainly overlooked factor in asset management. In accordance with the reliability of the systems, the failure of one element in a series causes the failure of the whole connection. Therefore, the failures of these "smaller" pieces of equipment with lower CoR_i, can similarly to the more expensive equipment, result in extensive load curtailment and higher $CoLC_i$. The results may also be the same, if these elements are located in parallel connections. This highlights the need to include all the equipment at the substations in risk assessment procedures. Otherwise, the achievable increase in the cost-efficiency of asset management is limited.

As described in Fig. 5 above, the RoF values are further implemented in asset management decision-making. Examples of using the RoF in the management decision process are given in [32, 36–38]. In them, the importance level of equipment is commonly obtained. It is used to determine the optimal inspection and maintenance scheduling of different equipment by considering the statistical change in the PoF_i and the CoF_i values. If specific equipment related values are above a preset threshold, then the frequency of condition inspection or monitoring as a part of the TBM or the CBM is increased for that equipment. The main disadvantage of these approaches are the requirement of having sufficient data on equipment condition. They also rely significantly on the equipment age for calculating its PoF_i based on statistical data. Still, for most equipment types, available condition data can be limited or even absent. This factor can alter the overall usability of the available methods for asset management decision-making.

Mainly, it is crucial to create an extensive overview of all higher risk equipment in a substation and propose appropriate methods for increasing the power system's reliability. In risk assessment and its relationship with overall reliability, some other factors are also important, such as the availability of funds and accurate condition data. The risk is determined in [39] to assist in directing asset management tasks within limited funds towards equipment with higher importance. The main objective is to increase the efficiency of maintenance scheduling in order to reduce overall management costs. The need for obtaining relatively accurate risk values to represent the importance of the substation is highlighted in [40]. They stated, that in the changing power system, the relatively accurate prediction of failures has become a necessity. This means, that either more frequent condition inspections or measurement solutions need to be used. Subsequently, this itself requires sufficient amount of condition data to calculate risk values and make justified management decisions, such as determining the amount of equipment to be included in the CBM.

Without sufficient condition data, most of the available approaches have a lower functionality and only evaluate asset management decision-making from the perspective of specific equipment types. In order to develop a substation wide asset management decision-making process, all substation equipment types should be included. The importance of including other substation equipment in risk calculations is highlighted in [41], where the failure-related risk of the substation busbars are analyzed. It is stated, that due an increase in potential threats to substation protection and measurement systems, a more broader perspective of risk assessment needs to be taken. Similarly, as mentioned in [42], the importance of the proper functionality of the substation equipment also affects the secondary side functionality, and therefore the corresponding equipment needs to be included in addition to considering the accuracy of condition measurement.

1.4 Optimization of Asset Management Cost

In addition to reliability assessment and failure risk calculation, more discussions are being held about the possibilities of increasing the cost-efficiency of asset management. This is partially because of the disadvantages of the widely used TBM. Due to periodic inspections, it is impossible to detect fast-evolving defects in equipment, which can lead to failures before an inspection. On the other hand, increasing the inspection frequency subsequently increases $CAPEX$. Therefore, the TBM becomes more similar to the CBM.

From this perspective, it is not cost-efficient to inspect all equipment relatively frequently. If the likelihood of failure is smaller, inspecting the equipment condition at a high frequency is unjustified. In addition, some equipment failures do not cause significant or any load curtailment. Because of that, it is initially necessary to analyze the CoI_i of these types of equipment from the perspective of the CoF_i. It might be more reasonable to discard the periodic inspections or increase their intervals, especially in the case of a lower PoF_i. If the risk is quite small, then discarding the inspections entirely and using a run-to-failure approach can be more cost-efficient than other methods.

Similarly to condition inspections, it might be unreasonable to add measurement solutions to most of the equipment. Firstly, it increases $CAPEX$ and secondly, if the PoF_i and the RoF_i are relatively low, periodic inspections may be preferable. This also depends on the $CoMS_i$, which is another important parameter in asset management cost-efficiency. If it decreases, then the CBM can be implemented more widely without increasing the $CAPEX$. Subsequently, the risk threshold in RBM can be lowered by including more equipment in the CBM. This means, more equipment can be mounted with measurement solutions within the same funds.

Therefore, an analysis of asset management costs based on the use of the different methods is required. This makes it possible to optimize by adjusting asset management decision-making processes. In literature, optimization of asset management costs is commonly done by changing equipment inspection frequency, maintenance time, and the overall number of measurement solutions used. Its main goal is to avoid the degradation of equipment condition by using an optimal inspection frequency and implementing on-time equipment maintenance. This also means determining the optimal distribution of equipment between management methods based on their RoF_i or priority. An overview of the options for maintaining the good condition of equipment and extending their operational time is provided in [43]. It ranges from "follow-the-manual" types to detailed probabilistic approaches. In order to increase the efficiency of maintenance, it is necessary to select a mathematical model allowing optimization. Another more popular choice among power system operators is to apply a maintenance policy, that is based not on a rigid schedule, but on an "as needed" principle. These approaches can also be implemented with or without mathematical models.

An analysis of the difference in time intervals used in asset management planning and its impact on management decisions is provided in [44]. It concludes, that more frequent condition monitoring is essential to prevent extensive degradation of equipment condition. On the other hand, without optimization, it could increase asset management costs. The potential options to tackle aging substations and determine the optimal time-frames for equipment replacement are given in [45]. They propose using life cycle cost analysis to compare different asset management strategies like equipment refurbishment, renewal or redesign. Similarly, a life cycle cost analysis is implemented in [46] to determine long term maintenance of equipment based on the available data on historical maintenance planning and equipment operational data. Subsequently, this makes it possible to decrease the $OPEX$ as part of preventive management. Another methodology for equipment maintenance planning considering statistical data in order to increase asset management cost-efficiency is provided in [47]. It incorporates equipment age, its estimated degradation characteristics in accordance to statistics, and potential failure consequences in decision-making process. Most available methods for asset management cost optimization indicate a strong relationship between the scale and frequency of condition assessment and asset management costs.

The optimization of equipment maintenance in order to minimize its impact on asset management costs is described in [48]. Its additional objective is also to increase cost-efficiently power system reliability. Similarly, an optimal asset management method for selected equipment in power systems is determined in [49], in accordance with their importance indexes. It states, that increasing the inspection frequency of equipment with higher risk and decreasing the inspection frequency of equipment with lower risk, can be economically feasible. Similarly, the process for obtaining optimal inspection frequency is proposed in [50] and by using the irregular inspections in [51]. The latter includes a more flexible condition inspections time frame for analyzing its impact on management decisions and explicitly considering equipment aging using the Markov process. The proposed model combines random and deterioration failure modes with appropriate maintenance activities. It concludes, that using opportunistic maintenance strategy over a long time span with non-periodic inspections can have economical benefits compared to a regular time-based approach.

Mainly, the common option is to predict the potential time of equipment replacement and failure by analyzing its available condition data. For example, a stochastic analysis is used in [52] to evaluate the remaining lifetime of power transformers in accordance with statistical data. A methodology for evaluating the remaining lifetime and the HI of power transformers is also provided in [53]. Similarly, the main requirement is to have an adequate awareness of the equipment condition and its probabilistic change. The previously gathered statistics are also implemented in equipment health modeling for predictive asset management decisions in [54] and for obtaining the failure rates of power transformers in [26]. The same principle is implemented in [55], where the actual equipment condition is assumed to be known, making it possible to obtain the HI values for further usage in their maintenance and inspection scheduling.

Another important aspect is also the gathering of equipment condition data. For that purpose, the importance of using condition measurement solutions is highlighted in [56].

This makes it possible to obtain relatively frequent or real-time data on equipment condition, avoid underestimating substation reliability, and obtain more accurate RoF_i values. The optimization of asset management using measurement solutions as part of equipment condition monitoring is additionally analyzed in [30]. Overall, these methodologies conclude, that it is important to have sufficient statistical data for decision-making procedures. This is considered to be a key parameter for increasing asset management efficiency and decreasing capital related investments.

It is also necessary to take into account the actual condition of the equipment near or at the age of the suggested replacement. It is suggested, that the majority of substation equipment should be replaced after 40 years. Therefore, power system operators need to increase their $CAPEX$ to replace equipment reaching or exceeding the suggested age of use. The cost related to extensive equipment replacement is high, so alternative solutions are sought. Statistically, the PoF_i increases with the aging of the equipment. Nevertheless, there are a lot of examples of equipment that have been operating beyond their suggested lifetime in relatively good condition. If the objective is to increase asset management cost-efficiency, then that factor needs to be considered. As stated in [27], it is not realistic to replace large amounts of equipment in a short time period based on aging, due to cost, construction, and network operational constraints. Therefore, in order to realize effective investment and equalization of the replacement amount, evaluation of equipment condition and consequence is necessary.

A similar conclusion is made based on the optimization of circuit breaker management in [57], wherein the older equipment does not always require more attention due to differences in important parameter values, such as deterioration process, failure rates, operation frequency, and the location of the equipment in the power system. An option to justify the delay in equipment replacement is using the RoF_i values as indicators of the importance of the equipment in the power system. If the RoF_i is lower, the replacement can be postponed, and if the RoF_i is higher, the replacement should be done even sooner. In that regard, a methodology for determining the optimal replacement time of circuit breakers and its financial justification is provided in [58]. The preventive or delaying equipment replacement with consideration of their condition is also discussed in [59]. They concluded, that distributing equipment replacement over a longer time period decreases the maximum $CAPEX$ needed in the narrower time-frame. Furthermore, its impact on $OPEX$ can be minimized by using corresponding asset management decision-making processes.

Subsequently, it requires optimal distribution of each substation's equipment between specific management methods. In addition, calculating cost related parameters for different distribution scales is needed. Thus, when considering the cost parameters of asset management methods, the optimization function F of the risk-based asset management method from the $CoRBM$ perspective can be expressed by (6).

$$F(CoRBM(t)) = \min \sum_{i=1}^{n} (CoI_i, CoLC_i, CoCBM_i) \tag{6}$$

The main objective is to minimize condition inspection cost (CoI), load curtailment cost ($CoLC$) and overall condition-based management cost ($CoCBM$). The latter includes the cost of measurement solutions ($CoMS$) as a major cost component. Nevertheless, the minimization of the $CoMA_i$, which is another related parameter in management cost-efficiency optimization, can be more difficult to achieve. It is based on the condition degradation occurrence probability and its pace. Therefore, it requires obtaining adequate statistical data to represent the aging characteristics for individual pieces of equipment.

To optimize the cost of asset management, comparing currently used management methods to other management methods is also necessary. Commonly, the TBM is implemented with the majority of equipment types [16]. Therefore, the cost of the alternative management methods, mainly the CBM and the RBM, needs to be evaluated in accordance with the $CoTBM$. Foremost, if increasing the frequency of the condition inspections or using a higher number of measurement solutions, the cost of overall asset management could increase. Because of that, obtaining optimal threshold values between these methods is important.

Due to their differences, the CBM can have a higher overall cost than the TBM. The RBM is a combination of the TBM and the CBM, and therefore its cost is expected to be lower than the TBM. This is due to the objective of asset management optimization. Therefore, it is necessary to estimate the threshold value, where the $CoRBM$ is equal to the $CoTBM$. Based on that, it is possible to adjust the scale of the RBM and determine the amount of equipment included in the CBM and other methods. Each included equipment in the CBM increases the management cost and the extent of the RBM. If all equipment is added in the RBM, then it becomes the same as the CBM.

The principle structure of the optimization of the $CoRBM$ is provided in Fig. 6. Initially, the analyzed time period is chosen. Next, the costs of the selected asset management methods are estimated. Then, the order of the equipment included in cost optimization is determined according to their risk of failure. Lastly, equipment is distributed between management methods by using dedicated approaches. Based on these approaches, an optimal equipment distribution is obtained.

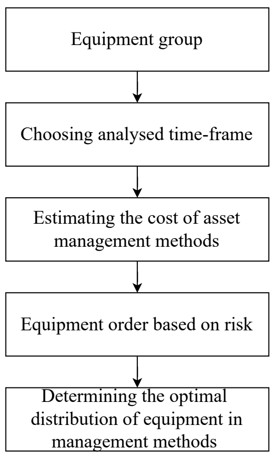

Figure 6: Principle overview of the stages in the risk-based asset management cost optimization

Nevertheless, relatively accurate data representing equipment condition is needed for that purpose. Thus, a part of the optimization process is also to gather necessary data. For that purpose, frequent inspections and measurement solutions are used in addition to statistical options. The data related to cost components can be divided according to their obtainment. The CoR_i is based on the equipment market value. Similarly, the $CoMS_i$ depends on their market value. The average CoI_i is determined by the contracts between the power system operator and the equipment inspection provider. It also depends on the level of inspections, which can be either superficial or relatively detailed. The expected $CoMA_i$ can be evaluated based on the statistical data for a specific condition degradation level. The $CoLC_i$ depends on the cost of undelivered energy for that load (demand or supply). The latter is commonly obtained based on contingency analysis results.

1.5 Risk of Failure Estimation and Uncertainty

The accuracy and, therefore, the uncertainty of the RoF_i depends on the accuracy of the risk components and the quality and availability of data. The cost-related components can be determined relatively accurately. The PoF_i, on the other hand, is based on the equipment condition and its change over time. An option is to obtain the PoF_i by using equipment inspections or measurement solutions. This means, that the PoF_i is directly related to the equipment condition. The latter is converted to PoF_i using the appropriate methodology. An example of that is described in [60], where a data-based equipment condition evaluation is implemented on the failure risk assessment of circuit breakers. The use of statistical data for obtaining circuit breakers' hazard functions is also discussed in [61]. A second option for obtaining the PoF_i values is using a Health Index (HI)-based approach. An overview of different HI obtainment methods is given in [62]. Mainly, the condition of equipment is evaluated on a preset scale. If a part of the equipment or its component is considered to be deteriorated, then a higher HI value is given. The overall HI usually represents the maximum HI of equipment components. Next, the HI is converted to the PoF_i, for example, by using a hazard function.

The PoF_i can also be estimated based on statistical data. This means using previously collected condition data to predict its values for current or future time-frames. The accuracy of the estimated PoF_i depends on the accuracy of the available data. In addition, it should be suitable for representing the analyzed equipment. As stated in [63], the statistical data can be enough to make adequate decisions. If estimating the PoF_i from statistical data, the value is commonly based on the equipment failure rate. The failure rate expresses the number of average failures in a specified time period. Therefore, it can be linked to the age of the equipment as well. According to [64], it can also be used to simulate the degradation of the equipment condition for an asset management decision analysis.

Thus, the extensive statistical data makes it possible to estimate or predict the change in equipment condition and PoF in upcoming time periods. For example, statistical data is used for modeling the deterioration of equipment condition in [65]. Its main objective is to evaluate the optimal proportion of limited funds to be spent on maintenance. In addition, the estimation of equipment failure rates based on the available statistics is described in [66,67] for the asset management decision framework. The accuracy and use of the statistical data depends foremost on the number of samples and their relation to the specific equipment. If the available samples are limited or even absent, data estimation needs to be implemented.

The quality of condition data also depends on the asset management method used. In the case of the CBM, a relatively accurate PoF_i can be obtained with high frequency. In the case of the TBM, the PoF_i is updated with a lower frequency. Therefore, the PoF_i estimation could also be implemented in addition to statistics. If using the run-to-failure method without condition inspections, a PoF_i estimation is needed. The latter still requires some initial data for preliminary analysis. An example of a procedure for determining the data quality in HI calculations is provided in [68]. They stated, that infrequent condition inspections and a lack of real-time measurement solutions decrease the accuracy of the data. Therefore, it is necessary to make adequate decisions in the presence of uncertainty. Furthermore, the impact of uncertainty in the equipment condition evaluation is analyzed in [69]. They conclude, that it can alter equipment order based on the RoF_i and the focus of asset management.

The accuracy of the PoF_i depends on the accuracy of the condition inspections and measurement solutions as well. It is assumed, that during periodic inspections, relatively precise measurement equipment is used. In addition, their accuracy should also be considered in the PoF_i. Thus, the accuracy of the PoF_i determines its uncertainty and, subsequently, the uncertainty of the RoF_i. Therefore, to obtain a relatively accurate RoF_i value, the accuracy of the PoF_i is important. If the uncertainty of the PoF_i is relatively high, then the actual RoF_i of equipment can be difficult to determine. For some equipment types, such as power transformers and circuit breakers, the CBM is used or there is sufficient statistical data. Therefore, the PoF_i can be calculated relatively accurately. With other equipment types, TBM is commonly used, and the statistical data can be limited or absent. As a result, the PoF_i is either updated during periodic inspections or is estimated and includes a higher uncertainty.

Commonly, though, the analysis of uncertainty in equipment condition and the RoF_i includes only specific equipment types. These are mainly power transformers and circuit breakers. For example, fuzzy processes are used to evaluate the power transformer risk in [29]. The stochastic nature of power transformer insulation degradation is included in the HI calculation in [70] and power transformer maintenance scheduling with consideration of its condition uncertainty is analyzed in [71]. Bayesian statistics and its approaches are implemented in [72] for obtaining the probabilistic HI of power transformers. The probabilistic HI values are used in [73] for assessing the condition monitoring of power transformers. In the case of circuit breakers, condition-dependent failure rates with an added uncertainty level are implemented in [74] for asset management cost optimization. For other substation equipment types, less methodologies or approaches are provided. Nevertheless, for maintaining proper functionality of substations and power systems, all equipment needs to be included for various analyses. This is also required for increasing the cost-efficiency of asset management.

According to another perspective, the uncertainty of failure probability is modeled by fuzzy processes in [75] to simulate the inaccuracy of the available data. Stochastic processes are also implemented in [76] to increase the real-life similarity of the equipment component aging. Commonly, an additional parameter is added to statistical data to indicate its uncertainty. In that case, the lack of sufficient data can be modeled making it possible to analyze its impact on management decision-making. Fuzzy processes are also used in [77] to simulate uncertainty in equipment condition and statistical failure rate. Its goal is to prevent equipment failures by implementing on-time maintenance tasks by avoiding further condition degradation. Another approach for equipment maintenance scheduling in the presence of uncertainty in failure rates is presented in [78]. It concludes, that uncertainty in data can have a significant impact on asset management costs. Nevertheless, for simulating data uncertainty, some extent of preliminary data is still needed.

Despite various approaches regarding failure risk estimation, their functionality is limited in the case of high uncertainty in the condition data of equipment. Therefore, obtaining the PoF_i and the RoF_i depends on multiple factors. Its principal overview is provided in Fig. 7. Initially, a specific equipment type or preset equipment group is selected. Next, equipment is divided based on awareness on their condition data. Mainly, the condition of the equipment in one group is known, and the condition of the equipment in second group is unknown. Data quality is assessed according to the samples in the first group. If it is relatively high, the PoF_i is calculated and assumed to have a lower uncertainty. The samples from the first group are also used to estimate the condition data for the second group. This also makes it possible to estimate their PoF_i values. In addition, the evaluation of availability, usability, and accuracy of statistical data related to the analyzed equipment type should be considered. It can strengthen the condition data estimation.

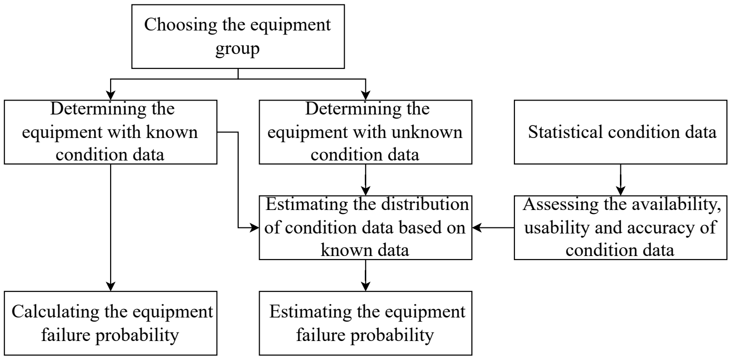

Figure 7: Principle overview of the failure probability obtainment in accordance to the available data of equipment condition

Thus, an option to bypass the impact of limited or absent data related to equipment condition is to use dedicated processes and methods for determining the importance of equipment and its RoF_i in the case of uncertainty. These solutions make it possible to improve the efficiency of asset management, gather more data about the actual condition of equipment, and update the PoF_i of equipment with a higher RoF_i more frequently. As an example, the process of HI prediction over a longer time period by improving the available condition data with a preset condition inspection frequency is provided in [79]. Foremost, it assists in improving awareness of equipment condition gradually. Still, similar approaches are also needed for other equipment types besides power transformers and circuit breakers.

1.6 Risk of Failure Reduction

An important objective of asset management is to maintain and increase the reliability of the power system. This requires focusing on equipment with higher RoF_i, which means determining their rank or importance in the power system. A simplified overview of equipment ranking for further use is given in [80]. In addition, the analysis of the equipment rank and its importance in asset management decision-making is provided in [81]. Risk calculation itself is used as an input in asset management decision-making. In accordance with the calculation results, optimal options to increase substations and power system reliability is determined. A significant part of that process is the failure risk reduction.

The RoF_i can be decreased based on multiple risk components. These components are the CoF_i, the $MTTR_i$, and the PoF_i. Firstly, the CoF_i can be reduced. This requires strengthening the power system by adding additional transmission lines or changing the topography of the substations. Foremost, load curtailment needs to be avoided or minimized to decrease the CoF_i Secondly, the replacement times ($MTTR_i$) of equipment can be reduced. This decreases the CoF_i due to the decrease in the load curtailment time. An option to reduce equipment replacement times is to arrange for spare equipment in the substation or in nearby substations. Another option is to optimize the replacement procedure. Thirdly, a decrease in the RoF_i can be achieved by decreasing equipment PoF_i.

This requires the use of predictive or preventive asset management methods, mainly the CBM or the RBM. It is assumed, that by increasing the inspection frequency or using measurement solutions, the PoF_i is reduced. It can be a more reasonable option from a cost perspective compared to changing the substation schematics or adding additional lines to the power system.

In the case of strengthening the power system, the impact of improving the substation configuration is discussed in [82, 83]. They concluded that adding more redundancy as alternative paths makes it possible to decrease the failure consequences. Therefore, it is necessary to determine paths that do not have redundancy. Similarly, in [84], potential improvements in the substation configuration to increase their reliability are proposed. The reliability analysis for multiple substations with a local grid is provided in [85–89]. They indicated, that the main difference between substations depends on the CoF_i values of individual failures of inner paths. Therefore, a failure risk calculation is required to determine the weakest links in the power system's substations. Next, it is possible to consider the potential options for decreasing the RoF. From that perspective, the optimization of the substation configurations in order to decrease the load curtailment after switching operations is presented in [90]. As a result, the topology of substations with higher impact on overall reliability is changed. Nevertheless, this analysis only includes circuit breakers or power transformers as the potentially failed pieces of equipment in the substations.

In terms of decreasing the CoF_i, the method to identify the specific combinations of equipment failures that would result in higher consequences is provided in [91]. The results are used in risk calculations based on the statistical data and the implementation of the CBM. Similarly, the combinations of simultaneous equipment failures and their impact on power system reliability are also analyzed in [92]. In addition, the CoF_i can be decreased by through power control of generation units as suggested in [93]. This makes it possible to reduce load curtailment as a result of the change in active and reactive power flow. From another angle, an evaluation of the impact of the load characteristic on the RoF_i values is provided in [94]. They stated, that by considering the average load levels, the actual failure risk is also lower. Therefore, it alters the RoF_i and changes the cost related parameters as well. In addition, the constraints in the maintenance team and their impact on the reliability of the power system are analyzed in [95]. This can be useful for reducing the equipment replacement or repair time and, therefore, the duration of load curtailment.

Regarding decreasing the PoF_i, it is foremost necessary to determine the equipment with higher importance. The methodology for reducing the substation risk and equipment failure probability is presented in [96], where the available resources are allocated to equipment with higher RoF_i based on the asset management decisions. From another perspective, an inspection pattern for evaluating equipment condition is proposed in [97], which considers the potentially different degradation characteristics of the equipment. The methodology for increasing the power system reliability by decreasing the PoF_i based on the real-time condition monitoring solutions is provided in [98]. Similarly, a condition-based asset management decision-making process is proposed in [99]. Overall, though, they all require data on equipment condition to determine the initial order of equipment for risk reduction.

Each of these options for decreasing the RoF_i have advantages and disadvantages. To determine the suitable options for an individual substation or power system, specific processes need to be followed that makes it possible to achieve higher cost-efficiency in failure risk reduction and asset management. The process itself contains multiple stages.

Firstly, the equipment failure risk is calculated. Next, the equipment order based on the risk is determined. After that, the potential options for decreasing the risk are evaluated. For example, this can be done by analyzing their risk reduction cost-efficiency. Finally, it is necessary to determine the extent of the risk reduction in accordance with the use of $CAPEX$ and the change in $OPEX$. These are based on the cost of asset management methods. The overall process of risk reduction is given in Fig. 8.

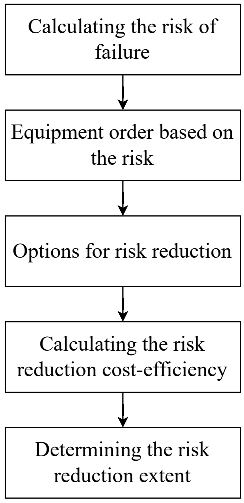

Figure 8: Principle overview of the main stages in the risk reduction process

The efficiency of failure risk reduction depends on the achievable decrease in failure risk and its cost. In order to increase the reliability of a substation cost-efficiently, the risk reduction process needs to be determined. In addition, it is necessary to specify the risk component that allows for the necessary decrease in risk. By calculating the cost of risk reduction and its cost-efficiency, it is possible to choose the potential solutions available for achieving the risk reduction in the actual power system substations. It can also indicate the efficiency of increasing the condition inspection frequency or using measurement solutions. Based on the process, the order of the equipment for which the measurement solutions are added or the inspection frequency are increased can be determined.

Commonly, the RoF_i reduction is analyzed from the perspective of more expensive equipment, such as power transformers and circuit breakers. For example, the process for determining the circuit breakers in the power system for condition monitoring is presented in [57]. Its optimization allows for a larger decrease in the RoF_i compared to more simplified approaches. A methodology is presented in [100] to obtain the amount of equipment needing additional management decisions in accordance with their ranking. Mainly, this equipment is included in the CBM as part of risk reduction. Nevertheless, the all primary equipment of substations should also be included in the process to obtain higher risk reduction efficiency for the whole substation.

In the case of risk uncertainty, the optimal solution for risk reduction can not be accurately determined. It is mainly caused by the uncertainty in the equipment condition data, which alters the PoF_i. Therefore, the PoF_i needs to be estimated and does not indicate the actual condition of the equipment. On the other hand, without the data estimations, the asset management decision process is even more stochastic. The options are to continue as usual and accept the risk of failure with a higher cost or to try to predict and prevent these failures. If cost-efficiency is an objective, then it is necessary to use the available data and methods to improve the overview and awareness of the equipment conditions and risks. The potential solutions for the RoF_i reduction within the scope of this thesis is described in more detail in Chapter 3.

1.7 Focus of Thesis

This thesis focuses on specific aspects considering the limitations of available methodologies, such as the requirement of sufficient data and providing partial overview of the reliability of substation, related to asset management decision-making processes and subsequent factors. These aspects are also depicted in Fig. 9.

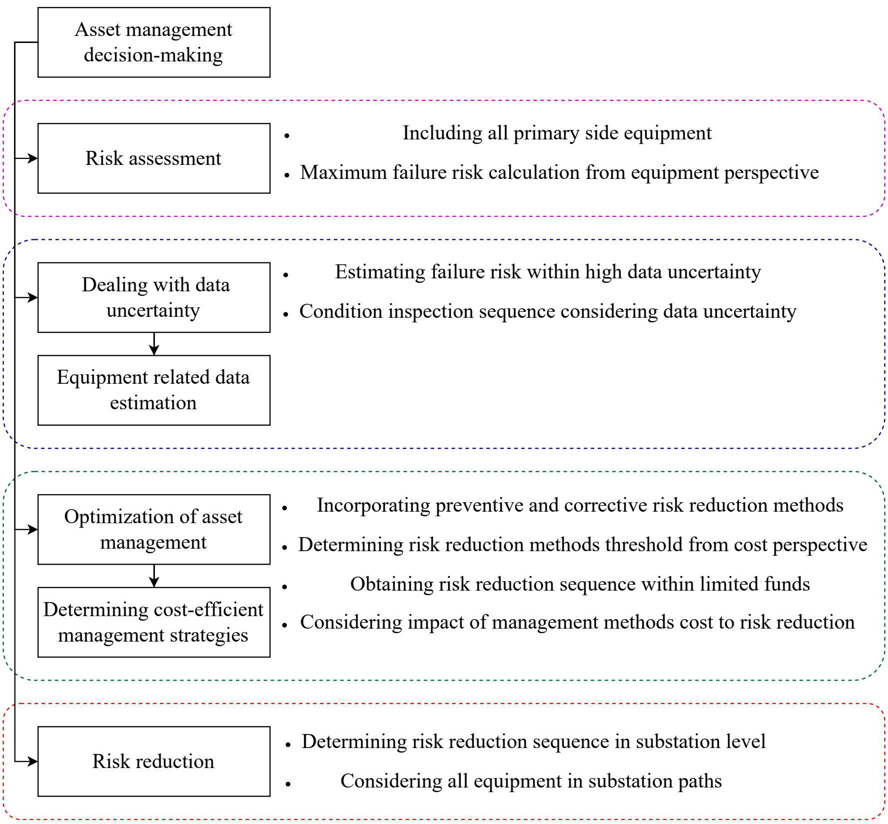

Figure 9: Aspects focused on asset management decision-making process considering with limitations in available methodologies

In the case of failure risk assessment, a maximum RoF_i calculation process of individual substation equipment is developed. Regarding uncertainty of equipment related data, RoF_i estimation method is proposed. It can also be used to determine the condition inspection procedure (sequence) of equipment in the case of data uncertainty. In terms of asset management optimization, preventive and corrective methods are used in order to obtain a RoF_i reduction process from a management costs perspective. The latter considers the available funds for implementing the RBM and the difference between cost components of management methods. Regarding the RoF_i reduction, a process for determining a risk reduction procedure (sequence) based on the extent of achievable decrease in failure risk and its cost is proposed. In addition, the RoF_i reduction process makes it possible to determine specific equipment and their types in substations with the most cost-efficient contribution to the decrease in risk of failure.

2 Calculation Process of Individual Equipment Risk

Improving asset management from a cost-efficiency and reliability perspective requires knowing the importance of equipment in the power system. Risk calculation methods are used for that purpose. Commonly, they only consider specific types of equipment, giving a partial perspective on substation equipment with higher risk. In accordance with the objective of this thesis, a risk calculation process including all equipment on the substation primary side is developed. This makes it possible to obtain the necessary input for other methods used in increasing asset management cost-efficiency. These methods are presented in Chapter 3.

This chapter is based on publication I and addresses **RQ1**. It provides an overview of the developed risk calculation process and describes its related aspects. The process itself is divided into multiple parts. Initially, the principles for the calculation of equipment risk are explained. This is followed by a description of determining load curtailment and linking substation equipment to the substation schematic and power system. Next, the overall structure of the risk calculation process is presented. The chapter ends with a case study.

2.1 Calculation of Equipment Risk

The main objective of the risk calculation process is to obtain the RoF_i for each individual piece of equipment on the substation's primary side. The risk value itself is used to determine the order of equipment indicating their importance or rank in the power system. Based on this, the asset management can be focused towards equipment whose failure could have higher or more significant consequences. Subsequently, it will assist in increasing the reliability of the power system and asset management cost- efficiency, as a main part of the RBM. In addition, the risk values are also used in the related processes for evaluating the potential options for risk reduction.

Commonly, risk of failure is calculated based on the disconnection of a single transmission line or connection (N-1 contingency) and a combination of double transmission lines or connections (N-2 contingencies). This can be inadequate in the case of substation equipment failures. In certain situations, the failure of equipment could cause the disconnection of more than two transmission lines or connections. This is usually related to substations that have configurations with lower redundancy. Therefore, the risk needs to be calculated from an equipment perspective. This means, that the N-1 contingency is a failure of equipment i and the N-2 contingencies are failure combinations of equipment i and j.

In addition, risk of failure is commonly calculated for specific equipment types. These are mainly power transformers, circuit breakers, and in some cases, cables. However, to obtain an overview of the risk of all the equipment in a substation, all of the values need to be calculated. This makes it possible to determine the overall, not partial, risk of the substations and power system. Subsequently, it is possible to more efficiently determine the pieces of equipment, that can cause higher failure consequences. Inclusion of all equipment in the risk calculation is also needed in order to analyze the potential risk reduction options and determine their cost-efficient distribution between different asset management methods.

Multiple inputs are needed in calculations of equipment risk. Mainly, they represent the cost of equipment replacement, the cost of load curtailment after failure, and the likelihood of failure. These inputs are indicated as:

- $CENS$ - cost of energy not supplied
- LC - load curtailment

- LF - load factor
- CoR - cost of equipment repair
- CoA - additional cost of equipment replacement or failure (related to substation location, environmental restrictions, maintenance team availability, and the reputation of the power system operator)
- $MTTR$ - mean time to repair equipment
- PoF - equipment probability of failure

Next, the inputs are combined in a risk calculation to determine its maximum value for each equipment. The maximum risk describes its highest value according to failure consequences and probability. The overall schematic for calculating the maximum risk is given in Fig. 10.

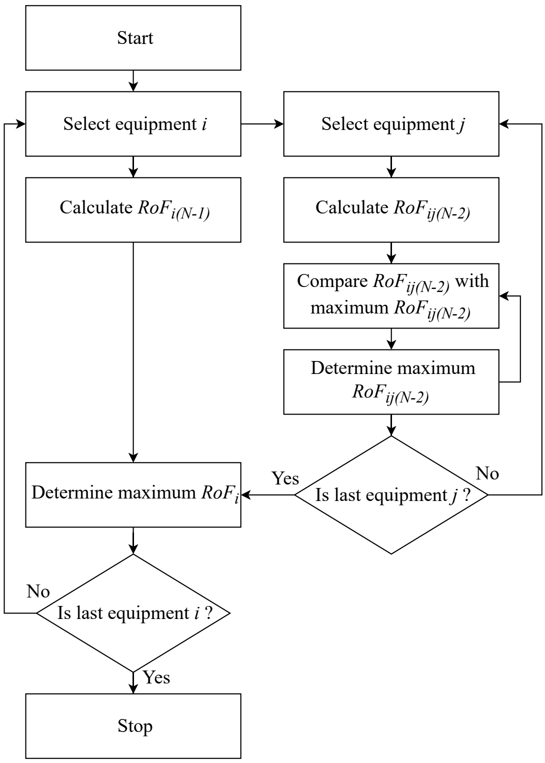

Figure 10: Principle of calculating the maximum risk of failure (RoF_i) of substation equipment

Initially, the risk of equipment i based on N-1 contingency ($RoF_{i(N-1)}$) and combination with equipment j in N-2 contingencies ($RoF_{ij(N-2)}$) is acquired by using (7) and (8). The $VOLL$, expressed by (12), is the value of lost load at time t, the CoR is the cost of repairing equipment i and j, the CoA is the additional cost of replacement of equipment i and j, the $CoLC$ is the cost of load curtailment after equipment i and j failures during the time period t, the $MTTR$ is the mean time to repair equipment i and j, and the PoF is the probability of failure of equipment i and j. In (12), the $CENS_i(t)$ is the cost of energy not supplied to load i at time t, the $LF_i(t)$ is a load factor for load i at time t and the $LC_i(t)$ is load i curtailment at time t.

$$RoF_{i(N-1)} = ((VOLL_i(t) \cdot MToR_i) + CoR_i + \\ + CoA_i) \cdot PoF_i = (CoLC_i + CoR_i + CoA_i) \cdot PoF_i \quad (7)$$

$$RoF_{ij(N-2)} = (CoLC_{ij} + CoR_i + CoA_i + CoR_j + \\ CoA_j) \cdot PoF_i \cdot PoF_j \quad (8)$$

$$CoLC_{ij} = \begin{cases} MTTR_i > MTTR_j, & use \text{ (10)} \\ MTTR_i = MTTR_j, & VOLL_{ij}(t) \cdot MTTR_i \\ MTTR_i < MTTR_j, & use \text{ (11)} \end{cases} \quad (9)$$

$$VOLL_{ij}(t) \cdot MTTR_j + VOLL_i(t) \cdot (MTTR_i - MTTR_j) \quad (10)$$

$$VOLL_{ij}(t) \cdot MTTR_i + VOLL_j(t) \cdot (MTTR_j - MTTR_i) \quad (11)$$

$$VOLL(t) = \sum_{i=1}^{n} (CENS_i(t) \cdot LC_i(t) \cdot LF_i(t)) \quad (12)$$

Due to calculating the risk from an equipment perspective, different RoF_i values are obtained for each equipment i - one based on N-1 contingencies and multiple based on N-2 contingencies. The number of values in N-2 contingencies depends on the total amount of equipment in the power system. The maximum $RoF_{ij(N-2)}$ is obtained based on all $RoF_{ij(N-2)}$ values in combinations between of equipment i and j in N-2 contingencies. As a result, the maximum RoF_i is determined by comparing the $RoF_{i(N-1)}$ in N-1 and the maximum $RoF_{ij(N-2)}$ in N-2 contingencies (13).

$$RoF_i = \max(RoF_{i(N-1)}, \max(RoF_{ij(N-2)})), \quad j = 1...n, \quad i \neq j \quad (13)$$

Therefore, the calculated value in the N-1 contingency makes it possible to evaluate equipment RoF_i in a individual failure case. The calculated value in the N-2 contingencies indicates the highest RoF_ij in a combined failure event of two different equipment. It represents the combination, which has the highest outcome in terms of consequences and probability. Values of other combinations have lower values and can be discarded. In certain areas, where the power system redundancy is limited or absent, the RoF_i can be higher than the maximum RoF_ij. If the redundancy of the local area is good, but not in a broader scope, then the maximum RoF_ij is most likely higher than the RoF_i. Especially, if the consequences of that combined failure event are significantly greater than its lower probability. This is related to the difference between the $CoLC_i$ and the $CoLC_ij$. On the other hand, it can also mean that the failure probability of these equipment in the combined event are also relatively high. Therefore, these equipment might be detected based on the RoF_i values. Thus, it is important to compare them and choose the maximum value. This is representing the equipment maximum risk of failure based on a single failure event and combined failure events, and thereon is used in asset management decision-making procedures.

The other RoF_ij values below the maximum can be analyzed in form of a distribution function. This makes it possible to evaluate, which RoF_ij values have the higher density. If the density is higher near the maximum $RoF_i j$, then more combined failure events could cause greater consequences. The density nearer the lower side indicates, that most of combined failure events do not cause significant damage and have lower probability of occurrence. Therefore, the maximum $RoF_i j$ is partially an outlier, which might require further attention in order to avoid that event from happening. However, a specific value is needed to represent equipment in the risk analysis. The density function makes the risk analysis more multi-dimensional and requires a dedicated parameter to convert it into comparable scale.

2.2 Obtainment of Load Curtailment

The failure consequences in risk depends on the amount of load curtailment (LC) after the equipment failure, its cost and the CoR. In the case of N-2 contingencies, the replacement cost of two pieces of equipment is included. The LC is usually considered to be smaller in N-1 contingencies and bigger in N-2 contingencies. This is due to the potentially higher number of disconnected connections after equipment failures in N-2 contingencies. Nevertheless, the LC in both cases need to be determined in risk calculations. Therefore, similarly to the RoF_i, one LC value in the N-1 contingency, and multiple LC values in N-2 contingencies, are obtained for each equipment. These values are further used in the calculation of the maximum RoF_i.

The LC itself is determined based on the necessary decrease in load (demand and supply) after equipment failure to maintain the functionality of the power system within allowed limits. These limits are the current (I) in connections (transmission lines and power transformers), and the voltage (U) at substation busbars. After equipment failure, the current in alternative paths and nearby connections could surpass the maximum allowed limit. Similarly, the voltage at the substation with the equipment failure or nearby substations could decrease below the minimum allowed limit. To restore the normal operation of a power system, the current (overload) needs to be decreased and the voltage needed to be increased. An option is to reduce the load, usually in the power system area near the failures. The load is decreased until the current and voltage values across the power system are between allowed limits, indicated by (14) and (15).

$$I_{connection} < I_{max} \tag{14}$$

$$U_{min} < U_{substation} < U_{max} \tag{15}$$

Overall, load curtailment needs to be avoided due to its higher cost. A potential solution is to use additional options for decreasing the overload and increasing the voltage. These are generating unit control - for decreasing or increasing in active or reactive power; adjustment of power transformers tap-changers - for increase in voltage; and implementation of inductive or capacitive elements - for increase in voltage. By changing the active and reactive power, it is possible to adjust the current and voltage. As a result, these options can decrease the LC or avoid it entirely. Nevertheless, they need to be available in the case of equipment failures. There might be areas in the power system without many of these options. The tap-changers of power transformers are still relatively common in substations, but their impact on decreasing the overload or increasing the voltage depends on the seriousness of contingency. In addition, the generating units control, and using inductive and capacitive elements, has its specific cost. Also, due to the rise in the renewable energy-based power plants, their active and reactive power control might be unavailable at the time of equipment failure. Therefore, the LC and its potential decrease after equipment failures through the available options depends on multiple factors. Based on the risk value, it is also possible to implement the additional solutions to decrease the LC.

The consequences of failures are commonly evaluated using specific software developed for power system analysis. Foremost, it makes it possible to obtain the current and voltage values throughout the power system after the simulated disconnections of user-defined connections. Some more capable tools also provide an option to calculate LC values. These can be obtained in cases of using or not using the additional options for decreasing the LC after failures.

To calculate the LC for selected contingencies, it is necessary to follow the preset sequence (formula) given in Fig. 11. Initially, it is necessary to load the power system data. For that, the power system is modeled in PSS/E based on buses, connections between them, and additional elements connected to buses, such as loads, generation units, and reactive shunts. Next, the current, voltage, and other parameters monitored are specified. Then, description of the analyzed contingencies are added. Also, the inclusion of generation units control, power transformer tap-changers and other reactive control elements, can be chosen as part of the corrective options. Thereon, contingency analysis is run and the LC values are calculated. Still, the LC values are based on the disconnection of power system connections, and therefore, linked to the connections. To link them to substation equipment, additional solutions need to be used.

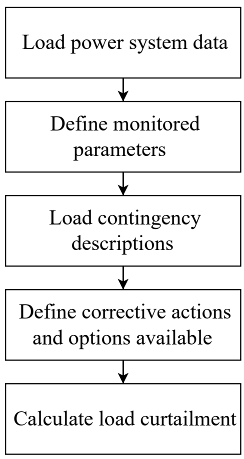

Figure 11: Overall sequence of calculating the load curtailment values

The structure of the contingency descriptions depends on the tool chosen for power system analysis. It mainly defines, which connections are disconnected and its order (sequence). Each contingency and combination of contingencies (disconnection of multiple connections at the same time) is described separately. In the case of more extensive contingency analysis and bigger power systems, the contingency description becomes relatively long. In that case, it can be generated based on additionally developed code.

In contingency description generation, a dedicated string structure is used. This includes the indices of disconnected connections (substations bays) as $Cnct$. The connections indices are added after the specific indexes a, b, d, e and f. If more than five connections are disconnected, then additional indices are added at the end of the string in (16). The index g indicates the combinations of disconnected connection types, which can include branches (including two-winding power transformers), three-winding transformers, loads, generation units, and other elements. In accordance with predefined connection types and combinations between them, the individual contingencies and contingency combinations are indicated by a dedicated index denoted as $CntgCbn$. For example, the $CntgCbn$ can describe a disconnection of two branches, branch and load, branch and generation unit, load and generation unit, or three branches. Based on the $CntgCbn$ and the $Cnct$, the contingency analysis results are linked to substation connections and, subsequently, to individual equipment. The index h is used for indicating the number of the contingency or its combination, denoted as $CntgNbr$.

$$a(Cnct1)b(Cnct2)d(Cnct3)e(Cnct4)f(Cnct5)g(CntgCbn)h(CntgNbr) \tag{16}$$

The pseudo-code of contingency description generation is provided in Algorithm 1. Initially, the power system data with connection and elements indices are read. This is used to generate a virtual structure of the power system. Next, the various combinations between the types of disconnected connections are predefined. Based on these, the contingency descriptions are generated in an iterative process. In each iteration, the indices of one disconnected connection is changed and the contingency description is saved as a string format in the corresponding file. There, the indices that make it possible to determine the disconnected connection and a combination of their types are also included. At the end of an iteration, the generated contingency description is added after previous ones. The iterative process stops, if all combinations between the considered connections are processed. Thereon, the process is repeated for another predefined combination. After generating the contingency descriptions for all predefined combinations, they are used in PSS/E to calculate the LC values.

Algorithm 1: Pseudocode of generating contingency descriptions

```
for Length of contingency combinations do
    Read power system data
    Generate virtual structure of power system
    Predefined combination of disconnected connections and their types
    for Length of contingency combinations based on predefined parameters do
        for Length of connections indices do
            Read connections indices
            Add connections indices after dedicated indices in contingency
              description string
            Add a dedicated index describing combination between connections
              types
            Save contingency descriptions
```

2.3 Equipment Link to Substation Schematic and Power System

Part of the dedicated failure risk calculation process is processing the extracted LC values. Its main objective is to load the LC values and link them with individual substation equipment. Firstly, this requires determining the location of the equipment in the substation's electrical schematic. Based on that, each equipment in the substation is added by

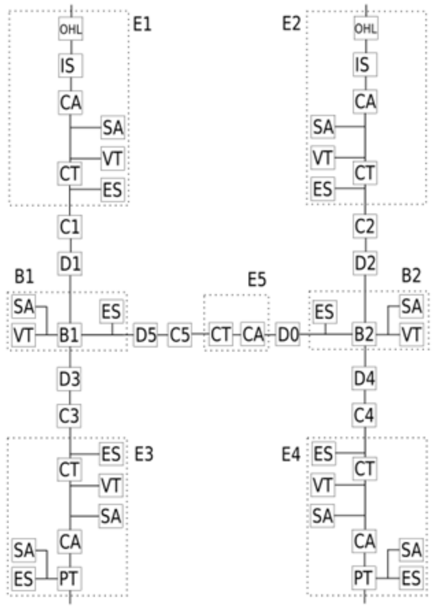

Figure 12: Schematic of a substation with single-breaker single-disconnector configuration (type 1) [101]

a specific index. Secondly, it is necessary to link the equipment failure to the disconnection of power system connections. Thanks to the equipment indexes, individual pieces of equipment can be linked to substations and their connections. This makes it possible to analyze the consequences of equipment failures and use these in the failure risk calculation process.

Therefore, the location of equipment in a substation is determined based on its index. The equipment indexes also depend on the substation schematics. In the risk calculation process, three different substation configurations common in power systems, are considered. These are type 1 - the single-breaker single-disconnector configuration in Fig. 12, type 2 - the double-bus single-breaker configuration in Fig. 13, and type 3 - the double-bus double-breaker configuration in Fig. 14. In substation schematics, indices E1…E4 are substation bays and E5 is the connection between substation section 1 (indicated by B1) and section 2 (indicated by B2). Other indices are C (CB) – circuit breaker, D (DC) – disconnector, VT – voltage transformer, CT – current transformer, CA – cable, ES – earthing switch, SA – surge arrester, PT – power transformer, IS – insulator chain. In Fig. 13 and Fig. 14, E1...E4 include the same equipment as in Fig. 12.

The impact of equipment failure to substation connections can be determined by (17). In that, the CS_i is the state of substation connection E1...E5. Its value 1 indicates a connected state and 0 a disconnected state. The Cn_i is the i-th connection of the substation, the Se_i is the switching units connected to the i-th connection or to the busbar connected to the i-th connection, the Bb_i is the busbar connected to i-th connection, the Sie_i are the circuit breakers and instrument transformers, whose failures or defects impact the circuit breakers of the i-th connection.

$$CS_i = \sum_{i=1}^{n} Cn_i \cdot Se_i \cdot Bb_i \cdot Sie_i \tag{17}$$

Multiple connections can also be disconnected after equipment failure. This depends on the location and functionality of the equipment, although it is more likely in the case of multiple equipment failures occurring in the same time period. Another factor in that is the substation schematic. In the case of a more reliable schematic, the equipment failure can have less impact to the connections. The reliability of substation schematic type 1 is lower than others, and type 3 is the highest.

The main logic of linking the substation equipment indexes to the power system is given in Fig. 15. Initially, the buses' numbers and their related substation configurations are extracted from the power system data. In each substation, a specific number of nodes exist based on the connections with the power system and its type. Therefore, each power system's connection and element is connected to a dedicated substation node with an individual number. These nodes can also be described as substation bays and busbar sections. In parallel, similar substation schematics are chosen in Python. It is assumed in the risk calculation logic, that the equipment is connected to fictive nodes corresponding to the same nodes in the power system data. This allows the creation of a virtual link between substation equipment and the power system. Its principle is given in Fig. 16, where E1...E5 are connections (substation bays) in the substation schematic and numbers 1...6 are substation nodes modeled in PSS/E. Based on that, the equipment indexes, and subsequently, their locations in the substations are acquired, and used in the risk calculation process.

A similar principle applies in the case of having more connections (bays) in the substations. Because of that, additional substation nodes are used in PSS/E. In a virtual substation schematic in Python, corresponding connections are also added by the same approach as implemented in E1...E4 and its related circuit breakers (C) and disconnectors (D). This subsequently alters the LC values and could decrease the equipment risk and increase the reliability of the substation. Fig. 17 provides an example of substation schematic type 1 with additional connections E6, E7, and related elements. Fig. 18 is a schematic of a virtual link between substation nodes 1...8 used in PSS/E and connections E1...E7 with sections B1 and B2.

It is also assumed in the risk calculation process, that different substation schematics (types) can be used. This makes it possible to assess the change in substation reliability and equipment risk based on the change in the individual substation schematic. Based on that, it is possible to determine the optimal risk reduction option and increase its cost-

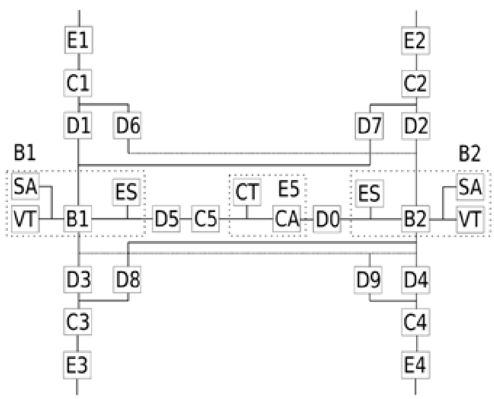

Figure 13: Schematic of a substation with double-bus single-breaker configuration (type 2) [101]

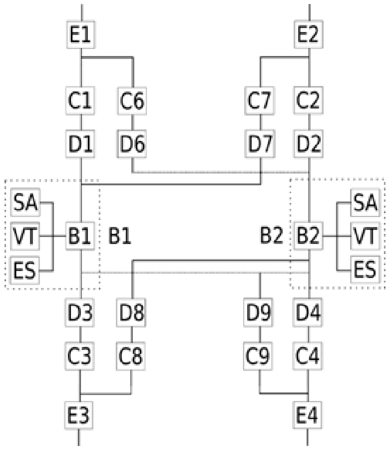

Figure 14: Schematic of a substation with double-bus double-breaker configuration (type 3) [101]

efficiency. In the risk calculation process, the substation types as indexes 1...3 (corresponding to Fig. 12, Fig. 13, and Fig. 14) are in a dedicated vector. Their values are used in linking the LC values to substation equipment. Due to the change in substation schematics, the LC for specific equipment changes as well. These are related to the substation section busbars B1 and B2, and connection E5. The amount and the risk of circuit breakers (C) and disconnectors (D) depends also on the schematic. Therefore, to have the possibility to implement different types of substation configurations, the contingency analysis results need to include the necessary data. This is necessary to consider when compiling the contingency descriptions.

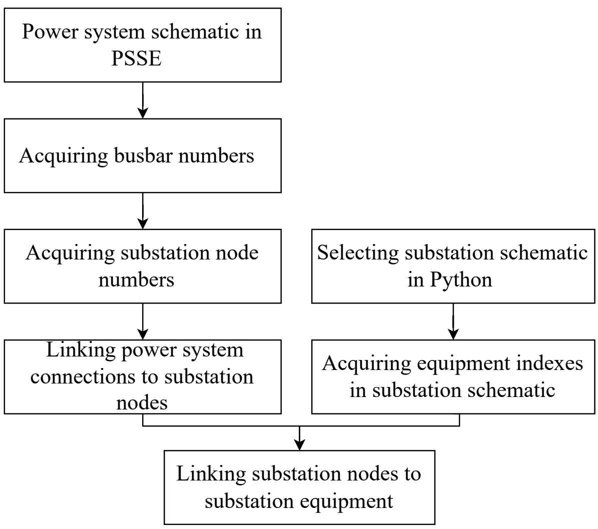

Figure 15: Principal logic to link power system data and substation configurations to individual substation equipment

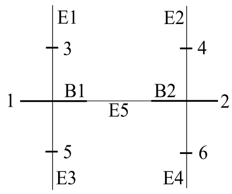

Figure 16: Principal of using substation node numbers, 1…6 in this case, to virtually link power system connections E1…E5 to substation sections 1 and 2 [101]

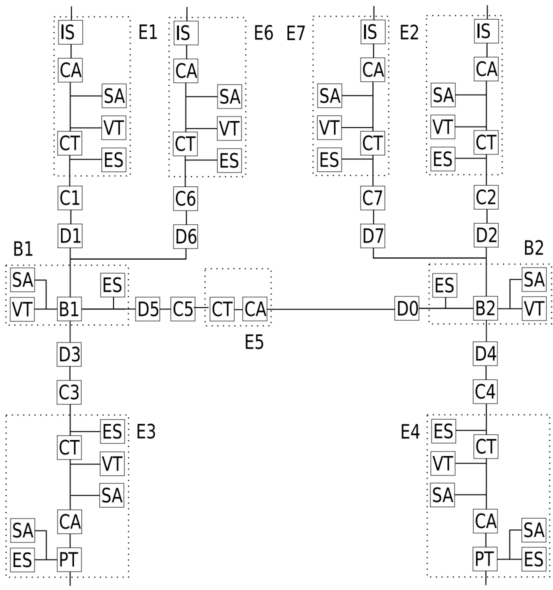

Figure 17: Substation type 1 schematic in case of additional connections E6 and E7

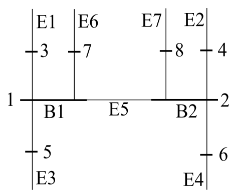

Figure 18: Principle of using substation node numbers, 1…8 in this case, to virtually link power system connections E1…E7 to substation sections 1 and 2

An additional logic process is added to the risk calculation process for determining the appropriate LC values used with the equipment based on the substation schematic. It consists of separate blocks of conditions in a linear sequence for contingencies in N-1 and N-2. Initially, the location of equipment in the substation schematic is analyzed. The equipment location is separated into three groups. For each group, different LC values apply, which are used according to equipment location. Firstly, the equipment can be placed in series in connections E1...E4. In this case, the LC values remain the same despite the change in the schematic. Secondly, it can be directly connected to substation section busbars B1 or B2. Thirdly, it can be in connection E5 between sections B1 and B2. For the last two groups, the substation schematic has an impact on the LC values. The inclusion of equipment in these groups is determined based on its index. Different equipment indices are listed in each group. Which group each piece of equipment is included in is determined according to a sequence of conditions. Subsequently, the corresponding LC is chosen and used in risk calculations. The corresponding logic process is presented in Fig. 19.

In N-1 contingencies, only the location of equipment i is analyzed. In N-2 contingen-

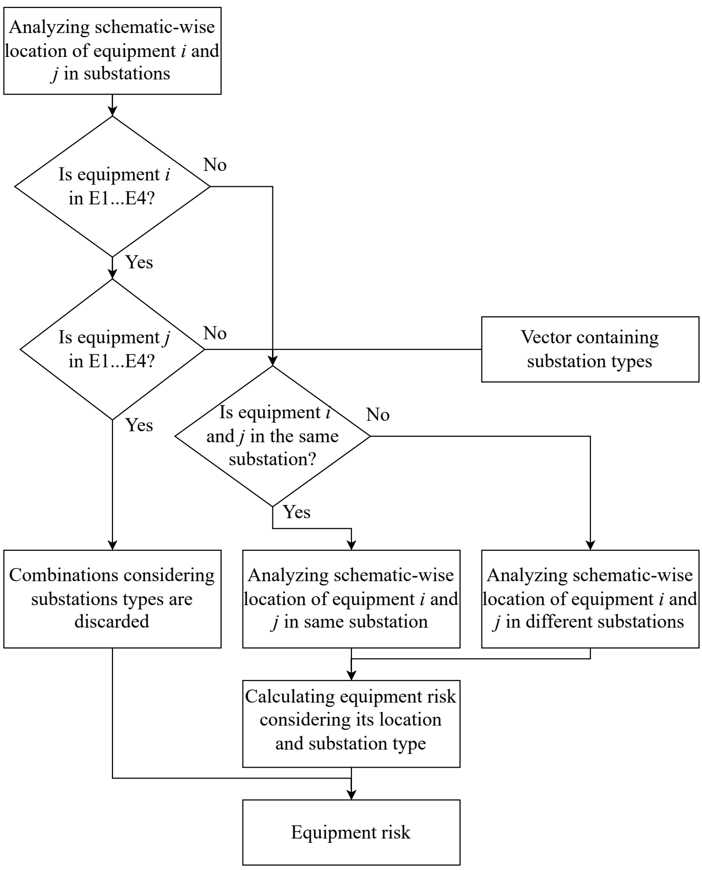

Figure 19: Process of linking the load curtailment to equipment location in different substation schematics [101]

cies, the location of equipment j is also needed. Therefore, in combined failures of equipment, initially the inclusion of equipment i in E1...E4 is checked. Next, the same condition is checked for equipment j. If both are true, then this logic part of the risk calculation process is bypassed. Due to the locations of equipment i and j in a series connection, the LC value is the same in all the analyzed substation types. If one of the conditions is not true, then the substation indexes are checked. Next, it is determined, whether the equipment i and j are in the same substation. Similarly to the equipment location in the schematic, the LC values can be different, if these pieces of equipment are in the same or in different substations. In accordance with the condition results, appropriate substation indices and the corresponding LC values are used. At the end of the logic process and sequence of conditions, the RoF_i in N-2 contingencies is calculated.

In this risk calculation, it is assumed that the buses in PSS/E also indicate substations. It is possible to combine different buses to one substation, if needed, though this is mainly related with the result analysis, and does not affect the main risk calculation logic. The approaches used in further implementation of the risk calculation process depends foremost on the power system analyzed, the risk calculation objectives, and the implementation of equipment risk. Therefore, the developed process can be modified based on the needs and the data required. For example, the extracted data can also indicate the changed active and reactive power of generation units in the case of corrective Multi-ACCC analysis. In addition, it may be reasonable to account for data related to power flow conversion and the calculation errors. This can assist in indicating the specific contingencies with potentially inaccurate LC values for a more detailed analysis.

2.4 Structure of Risk Calculation Process

For linking the parameters representing equipment failure consequences and their probabilities to individual equipment, a hybrid risk calculation process is developed. Its inputs are the power system data and contingency analysis results from PSS/E, and cost and probability related values of the equipment. The input data are combined in a dedicated logic process in Python for calculating the maximum risk of equipment. The overall structure of the hybrid risk calculation process is given in Fig. 20. A schematic of risk calculation logic from another perspective is presented in Fig. 21. The developed process structure allows for separate contingency analysis in PSS/E and risk calculations in Python.

The main input of the risk calculations is the power system, which is modeled in the PSS/E software. This makes it possible to acquire the power system data and the LC values in contingencies. The power system data describes its structure and connections between its elements. It includes all the buses, branches (connection lines and power transformers), loads, generation units, and other elements. In addition, the substation configuration with numbered nodes are added as well. Nevertheless, a dedicated logic process is needed to link these elements with each other to form a virtual power system outside of PSS/E for further use. This is necessary, when combining individual pieces of equipment to the LC values and calculating their risk. In this case, the logic process for a power system data analysis and risk calculation process is developed in Python.

For calculating the LC values representing the consequences of equipment failures, a ACCC (AC contingency analysis) and Multi-ACCC analysis is run in PSS/E. In the ACCC analysis, the overload in connections and power transformers, and the voltage violations at the busbars are indicated. The LC values, though, are only obtained in the case of full disconnection of load. This means, that the LC values are calculated for specific contingencies, and are not related to overload and voltage violations. To obtain the potential LC values for each individual contingency and their combinations, the Multi-ACCC analy-

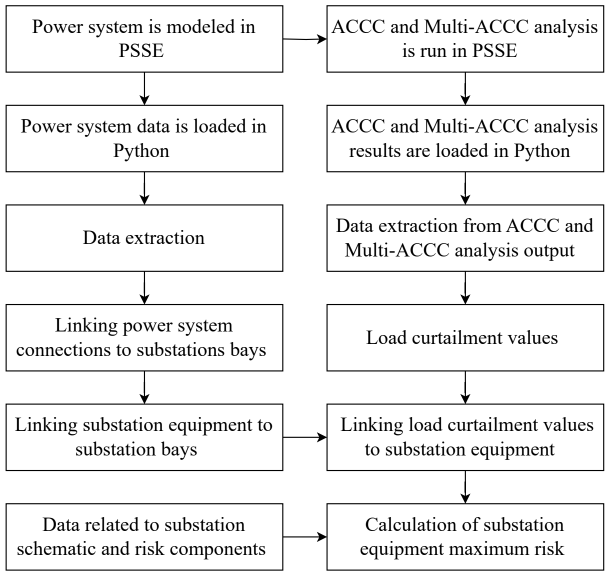

Figure 20: Principal concept of the risk calculation of substation equipment

sis is run. Compared to the ACCC analysis, it makes it possible to use corrective measures. These are needed to curtail the load in order to eliminate overload and voltage violations. The corrective measures are related to active and reactive power control, and can include generation units, shunts and loads. Therefore, the Multi-ACCC analysis calculates the potential LC values for all other contingencies besides the ones mentioned with ACCC analysis.

Initially, the ACCC and Multi-ACCC analysis results are loaded in the risk calculation logic process as .acc files. The LC data from these files are extracted in an iterative loop. In each iteration, the LC values for a specific N-1 contingency or N-2 contingencies are obtained. These values are inserted into dedicated matrices in accordance with the contingency description. The correct matrix chosen for each LC depends on the disconnected connections and the related data in contingency descriptions. The indices of rows and columns in these matrices indicate either the substations (buses) or power system connections. This makes it possible to find the LC values for further use based on the equipment index, which indicates its location in substation schematic, and substation number. The pseudo-code of that process is provided in Algorithm 2.

Based on the substation schematic, the number of connections disconnected after equipment failure can be different. It is common in the case of substation schematics with a lower reliability. This is mainly caused by the failure of the overall substation section busbar. In order to use 2-dimensional matrices to represent the LC values after multiple disconnections, these connections need to be combined into a single index. Subsequently, this makes it possible for the row and column indexes of the matrices to indicate the disconnection of more than one connection. For different substation schematics, additional sets of matrices with corresponding LC values are added. In accordance with the $CntgCbn$ value, the risk calculation logic process can determine the combinations of connections in the matrices. These are used further to link the LC to related risk components of equipment. In accordance with the vector indicating the substation type in the risk calculation logic process, appropriate matrices with LC values are chosen.

In order to link the LC values to individual equipment, the power system data are used. This is loaded into the risk calculation logic process as a .raw file. Next, the data is extracted by API commands and the virtual power system structure in Python is generated in the form of various matrices. These contain the number of buses, branches, loads, generation units, and other elements. Another matrices indicate the links between these elements. This requires using part of the power system data including the substation configurations modeled in PSS/E. Mainly, it describes the connections between branches, loads and other elements to buses and substation nodes. This makes it possible to link the power system connections to substation bays. The virtual substation configuration is generated based on the data in the matrices. The pseudo-code of that process is provided in Algorithm 3. Subsequently, it is used to link individual equipment to substation bays and busbar of its sections.

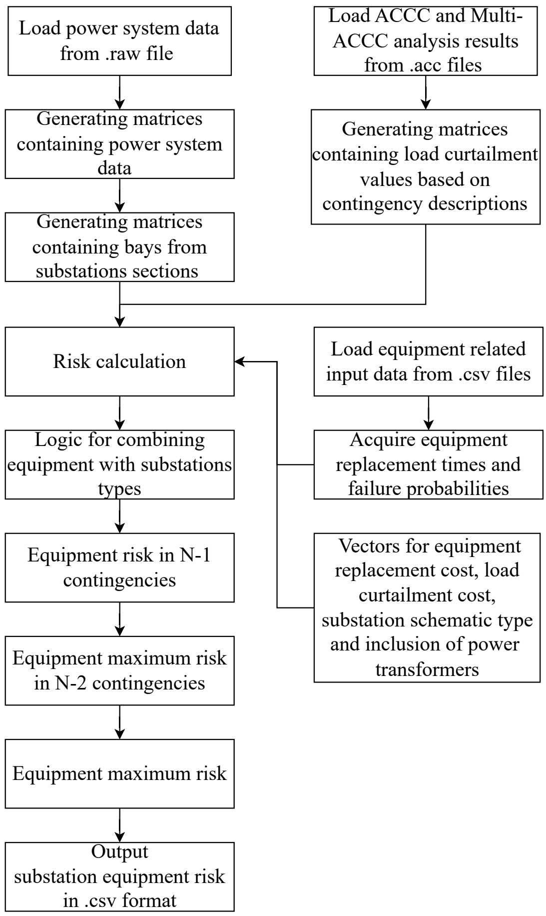

Figure 21: Main logic of the hybrid risk calculation process [101]

Algorithm 2: Pseudocode of linking LC to specific vectors or matrices

```
for Contingencies descriptions i = 1...n do
    Read contingency data of ACCC analysis
    Read contingency data of Multi-ACCC analysis
    Extract LC_i values
    Extract the indexes of disconnected connections or buses
    Extract the CntgCbn_i value
    Generate vectors and matrices for LC values
    if CntgCbn_i is equal to CntgCbn of vectors or matrices then
        for Length of vectors or matrices do
            Add LC values to vectors or matrices in accordance to connections or
            buses indices
```

Algorithm 3: Pseudocode of generating virtual structure of power system

```
for API commands of power system elements i = 1...n do
    Read elements data
    Extract elements indices
    Generate matrices for elements indices
    Generate matrices for links between elements
    for Length of elements indices do
        Link elements indices to buses
    for Length of substation node indices do
        Link substation node indices to buses
        Link substation node indices to elements indices
    Add extracted indices to vectors and matrices
    if Elements are connected to nodes 3, 5, 7, 9, 11 then
        Set connected substation section number to 1
    if Elements are connected to nodes 4, 6, 8, 10, 12 then
        Set connected substation section number to 2
```

Next, it is necessary to add the LC values, related cost parameters, and the PoF_i values to individual equipment for risk calculations. This is done in a dedicated part of the logic process. In that, multiple parameters are combined for the RoF_i calculations. The data about the LC values are obtained from matrices consisting of contingency analysis results. The equipment indices itself are specified in a dedicated matrix for each substation. The $MTTR_i$ and the PoF_i values are loaded as .csv files and then extracted. In addition, the vectors with the CoR_i, the $VoLL_i$, substation schematic type, and inclusion of power transformers in substation bays, are inserted into risk calculations. From another input, the matrices consisting of a virtual power system structure are also added.

Based on the matrices with buses, connection numbers, substations and their nodes, and links between them, the main matrices for risk calculation results are created. The initial column in these indicates the substation (bus) number and the second column indicates the substation bay or section busbar. If the substation bay is connected to the power system connection (transmission line or power transformer), then the connection number is used as a bay index. In the case of equipment related to substation busbar of sections, the bay index is 0. For indicating the connected loads, index value -1, and for the connected generation units, index value -2, is used. In accordance with bay indices, the corresponding LC values are added for each equipment in the risk calculation process.

The columns following the indices of substations and its bays are intended for the RoF_i values. In each column, the calculation results for specific equipment is added. The equipment indices based on the columns are: C(B1), C(B2), VT, CT, CA, ES, SA, PT, IS, ES(PT), SA(PT), D(B1), VT(B1), ES(B1), SA(B1), D(B1E5), D(B2), VT(B2), ES(B2), SA(B2), D(B2E5), C(E5), CT(E5), CA(E5), ES(E5). B1 and B2 indicate the sections busbars, where the equipment is connected. The index E5 is added, if the equipment is related to the connection E5 between sections busbars. Compared to the schematics in Fig. 12, Fig. 13, Fig. 14 and Fig. 23, the actual connections of the power system to E1...E7 are known and expressed by indices in initial columns. The same principle is also used in converting the C1...C9 and D0...D9 to C(B1), C(B2), C(E5), D(B1), D(B2), D(B1E5) and D(B2E5). Subsequently, this makes it possible to link individual pieces of equipment to the LC values. If the specific equipment is excluded from the substation bay or section busbar, then value 0 is added into the matrices.

In order to determine the LC for N-1 and N-2 contingencies, separate matrices for risk calculation results are used. Their structure is the same, besides the different LC values inserted. In an iterative process of risk calculation, they are combined with the $MTTR_i$ and the PoF_i values. The matrices with the $MTTR_i$ and the PoF_i also follow the main structure of risk calculation results matrices. Therefore, the appropriate values are added to the LC based on indices of substations and their bays or busbars.

Initially, the RoF_i in N-1 contingencies is calculated. This is based on the double iteration loops. In the outer loop, the indices of the substation, and its bay or section busbar are obtained row-wise. In accordance to these, the corresponding LC value is inserted into the calculation process. In the inner loop, the equipment indices are obtained column-wise. These indices are used to insert the corresponding $MTTR_i$ and PoF_i values in the calculation process. The $VoLL_i$ is also added, and as a result, the RoF_i in N-1 is determined. The pseudo-code of that process is provided in Algorithm 4.

Algorithm 4: Pseudocode of calculating RoF_i in N-1 contingencies

```
for Length of substation bays and sections busbars indices do
    Read substation index for equipment i
    Read substation bay or section busbar index for equipment i
    for Length of equipment indices do
        Read equipment i index
        Read LC value based on indices of substation and its bay or section
          busbar
        Read MToR and PoF value for equipment i
        Read VoLL value
        Read CoR value for equipment i
        Calculate RoF_i(N-1)
```

Next, the maximum RoF_i in N-2 contingencies is calculated. The overall process of obtaining the corresponding values of risk components is similar to the process implemented with the N-1 contingencies. Still, since the combined failures of equipment i and j need to be considered, four iterative loops are used: two for equipment i related indices and two for equipment j related indices. The risk is calculated for the perspective of equipment i. Therefore, for each failure of equipment i, the failures of other equipment, indicated as j, are looped. In the outer loop, the indices of the substation, and its bay or section busbar for equipment i is determined row-wise. In the loop inward, these indices are determined row-wise for equipment j. The next loop inward is for obtaining the $MTTR$ and the PoF values for equipment i, and the inner loop is for obtaining the $MTTR$ and the PoF values for equipment j. Because equipment j is virtually equipment i, and is referred to as equipment j to describe the combined failure event between two pieces of equipment i, the $MTTR_i$ and the PoF_i values are used in both cases. A similar approach is implemented with the $VoLL_i$ values.

In N-2 contingencies, the RoF_i expresses the maximum $RoF_{ij(N-2)}$. Due to the multiple combinations of combined failure events between equipment i and j, the $RoF_{ij(N-2)}$ is calculated in each iteration. To use a single risk value for individual equipment, the maximum $RoF_{ij(N-2)}$ based on all iterations is determined. For that, the maximum $RoF_{ij(N-2)}$ in each iteration is compared to its previous value. If the $RoF_{ij(N-2)}$ in a current iteration is higher than the maximum $RoF_{ij(N-2)}$ based on a previous iteration, then it is updated and set as maximum $RoF_{ij(N-2)}$. If it is lower, then the previously set maximum $RoF_{ij(N-2)}$ remains unchanged and used in the next iteration. The initial maximum $RoF_{ij(N-2)}$ is set to 0. As a result of the iterative process, the RoF_i in N-2 contingencies is determined. The pseudo-code of that process is provided in Algorithm 5.

Algorithm 5: Pseudocode of calculating RoF_i in N-2 contingencies

```
for Length of substation bays and sections busbars indices do
    Read substation index for equipment i
    Read substation bay or section busbar index for equipment i
    Set maximum PoF_ij(N-2) as 0
    for Length of substation bays and sections busbars indices do
        Read substation index for equipment j
        Read substation bay or section busbar index for equipment j
        for Length of equipment indices do
            Read equipment i index
            for Length of equipment indices do
                Read equipment j index
                Read LC value based on indices of substations and its bays or
                  sections busbars
                Read MTTR and PoF values for equipment i and j
                Read VoLL value
                Read CoR values for equipment i and j
                Calculate RoF_ij(N-2)
                Compare RoF_ij(N-2) to maximum RoF_ij(N-2)
                if RoF_ij(N-2) > maximum RoF_ij(N-2) then
                    Set RoF_ij(N-2) as maximum RoF_ij(N-2)
    Obtain maximum RoF_ij(N-2)
```

The calculation of the $RoF_{i(N-1)}$ and the maximum $RoF_{ij(N-2)}$ is included in a larger logic process. Its pseudo-code is provided in Algorithm 6. It is used to select the correct LC values from matrices in accordance with substation types and connection types of substation bays. Based on the indices of substation types, the LC values of equipment failure in the N-1 contingency and equipment failures in N-2 contingencies are taken from the corresponding matrices. The indices of connection types of substation bays are also used for determining the correct LC value. Due to the commands implemented in contingency descriptions in PSS/E, the connections are indicated as branches (including two-winding power transformers), three-winding transformers, loads, generation units, and other elements. Therefore, the LC values are added into different matrices according to connection type. Subsequently, these indices are used in the risk calculation logic process besides substation types.

Algorithm 6: Pseudocode of calculating the maximum RoF_i

```
for Length of substations equipment indices do
    Read risk components data
    Function Determine substation types
        Read substations types based on substation index
        Read LC values of equipment according to substations types and
          equipment locations in substations schematic
    Function Determine connections types of substations bays
        Read connection type of substations bays
        Select corresponding matrix with LC value based on connection types
        Read LC value of equipment according to connections types
    Calculate RoF_i(N-1) and maximum RoF_ij(N-2)
    Function Determine substations bays with power transformers
        Set corresponding equipment RoF_i to 0 for substations bays without
          power transformers
    Function Determine number and connection of elements C and D based on
      substations types
        Exclude elements C and D in accordance to substations types from risk
          calculations results
    Obtain maximum RoF_i
```

In addition, it is necessary to indicate the correct substation bays with power transformers. Because power transformers are connected between buses in PSS/E, they are included in data of both buses. Therefore, a dedicated vector is used for indicating these buses, in which side the power transformers are included in the risk calculation logic process. They are also added to substation bays in accordance with bus indices and their RoF_i is calculated. The power transformers from the substation bays of other buses are excluded and their RoF_i is set to 0. It is also necessary to include the proper number of circuit breakers and disconnectors based on the connections of substation bays and their schematic type. For that, the indices of substation types are used with the matrix containing data describing the link between these elements and substation section busbars. If some of these elements do not exist in substation based on their type, their RoF_i is set to 0.

As a result of the risk calculation process, the $RoF_{i(N-1)}$ and the maximum $RoF_{ij(N-2)}$ are obtained. These values are compared to determine the maximum RoF_i. If the $RoF_{i(N-1)}$ is higher than the maximum $RoF_{ij(N-2)}$, then the maximum risk is based on the N-1 contingency. Otherwise, the maximum risk is caused by a combined failure event of two pieces of equipment in the N-2 contingency. The risk calculation results are also extracted from the logic process as .csv files for further analysis. The RoF_i, the $RoF_{i(N-1)}$, the $RoF_{ij(N-2)}$, and other risk components' values can be used as inputs in asset management decision-making. Based on their analysis, it is possible to direct focus towards equipment with higher importance in the power system and optimize approaches used.

2.5 Case Study

The results of this case study are based on publication I. They are obtained using the IEEE 39-bus power system, the schematic for which in in Fig.22. The power system includes 34 transmission lines, 12 branches modeled as power transformers, 19 loads, and 10 generation units. The voltage of its main buses is rated as 330 kV.

The PSS/E is used to model the power system for obtaining the load curtailment values after equipment failures. In Python, various substation schematics with individual equipment placements are implemented in the dedicated logic process. In addition, the load curtailment values are also linked with substation equipment. The dedicated vectors and matrices are used for values of the risk related components and are included in the calculation process by considering equipment indices.

The values of the risk components are provided in following. The CoR_i of equipment types are: C - 30 k€, D - 10 k€, VT - 20 k€, CT - 20 k€, CA - 10 k€, ES - 5 k€, SA - 2,5 k€, PT - 300 k€, and IS - 2,5 k€. The $MTTR_i$ in hours for equipment types are: C - 8, D - 6, VT - 8, CT - 8, CA - 8, ES - 6, SA - 6, PT - 24, and IS - 6. The relatively fast replacement time of PT can be assumed achievable as there is a similar spare unit available. In the opposite case, the RoF_i of that equipment type in N-1 contingencies increases. The $VoLL_i$ is set to 1 k€ for all the loads. The PoF_i values is initially set to 0,1. The latter represents equipment with certain degree of condition degradation.

The results depict the change in the PoF_i, the change in the $MTTR_i$, and the change of substation type. These values are based on the equipment chosen as examples, such as VT1 (branch 8 at busbar 7) and VT2 (branch 21 at busbar 19) provided in Fig. 23, and DC1

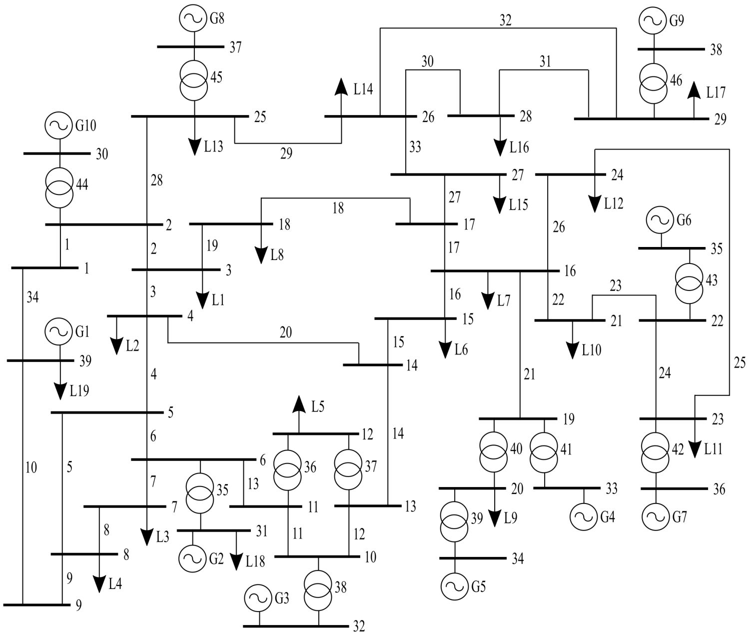

Figure 22: Schematic of the IEEE 39-bus power system used in the risk calculations. Power system data is available in [102].

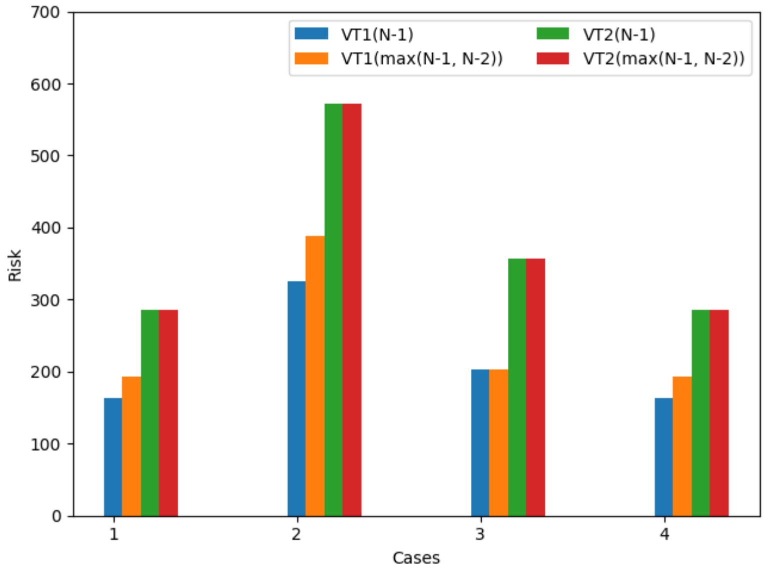

Figure 23: Risk of substation equipment (VT1 and VT2) based on cases: 1 - initial, 2 - PoF_i is increased to 0.2, 3 - $MTTR$ is increased to 10, 4 - substation type is changed to 1 [101]

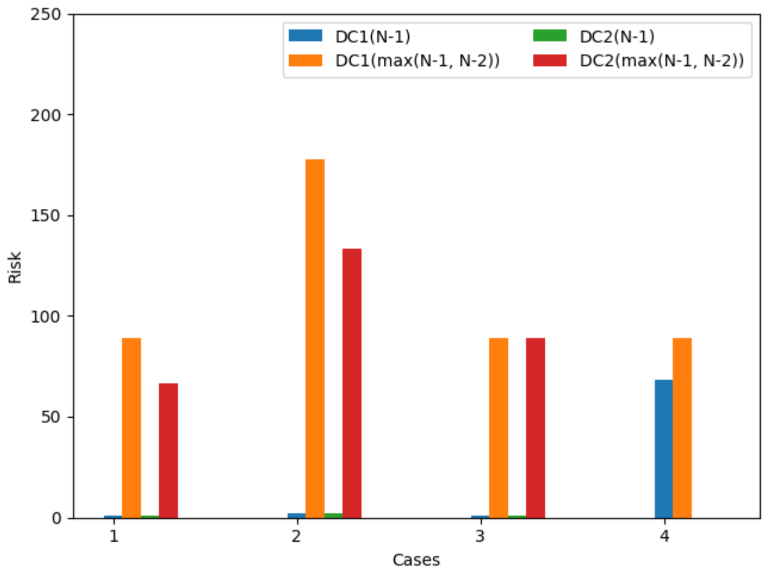

Figure 24: Risk of substation equipment (DC1 and DC2) based cases: 1 - initial, 2 - PoF_i is increased to 0.2, 3 - $MTTR$ is increased to 10, 4 - substation type is changed to 1 [101]

and DC2 (branch 20 at busbar 4) provided in Fig. 24. The results indicate the risk in the N-1 contingency and its maximum value in N-1 and N-2 contingencies. It is apparent from Fig. 23, that increasing the PoF_i to 0.2 (case 2) also increases the RoF_i (compared to case 1). The increase in $MTTR_i$ also increases the RoF_i (case 3 compared to case 1), though the change in case 3 is smaller than in case 2. In conclusion, the increase of $MTTR_i$ by 2 hours has less impact on the RoF_i compared to the change in PoF_i from 0.1 to 0.2.

Moreover, the RoF_i of VT1 is lower in N-1 contingencies than its maximum value, meaning that the maximum RoF_i is obtained in N-2 contingencies. In contrast, the maximum RoF_i of VT2 is based on N-1 contingencies. Changing the substation type does not increase the RoF_i, due to equipment placement in a branch (E1 in Fig. 12).

The RoF_i of equipment DC1 and DC2 is provided in Fig. 24. Similarly, the RoF_i is increased due to the increase in the PoF_i and the increase in the $MTTR_i$. However, the latter's impact is smaller compared to case 2. The RoF_i of DC1 in N-1 increases from near 0 to 70, when comparing case 4 to case 1. Nevertheless, the maximum RoF_i remains the same. The RoF_i of DC2 can not be calculated in case 4 because that equipment is not included in the less reliable substation schematic (schematic in Fig. 14 is changed to Fig. 12).

The results indicated, that the impact of the change in risk components depends on equipment location in the substation and its type. Similarly, it alters the RoF_i in the N-1 contingency and the maximum RoF_i. Overall, the developed risk calculation process provides options to evaluate equipment importance in the power system, determine the potential causes for higher RoF_i, and assess suitable methods for RoF_i reduction.

3 Equipment Risk Reduction in the Case of Unknown Condition Data

In the previous chapter, the maximum risk calculation process was described. The risk values of equipment are further used in different asset management related processes. They are the main input for various management decisions, task planning, and analysis. Foremost, asset management needs to focus on equipment with a higher failure risk. Based on the risk, an efficient management method for each piece of substation equipment can be chosen. In addition, it is also possible to determine suitable options for risk reduction and the amount of equipment included in its options. The increase in the cost-efficiency of asset management is achieved with the adjustment of risk reduction related parameters. Another aspect is the uncertainty in risk and its components. Before analyzing the risk reduction methods, it is necessary to obtain data on equipment condition, and subsequently failure risk, as well. Thus, risk reduction is a complicated process consisting of multiple factors.

This chapter is based on publications II, III and IV consisting of two main aspects. Firstly, addressing **RQ2**, an overview of the failure risk estimation process in the case of uncertainty in equipment condition data is presented. It initially describes the estimation of unknown condition data of equipment. Next, the process for using estimated data in risk-based asset management is provided. Secondly, addressing **RQ3**, an overview of risk reduction related factors are presented. The chapter continues by explaining options for achieving cost-efficient decrease in failure risk. This is followed by the corresponding failure risk reduction process. In addition, addressing **RQ3** and **RQ4**, the cost limits of risk reduction are evaluated. The chapter ends with a case study.

3.1 Principles of Failure Risk Reduction

The risk calculation process is an important part of asset management decision-making. Its main purpose is to identify equipment with a higher RoF_i. Based on that, suitable measures can be taken to reduce equipment risk. Failure risk reduction is achieved by strengthening the power system with alternative paths between substations or by reducing the equipment's likelihood of failure. The suitable method can be selected based on the cost of risk reduction, its efficiency, and the available funds. It is also important to analyze the cost related factors of asset management methods to determine the scale of risk reduction from a cost perspective. This is necessary for increasing the efficiency and justification of using the RBM. The principles of failure risk reduction are also described in Fig. 25. Overall, the process of the risk reduction consists of:

- Determining the condition of the equipment based on available data
- Estimating the condition of the equipment based on available data
- Using the known and estimated data in asset management decision-making
- Calculating the equipment risk
- Analyzing the options for risk reduction
- Decreasing risk based on the chosen risk reduction methods
- Analyzing the cost limits of risk reduction

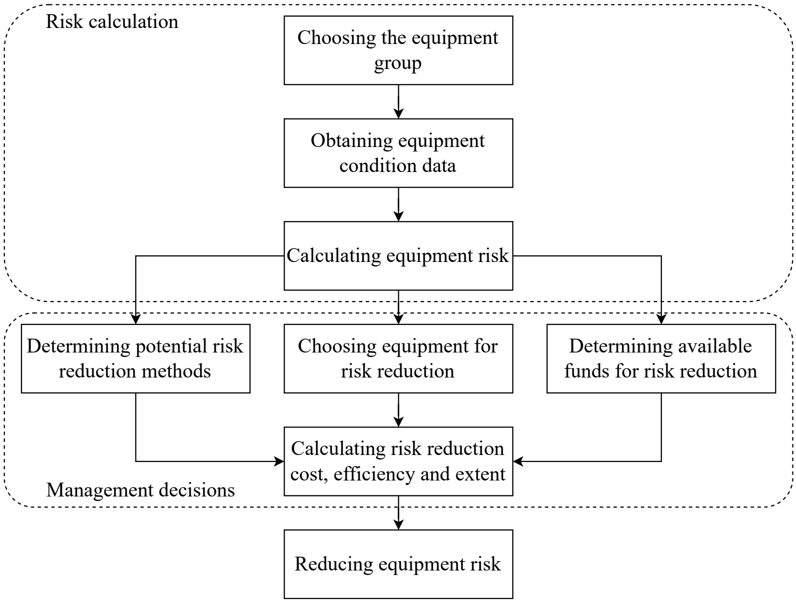

Figure 25: Principle process of risk reduction

In the case of uncertainty in equipment condition data, risk reduction can be used as an option to increase awareness on the condition of higher-risk equipment. Depending on the scale of risk reduction, the overall uncertainty could decrease as well. Thereafter, the efficiency of risk reduction and the cost-efficiency of risk-based asset management is gradually increased based on the increase in accuracy of condition data.

3.2 Risk Assessment in Condition Data Uncertainty

3.2.1 Health Index Based Condition Indication

Before risk calculations and asset management decision-making, actual or estimated equipment condition needs to be determined. This can be achieved based on condition inspections or measurement solution data. Another option is to use statistical data, but this only provides an overview of equipment's probabilistic condition for the whole group. Therefore, to determine the actual condition of an individual piece of equipment, it needs to be inspected or monitored. It is also possible to estimate the condition of equipment with unknown data based on the known data. Nevertheless, the results also indicate the probabilistic condition of the whole group instead of a single piece of equipment.

It is relatively common to express equipment condition by its Health Index (HI_i) value. Its principle of use is illustrated in Fig. 26. For HI_i obtainment, the equipment parameters are measured on a predefined scale. The HI_i is calculated based on the results and their deviation from the reference values. If the evaluated parameter is within the expected range, the equipment condition is stated as good. If the evaluated parameter exceeds the threshold value, then condition degradation is detected. The HI_i values can be within 1 and 5, 1 and 10, or 1 and 100, based on the methodology used. Usually, HI_i value 1 indicates the good condition of equipment, and HI_i value 5 (10 or 100) indicates its highly deteriorated condition. It can be determined separately for various components of equipment.

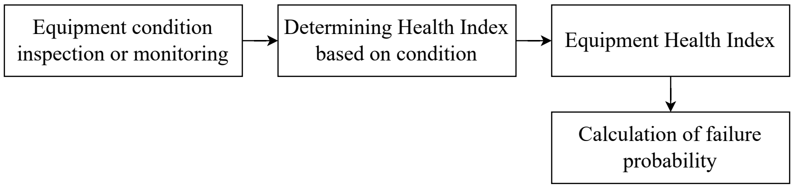

Figure 26: Principle process of obtaining and using equipment Health Index

Thereon, the dedicated equations are used to calculate overall HI_i. Based on equipment type and functionality, its calculation process can also be different.

The usage of HI approach can be preferred if the age-related factor of equipment is diminished or discarded by subsequent factors. For example, in the case of absent or limited condition data or when the equipment age is not correlating with the previously gathered data. Therefore, the HI makes it possible to express the equipment condition without having sufficient information regarding the degradation patterns of equipment with respect to equipment age. Furthermore, it indicates the exact condition of equipment if that is evaluated directly. Secondly, the results are not linked with the equipment age. Thus, the older equipment can be in a relatively good condition, and the newer one might have deteriorated significantly. This can be undetected when using statistical data. On the other hand, the gathered HI values need to be converted to degradation characteristics in order to predict the changes in the equipment's condition over a longer period of time. The HI approach is also used in the process of asset management of transmission overhead lines [103], where assets age was not correlating with their actual condition.

An option is to implement HI_i values directly to asset management decision-making. If using relatively frequent condition inspections or monitoring, equipment maintenance or replacement can be scheduled based on the HI_i. However, these values alone are not enough for optimizing asset management. To increase cost-efficiency, knowing the equipment's importance in the power system is necessary. For that, the HI_i values need to be converted to the PoF_i. It is relatively common to use methods based on hazard rate to obtain the PoF_i from HI_i.

An overview of different HI obtainment methods is given in [62]. These methods are usually intended for specific equipment types. For example, HI calculation methodology for power transformers is presented in [70], [71], [72] , [73]. In the case of circuit breakers, HI obtainment is provided in [74], and for cables, it is presented in [34]. For other equipment types, dedicated approaches to obtain HI values are majorly absent.

3.2.2 Estimation of Unknown Condition Data

In an idealized situation, the condition of all equipment in the power system is known. Furthermore, it is updated relatively frequently or in real-time. Therefore, equipment failures can be avoided. Also, knowing the actual data on equipment condition makes it possible to increase asset management cost-efficiency. In real power systems, though, it is quite common that the condition of the majority of the equipment is updated at a slow frequency or their actual state is unknown. As a result, predicting and preventing equipment failures is a challenge. In addition, this makes increasing the efficiency of asset management more complicated.

To optimize asset management and use the RBM, it is necessary to calculate the risk of all equipment. Subsequently, this requires knowing their condition for determining the PoF_i. If the condition data is available, relatively accurate RoF_i values can be calculated.

On the other hand, if there is limited condition data or no awareness of the actual condition of the equipment, the RoF_i values have higher uncertainty. Also, it is necessary to determine the condition of equipment, for which sufficient data is unavailable. This equipment could have higher risk, and therefore, their failures may cause significant consequences. This requires some additional steps to be taken. Mainly, the unknown data need to be estimated based on the known and available data.

The equipment condition estimation is necessary for multiple reasons. Firstly, it can be used to obtain the PoF_i in the case of unknown condition data for the RoF_i calculations. Because the estimation is done based on the known condition data, all the RoF_i values are found on the same basis. This means, that the RoF_i values are comparable between equipment with a known condition and equipment with an unknown condition. Secondly, it increases awareness about an equipment's potential condition, represented by the HI_i. Based on that, the amount of equipment with condition degradation and potential equipment failures in the upcoming time period can be estimated. Thirdly, it improves the cost-efficiency of asset management and helps to avoid failures with a higher cost. If the estimated RoF_i or condition degradation of equipment is relatively high, then it is reasonable to consider the reduction of its risk.

Therefore, having knowledge of equipment condition is necessary in order to optimize asset management. For data estimation, though, it is necessary to analyze the availability and usability of the known condition data. Its availability is higher, when gathered periodically within all equipment groups. Access to statistics representing the analyzed equipment groups increases the quality of data and its usability as well. The overall quality of condition data depends on the amount of equipment with known condition and equipment with unknown condition, denoted as K and M, respectively. Combined, they represent the equipment group S (18).

$$S = K + M \tag{18}$$

If $K >> M$, there is a good overview of equipment condition in group S. This allows for relatively accurate HI_i, PoF_i and RoF_i calculations for most of the equipment. The estimation of these values for group M can also have lower uncertainty due to a higher quantity of known data. If $K << M$, then the condition of most equipment is unknown. This leads to higher uncertainty in their HI_i, PoF_i and RoF_i values. Therefore, these values need to be estimated based on the known data on group K or by using related statistics.

In the case of limited information regarding the condition of equipment in group M, some assumptions are necessary to be made. Foremost, the degradation pattern of these equipment is expected to be similar to equipment in group K. As a result, it is possible to estimate the condition data of group M from group K. The estimation process creates a probabilistic understanding of their condition states compared to a situation without any or with limited information related to group M. This becomes more accurate if the proportion of group K increases. However, it should be reasonable to exclude outliers, such as equipment, which stands out from the overall group S. They can be related to their significant age, manufactory- or producer-related issues, and previously occurred overloading or over-voltage incidents. Furthermore, if the equipment for group K is chosen based on random selection, the likelihood of being chosen is the same for each piece of equipment. Thus, it can provide a probabilistic overview of the overall condition of group S.

Initially, it is necessary to gather data about the equipment in group K. This data is expressed by the HI_i values. Next, the known HI_i values need to be evaluated to obtain the number of pieces of equipment with different condition states. One option is to distribute the acquired samples of $HI_{i...k}$ values of group K by using a histogram. It is also

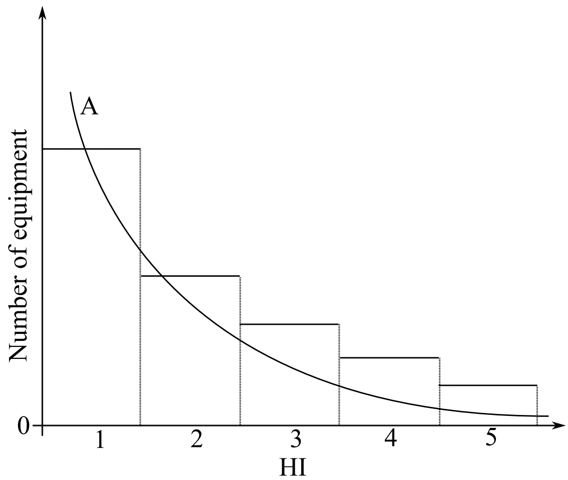

Figure 27: Fitting the probabilistic distribution (likelihood function) A to the number of HI_i values

necessary to scale the summarized HI values between 0 and 1. This makes it possible to obtain the proportional values of HI indices (for example, 1 to 5) based on the numbers N of equipment in group K (19).

$$HI_{i(prop)} = \frac{N_{\sum(HI_i)}}{N_{\sum(HI_{i...k})}} \tag{19}$$

For further data analysis, the proportional sample sizes need to be expressed by a specific likelihood function. This represents the change in proportional samples after the increase in HI indices. For that, the distribution of HI indices is fitted to various probabilistic distributions. Commonly used distributions are exponential, normal, lognormal, weibull, and uniform [17]. Choosing between these also depends on the analyzed subject and the goals of the analysis. The principles of this approach are provided in Fig. 27.

After fitting the chosen distribution functions to the distribution of HI indices, the function with the best fit is determined. For that, various methods can be implemented. An option to evaluate the goodness-of-fit of probabilistic characteristics to sample data is to use the sum of squared error (SSE) (20). In that, the n is the number of data points, y_i represents the observed value for the i-th data point and $\hat{y}_i$ represents the predicted value for the i-th data point.

$$SSE = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \tag{20}$$

The distribution function with the best fit is used in equipment condition data estimation processes. Its shape represents the probability to obtain the specific HI indices based on condition data of group K. If assuming that the pieces of equipment in group S are relatively similar by their functionality and type, the likelihood function should describe the condition data of group M as well. This makes it possible to increase awareness about equipment condition with unknown data and use it in risk assessment decision making.

3.2.3 Use of Estimated Data in Risk-Based Asset Management

If the exact condition of the equipment is known, represented by group K, then the corresponding HI_i, PoF_i and RoF_i values can be directly calculated. They are assumed to have relatively low uncertainty, if dedicated approaches and solutions are implemented to determine their condition. In the case of an unknown condition state of equipment, represented by group M, the HI_i needs to be estimated. Next, these HI_i values are used to obtain the PoF_i for further risk calculations. Due to the lack of knowledge on the exact condition of the equipment, the mean PoF_i value is used with all the equipment in group M. Despite that, the HI_i estimation based on known HI_i values makes it possible to scale the RoF_i values of group M to all other equipment RoF_i values in group K. Therefore, it is possible to obtain a rank or order of equipment based on their RoF_i. This can be used in asset management decision-making.

To increase asset management cost-efficiency, one option is to reduce equipment failure risk based on its order. Therefore, the uncertainty in risk components can have a significant impact on the RoF_i and risk reduction. If the RoF_i is noticeably higher than most equipment RoF_i, then it also has a relatively high cost component. This can be considered reason enough to include the equipment in the CBM, even if their exact PoF_i is unknown. Similarly, relatively low RoF_i values may be caused by relatively low CoF_i values. Therefore, their failures alone would not have a significant impact on overall asset management costs. If the majority of equipment RoF_i are around the same values, illustratively grouped together, then determining their order based on risk becomes complicated. It is also possible to compare the RoF_i values of different equipment groups for a higher amount of samples and better separation.

The main downside of data estimation is the potential possibility to under- or overestimate the RoF_i values. Its probability and extent in a whole equipment group S depends on the proportional scale between group K and M. If K » M, then most of the equipment RoF_i is determined relatively accurately. Therefore, the uncertainty in the RoF_i of group M has a lower impact on overall equipment rank in group S. If K « M, then most of the equipment RoF_i is estimated. Nevertheless, they are affected similarly due to the use of mean PoF_i. It also means, that their rank is determined mainly by the cost components of risk.

The uncertainty in the equipment condition of group S depends on the amount of equipment in the groups K and M. It also represents the proportional sample size $\hat{p_K}$ of group K from group S (21). Therefore, it makes it possible to evaluate the scale between the known and unknown condition data. If the $\hat{p}_K$ is relatively high or near 1, then there is a good level of awareness of equipment condition in group S. Subsequently, determining the HI_i and the PoF_i for the majority of equipment is quite accurate. If the $\hat{p}_K$ is relatively low or near 0, then the equipment condition is largely unknown and there is not enough data to determine the HI_i within a lower level of uncertainty.

$$\hat{p}_K = \frac{N_K}{N_S} \tag{21}$$

Because data estimation does not indicate the actual condition and the HI_i of equipment, it can have HI_i value between 1 to 5. Therefore, it can be complicated to evaluate the potential amount of equipment with actual higher HI_i values. This causes uncertainty in asset management cost estimation as well. If the amount of equipment with higher HI_i values is unknown, then the amount of equipment failures and maintenance during the upcoming time period is also difficult to assess. As a result, comparing asset management methods based on cost becomes unreasonable and inefficient. Nevertheless, for risk reduction and the use of RBM, it is necessary to know these values to evaluate its extent.

The objective of the RBM is to minimize $CAPEX$ and $OPEX$ during the time period t (22). These values depend on the various cost components. Mainly, the cost of inspections and its frequency, the cost of maintenance, the cost of equipment replacement, and the cost of equipment failure.

$$\min(CAPEX(t), OPEX(t)) \tag{22}$$

If the $\hat{p_K}$ is relatively low, meaning that the exact condition and HI_i of the majority of equipment is unknown, an alternative approach is necessary for determining potential values of asset management cost components. This can be done based on estimated HI_i values. Based on the HI_i values in group K, the HI_i values for group M are estimated. As a result, an assumed amount of equipment with each HI_i is obtained. Next, these values are analyzed to determine the overall condition of equipment in group M.

For example, if using a HI_i scale of 1 to 5, then a value below 4 indicates relatively good functionality of equipment. If HI_i is 2 or 3, some defects in their earlier stages may be noticed and there are signs of degradation. Overall, though, its likelihood of failure can be considered relatively low and there is no urgent need for equipment maintenance or replacement. If HI_i is 4, referred to as event $P(HI_i = 4)$, then there are signs of more extensive degradation, which could have an impact on its functionality. Without intervention, this can lead to HI_i value 5, and eventually to equipment failure. HI_i value 5, referred to as event $P(HI_i = 5)$, indicates the importance of equipment replacement due to higher failure probability.

Therefore, if the (23) applies, then equipment condition in group M can be considered mostly sufficient and urgent asset management activities are unnecessary. Otherwise, a large amount of equipment in group M is deteriorating and could cause equipment failures in the upcoming time period. Based on the evaluation of HI_i values, additional steps in risk analysis can be taken. Similarly, potential values of asset management cost components can be evaluated.

$$\sum_{i=1}^{m} P(HI_i < 4) >> \sum_{i=1}^{m} P(HI_i = 4,5) \tag{23}$$

The HI_i values can be linked based on their related tasks and consequences to specific cost components of asset management, described by (24)...(27). These cost components depend on the awareness of equipment condition and the availability of relevant data. Therefore, they can be different for group K and M. In the case of group K, due to more extensive condition degradation indicated by $P(HI_i = 4)$, equipment maintenance is usually implemented. This is represented by the $CoMA_i$. In $P(HI_i = 5)$, instead of maintenance, it may be reasonable to replace equipment as a preventive measure. This is expressed by the CoR_i. In the case of group M, without knowing the condition deterioration of equipment, its HI_i increases from 4 to 5 over time. For the same reasons, events $P(HI_i = 5)$ could go unnoticed. As a result, the $P(HI_i = 5)$ eventually causes equipment failure, which is represented by the CoF_i.

$$P(HI_i = 4) = CoMA_i, if \;\; i \in K \tag{24}$$

$$P(HI_i = 5) = CoR_i, if \;\; i \in K \tag{25}$$

$$P(HI_i = 4) \longrightarrow P(HI_i = 5), if \;\; i \in M \tag{26}$$

$$P(HI_i = 5) = CoF_i, if \;\; i \in M \tag{27}$$

Based on the HI_i values 4 and 5, and their related cost components, (28) is obtained. This makes it possible to analyze the total cost of asset management based on actual or estimated data. This can be beneficial for evaluating the impact of data uncertainty on cost component, as well as for analyzing the outcome of having limited or absent data on equipment condition. Based on that, an appropriate asset management decision can be made.

$$\sum_{i=1}^{k}(CoMA_i + CoR_i) = \sum_{i=1}^{m} CoF_i, if \;\; P(HI_i = 4,5) \tag{28}$$

Overall, these decisions depend on the justification of using preventive measures to avoid equipment deterioration and failures or accepting potential failure consequences. In order to perform equipment maintenance on time, prevent its ongoing condition deterioration, and avoid failure consequences with higher cost, the PoF_i, RoF_i and HI_i need to be linked to individual equipment. In the case of group K, due to the knowledge of the exact equipment with a specific HI_i value, it is possible to directly focus on that equipment and arrange maintenance or schedule replacement. The potential consequences of the equipment failure are also known. Therefore, asset management can be addressed based on individual equipment. In the case of group M, the HI_i values are estimated, so equipment with higher HI_i values are not precisely known. Subsequently, addressing this equipment is difficult.

In the case of an assumption, that group M has a relatively high amount of equipment with HI_i values 4 or 5, the total cost of their failures could be significant. Therefore, to avoid the potential failures of equipment in group M, the pieces of equipment with assumed condition degradation need to be determined. One option is to assess the condition of each equipment in M, but this can be time-consuming and come with a higher cost. Without inspections, pieces of equipment with events $P(HI_i = 5)$ are not detected. Similarly, the occurrence of the event $P(HI_i = 4)$ leads to event $P(HI_i = 5)$ without on-time maintenance, which subsequently causes equipment failure. From the cost perspective of asset management, neither option is ideal. Therefore, additional parameters are necessary in order to locate pieces of equipment, whose failures may have higher consequences.

To assess the significance of the events P_i, additional parameters indicating its weight are necessary to implement. For that, vector $W(P_i)$ representing a function of individual weight parameters w_i is used (29). The inclusion of different parameters w_i depends on the objectives of the analysis and their availability. In this case, the w_1 is a cost related parameter, w_2 is a risk related parameter and w_3 represents the time-frame t.

$$W(P_i) = f(w_1, w_2, w_3, ..., w_n) \tag{29}$$

Parameter w_1 can be linked to the cost of events $P(HI_i = 4)$ and $P(HI_i = 5)$ to obtain their individual equipment-based cost or their overall equipment group-wise cost. The cost function CoP_a for the group K can be determined by (30) and the cost function CoP_b for the group M by (31). It represents the cost of reacting to these events in the case of group K and the cost of not reacting to these events in the case of group M. The total cost of the corresponding asset management decisions depends on the amount of equipment p with events $P(HI_i = 4)$ and $P(HI_i = 5)$ in groups K and M.

$$CoP_a(HI_i = 4,5) = \sum_{i=1}^{p} CoMA_i + \sum_{i=1}^{p} CoR_i, if \;\; i \in K \tag{30}$$

$$CoP_b(HI_i = 4 \longrightarrow 5,5) = \sum_{i=1}^{p} CoF_i, if \;\; i \in M \tag{31}$$

Another factor to consider is the cost of reacting the opposite way to events $P(HI_i = 4)$ and $P(HI_i = 5)$. In the case of group K, represented by cost function CoP_b (32), this includes the same cost component as with group M. In the case of group M, reacting the opposite way means using condition inspections to determine the equipment i, which can cause the estimated events P. For that, the exact condition and HI_i of each piece of equipment in group M need to be assessed. Usually, condition inspections are necessary to determine the equipment with higher HI. It can be impossible or quite difficult to obtain the actual equipment condition using alternative methods. The equipment inspections also have specific cost. The total CoI_i depends on the amount of inspected equipment. This task is expressed by the cost function CoP_a (33).

$$CoP_b(HI_i = 4,5) = \sum_{i=1}^{p} CoF_i, if \quad i \in K \tag{32}$$

$$CoP_a(HI_i = 4,5) = \sum_{i=1}^{m} CoI_i, if \quad i \in M \tag{33}$$

Due to the different options of reacting to events $P(HI_i = 4)$ and $P(HI_i = 5)$ and their related cost functions, the equilibrium in (34) needs to be evaluated. This is expressed by cost functions (35) for group K and (36) for group M. If the amount of equipment needing maintenance and replacement in group K is known, it is possible to compare their cost to the equipment failure cost. Based on that, an appropriate management decisions is made. In the case of group M, the total values of cost components can only be compared.

$$CoP_a(HI_i = 4,5) = CoP_b(HI_i = 4,5) \tag{34}$$

$$\sum_{i=1}^{p} CoMA_i + \sum_{i=1}^{p} CoR_i = \sum_{i=1}^{p} CoF_i, if \quad i \in K \tag{35}$$

$$\sum_{i=1}^{m} CoI_i = \sum_{i=1}^{p} CoF_i, if \quad i \in M \tag{36}$$

Based on the objective of the asset management and whether the equipment is in group M the overall CoI_i and the CoF_i need to be minimized to meet the condition in (36). Otherwise, the cost-efficiency of asset management decreases. Based on the cost functions CoP_a, CoP_b, and the weight vector W_i, the minimization function (37) for group M is obtained.

$$F(CoP_a, CoP_b, W_i) = \min\left(\sum_{i=1}^{m} CoI_i, \sum_{i=1}^{p} CoF_i\right), if \quad i \in M \tag{37}$$

The parameter w_2 in vector W_i represents the RoF_i calculated based on the known and estimated PoF_i. It can be used as an additional value to determine the sequence of reacting to events P. Still, it is more considerable in the case of group K, because the equipment have different PoF_i values. Therefore, the RoF_i indicates equipment rank or order in the sequence more accurately. This is especially important, if $K >> M$. If the size of group K decreases, then a less accurate awareness of equipment conditions exists. Subsequently, the PoF_i represents its mean value for the whole group M instead of individual equipment. Because of that, parameter w_1 can indicate equipment importance better than w_2.

The parameter w_3 expresses the time-frame t, when the decisions or measures related to event P are taken. It means either reacting or not reacting to equipment with known or estimated higher HI_i values. Based on that, asset management costs for a specific time-frame can be determined. If the time-frame is narrower, then the likelihood of events P decreases. In the case of a wider time-frame, more events P probably occur. Subsequently, it changes the $CAPEX$ and $OPEX$ values used in asset management decision-making. In addition, the event $P(HI_i = 4)$ in t is assumed to become the event

$P(HI_i = 5)$ in $t+1$, if the equipment is in group M. Therefore, these events need to be separated between different time-frames. For that, the length of time-frame t is necessary to determine. This also makes it possible to increase the accuracy of asset management cost evaluation.

The length of time-frame t depends mainly on the degradation characteristics of individual pieces of equipment. The pace of these can be different and are impacted by various parameters. Therefore, without relatively frequent condition inspections, the end of time-frame t is difficult to determine. For specifying it, an option is to link parameter w_3 to equipment age. Statistically, the likelihood of having more equipment with higher HI_i values increases, when the equipment begins to near the end of its life expectancy. This means, that the length of the time-frames decreases and the costs related to events P increase. These patterns represent a larger equipment group rather than an individual piece of equipment. For this reason, the age of equipment itself can not be taken as a justification to use higher HI_i and PoF_i values. In addition, linking degradation patterns to equipment HI_i can cause relatively high uncertainty, if the available data is limited.

Without actual data on equipment condition, the accurate length of time-frame t is impossible to obtain. This can be considered as a distinctive outcome of using the TBM. Therefore, as part of implementing the RBM and risk reduction, the parameter w_3 is initially estimated. Mainly, this depends on the overall age and other similarities of equipment in group S. Based on that, the known HI_i values of group K and their estimation for group M are used to represent the time-frame t. It is still an approach with relative uncertainty, but during implementation of the RBM, the quality of data increases, allowing for these time-frames to be determined more accurately.

Nevertheless, for risk reduction, all weight parameters w need to be considered. The parameter w_1 can be determined relatively accurately. Its values are represented by the cost components and are calculated by dedicated solutions used in power system analysis. Therefore, the proportional scale of equipment in group K or M is irrelevant. The parameter w_2 depends on the cost components as well as on the PoF_i values, which are combined in the RoF_i values. If equipment is in group K, its RoF_i is considered to be accurate. If equipment is in group M, the RoF_i has uncertainty, as data estimation was based on the mean PoF_i. The parameter w_3 partially depends on the average HI_i of group S, and its estimation based on group K to group M. If the average HI_i is relatively low, then fewer events P could occur during time-frame t. On the other hand, having higher HI_i values also means an increased probability of events P. Subsequently, the time-frame t decreases. The parameter w_3 is used for indicating asset management cost, not the equipment risk of failure directly. It is more useful for evaluating the scale of risk reduction.

These parameters are the main inputs in risk reduction processes. based on their values, the order of equipment to be included in the RBM is determined. They also makes it possible to adjust the scale of risk reduction. Due to the sequential nature of that process, its extent and the amount of equipment included depends on the available funds intended for that purpose. This is subsequently related to asset management cost components. Therefore, the risk reduction process requires determination of the sequential order of equipment, the CoP_a, the CoP_b, and the cost of using the CBM.

For the risk reduction sequence, the parameter w_1 is used to indicate the CoF_i and the w_2 to indicate the RoF_i. Based on their values, it is possible to obtain the rank of a piece of equipment. Next, the rank index makes it possible to obtain the sequential order of equipment for risk reduction. This can be considered an iterative process, where in each iteration, a specific equipment risk is decreased. The total number of iterations depends on the cost of reacting to the event P, the cost of risk reduction, and the available funds indicated by $CAPEX$. For $OPEX$, the parameter w_3 is used to indicate the total CoF_i during time-frame t. In a more extensive risk reduction analysis, the comparison between $CAPEX$, $OPEX$, and the risk reduction cost need to be made.

Another factor is related to choosing the CoF_i values used in the parameter w_1 and w_3. In risk calculation, the maximum RoF_i is determined in accordance with the $CoF_{i(N-1)}$ and the maximum $CoF_{ij(N-2)}$. Therefore, the CoF_i can be based on the failure event in N-1 contingencies or the combined failure event in N-2 contingencies. This also means, that at least two different CoF_i values need to be considered in the failure cost analysis.

The difference between choosing the CoF_i in N-1 and N-2 contingencies depends mainly on the probability of having a combined failure event of two pieces of equipment. If the overall PoF_i is relatively low, then the probability of a combined failure event is even lower. Subsequently, using the CoF_i in N-1 contingencies represents load curtailment values with higher probability than the CoF_i in N-2 contingencies. If the PoF_i of most equipment is relatively high, using the CoF_i in N-2 contingencies is more adequate.

In this case, it is reasonable to make the assumption, that failures of equipment in group M do not occur in the same time-frame. This makes it easier to obtain CoF_i, which equals the CoF_i in N-1 contingencies (38).

$$\sum_{i=1}^{p} CoF_i \longrightarrow \sum_{i=1}^{p} CoF_{i(N-1)}, if \;\; i \in M \tag{38}$$

If the equipment is in group M, then because of data estimation, they have similar PoF_i values. However, this is based on an assumption where age-related factors are not considered. Therefore, equipment in group M can also be ranked by their maximum CoF_i value. Furthermore, if assuming that the probability of having combined failure events of equipment is relatively low, the $CoF_{i(N-1)}$ is used for ranking purposes.

Equipment order can be used to determine the focus of asset management activities. One of these activities is a risk reduction. To increase the cost-efficiency of asset management and risk reduction, it is necessary to obtain the optimal sequence of equipment, by decreasing risk of failure. In the case of uncertainty in condition data, a couple of parameters are used. These are the CoF_i, the RoF_i, and the estimated number of equipment with higher HI_i values.

3.2.4 The Process of Choosing the Equipment for Condition Inspections

Before choosing suitable and cost-efficient options for equipment risk reduction, it is necessary to determine the exact condition of higher risk equipment. In the case of group K, the actual condition data and the HI_i values are known. Therefore, the equipment order can be obtained relatively accurately and with a low uncertainty. In the case of group M, the actual condition data and the HI_i values are unknown. This causes specific limitations in risk reduction.

Mainly, the estimated RoF_i values need to be adjusted to obtain RoF_i values that are based on the actual condition of the equipment. This means assessing the condition of the equipment. An option for that is to use condition inspections. The latter is also related to specific cost components. If group M consists of a large amount of equipment, then inspecting them all could have a high cost. In addition, it is not cost-efficient or optimal, because the risk of the pieces of equipment are most likely different. Some equipment failures' cost and probability could be higher. On the other hand, some equipment' failure cost and probability is relatively low. Therefore, inspecting them all is inefficient. Especially, without a predetermined order. Thus, it is necessary to use specific procedures to increase asset management cost-efficiency. This is also important for further reduction processes of the RoF_i.

For determining the actual risk of equipment cost-efficiently, it is necessary to obtain the optimal sequence of equipment inspection. Another reason for that is an estimated knowledge of having HI_i values 4 and 5 in group M. If these potential events are ignored, then the consequences of failure could have a higher cost. Therefore, detecting this equipment is crucial. For that, the function W of the equipment in group M is used. This is added to the minimization function in (37). Based on these functions, a cost-efficient sequence of equipment condition inspection is determined.

The principle is to avoid higher CoF_i values by inspecting equipment condition based on a predetermined order. If the inspected equipment has higher HI_i value, then appropriate measures are implemented, such as condition maintenance or replacement. This makes it possible to improve equipment condition and decrease failure probability. As a result, equipment failure and the CoF_i are prevented as well. Another objective is to minimize the overall cost of equipment inspection used to detect equipment with higher HI_i. This is also partially related to distributing equipment between management methods. In accordance with (36), the total remaining CoI_i needs to be lower than the highest CoF_i in the analyzed equipment group.

The overall principle of this process is depicted in Fig. 28. Initially, equipment in group M is ranked by the CoF_i values. Also, the number of equipment in group M with the HI_i values 4 and 5 is estimated. In addition, equipment p in M with estimated HI_i values 4 and 5 and indicated by $\sum_{i=1}^{p}(HI_i = 4,5)$ is summarized. Next, an iterative sequence of equipment condition inspection is used. In each iteration, the equipment with the highest CoF_i is chosen. Thereon, an inspection of that equipment is carried out. Based on the inspection, the equipment's actual condition and the HI_i value is determined. If the HI_i of that equipment is 4 or 5, appropriate management activities are implemented. Afterwards, a suitable risk reduction method is chosen to decrease the equipment risk. Subsequently, it is assumed that the equipment's CoF_i is minimized, or in other words, prevented. This makes it possible to remove the value from further iterations and the RBM cost calculations.

It also means, that at the end of each iteration, the highest CoF_i value decreases. Therefore, the maximum potential failure consequences after equipment failure become smaller. The iterations are done until the highest CoF_i is lower than the $\sum_{i=1}^{m} CoI_i$ for the remaining equipment in group M. This means, that it is not cost-efficient to inspect more equipment in group M. Otherwise, the total cost of the inspection to detect equipment with HI_i values 4 and 5 would be higher than the costs of potential equipment failure. The process stops, if the condition in (36) based on the minimization objective (37) is not met or the $\sum_{i=1}^{p}(HI_i = 4,5)$ is lower than 1.

The process of determining the equipment inspection sequence also makes it possible to determine the amount of equipment in different asset management methods. The equipment inspected is added to the CBM, if economically feasible, based on cost related parameters such as available funds, cost of measurement solutions, or cost of arranging spare equipment. The equipment not inspected and with the lower CoF_i can be included in the TBM or the run-to-failure approach. If the equipment is included in the CBM, a suitable risk reduction method needs to be chosen. It is the main component for achieving a decrease in CoF_i values in asset management cost analysis.

3.3 Risk of Failure Reduction

Risk of failure reduction is used as an option to increase the reliability of a power system. Higher reliability means, that the impact and likelihood of equipment failures are

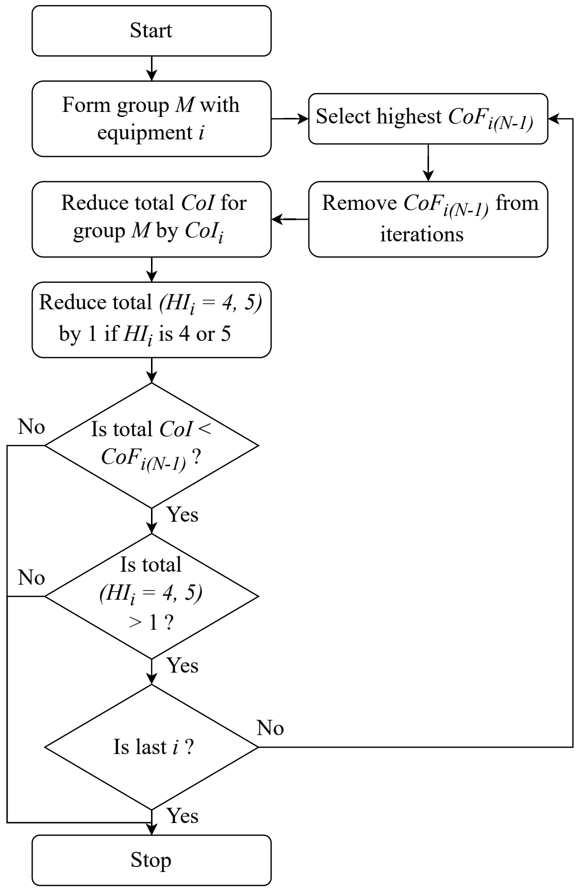

Figure 28: Process of determining equipment inspection sequence

decreased within an achievable extent. This also makes it possible to reduce the amount and related cost of equipment failures. Beforehand, though, it is necessary to determine higher-risk equipment. For that, the corresponding RoF_i values need to be calculated. Next, the equipment is ranked based on the RoF_i. Thereon, it is possible to focus on equipment with higher risk and take appropriate measures to reduce it. The risk of failure can be reduced by decreasing the value of the risk components, which are:

- The cost of load curtailment ($CoLC_i$)
- The failure probability (PoF_i)

The $CoLC_i$ can be decreased by increasing the reliability of the power system or substations or decreasing the equipment replacement times. The main option to increase reliability is to add alternative paths in the power system between substations. These make it possible to maintain the connection between demand and supply in the case of the equipment failure and a disconnection of one of the paths. However, it can have a relatively high cost due to additional transmission lines. Another option is to use substation schematics, which provide higher reliability. For that reason, the schematic with the double-bus and double-breaker is preferred. Nevertheless, it increases overall reliability less compared to adding alternative paths into the power system. Improving substation schematics only reduces the failure impact of equipment connected directly to substation sections busbars. Alternative paths between substations are still necessary in the case of equipment failures related to connections of the power system. Therefore, both additional connections and improved substation schematics need to be used to maximize the increase in reliability.

The third option is to decrease the $CoLC_i$ by reducing the replacement times of equipment after failure. This makes decreases in the duration of load curtailment. For that, it is necessary to have availability and fast access to spare equipment. It can be partially considered a preventive measure. Nevertheless, for a higher decrease in the $MTTR_i$, the optimal paths to spare equipment and its locations need to be determined. Similarly, the risk values of equipment are used for that purpose. In addition, it can decrease the risk of multiple equipment in the same equipment group. If one of these pieces of equipment has had a failure, then a spare is used. Therefore, it is not dependent on specific equipment and can be implemented within a substation or a group of nearby substations. Still, this option decreases the $CoLC_i$ and the RoF_i instead of increasing overall reliability. Because of that, it can be considered an additional risk reduction measure besides reliability-oriented approaches.

An alternative option is to increase the reliability of the power system by decreasing the equipment PoF_i. Mainly, it can be decreased by maintaining good condition of equipment. Subsequently, this requires the use of more frequent equipment condition inspections or measurement solutions. It is assumed, that by evaluating equipment condition in high frequency or real-time, the occurred defects and condition degradation are detected at earlier stages. This allows for on-time asset management action, such as planning maintenance. As a result, the increase in PoF_i due to aging is avoided, and its value is kept relatively similar within a longer time period. Overall, it means using the CBM for predictive and preventive reasons. The cost of decreasing or maintaining a steady PoF_i value depends on the equipment type, inspection or measurement solution costs, and the amount of equipment included in the risk reduction. Therefore, it is partially a multi-parameter optimization. On a larger scale, a comparison between increasing reliability by adding alternative paths with improving substation schematics and decreasing PoF_i is also necessary for a more extensive risk reduction analysis.

In addition, the extent of the risk reduction depends on the available funds. If funds are unlimited, the reliability can be increased to its highest achievable and reasonable level. If not, then its extent and the increase in reliability is limited. This is the common case in power system asset management. Usually, risk reduction requires increasing the $CAPEX$. It is used for adding alternative paths to the power system, improving substation schematics, and decreasing the failure likelihood of equipment. On the other hand, the risk reduction can decrease the $OPEX$ as well due to the potentially avoided higher cost equipment failures. Therefore, in order to determine the change in the $CAPEX$ and the $OPEX$, it is necessary to evaluate the change in asset management costs based on risk reduction. This is also needed in order to justify the decisions made in risk reduction. Overall, risk of failure reduction depends on the:

- Uncertainty in the risk components

- Calculation of risk values

- Achievable decrease in the risk
- Cost of decreasing the risk
- Change in the cost of asset management

The increase in the power system's reliability can be achieved by decreasing the risk in substation equipment. Commonly, the funds needed are taken from the $CAPEX$ planned for the time period T, described as $(CAPEX_{lim}(T))$. Thus, the $CAPEX$ used in risk reduction in time period T should be within the limit of $(CAPEX_{lim}(T))$ as expressed by (39).

$$CAPEX(T) < CAPEX_{lim}(T) \tag{39}$$

The objective is to achieve maximum risk reduction efficiency within the available $CAPEX(T)$. The extent of risk reduction is described by the difference of risk value (ΔRoF_i) before the reduction $RoF_{i(Bef)}$ and after the reduction $RoF_{i(Aft)}$, expressed by (40).

$$max(\Delta RoF_i) = max(RoF_{i(Bef)} - RoF_{i(Aft))} \tag{40}$$

For the risk reduction, specific methods should be used. The risk reduction methods considered are:

- Method A - reducing the failure probability (PoF) of substation equipment;
- Method B - reducing the replacement time ($MTTR$) of substation equipment.

3.3.1 Risk Reduction by Decreasing Failure Probability (Method A)

An option to decrease the equipment risk and increase the reliability of power system is to decrease or minimize the change in their PoF_i values. The overall principle is illustratively represented in Fig. 29, in which function A indicates the increase in PoF_i over time by equipment aging and wear, and function B indicates the potentially maintained PoF_i value, if using relatively frequent condition inspections or measurement solutions. Subsequently, this requires the equipment to be included in the CBM. The achievable decrease in PoF_i (41) is the difference (ΔPoF_i) between the equipment potential PoF_i in the time period t without the CBM and with the CBM.

$$\Delta PoF_i(t) = PoF_{i(notCBM)}(t) - PoF_{i(CBM)}(t) \tag{41}$$

Another option is to compare the PoF_i at the current time period with the assumed PoF_i representing the use of the CBM. Therefore, it is not required to assess the potential PoF_i after a longer time period. Also, it makes it possible to discard the time factor. For that, the condition of the equipment needs to be estimated or inspected to obtain the PoF_i. Next, it is compared to the PoF_i value indicating the equipment in a good condition. Subsequently, the ΔPoF_i can be calculated with (42).

$$\Delta PoF_i = PoF_{i(actual)} - PoF_{i(CBM)} \tag{42}$$

Both options require the use of the PoF_i values in the case of the CBM. For that, the predefined PoF_i that represents the good condition of the equipment can be used. If using a HI-based approach, the corresponding HI_i values can be 1 or 2.

If the risk of failure reduction is accomplished by decreasing the PoF_i, then the $CoLC_i$ and the CoF_i remain the same. Therefore, the change in risk (ΔRoF_i) is based on the ΔPoF_i. Due to the different values of the $CoLC_i$, the CoF_i and the ΔPoF_i, the ΔRoF_i values vary between the equipment.

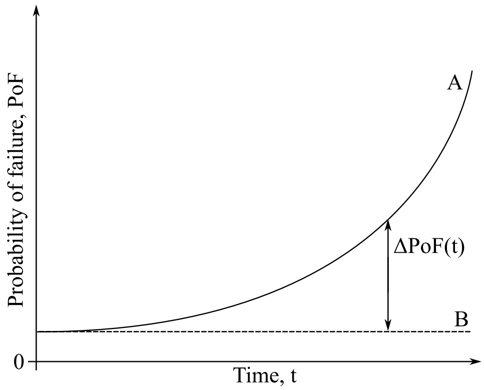

Figure 29: Illustrative probability of failure (PoF_i) functions: A - without on-time maintenance and condition inspections, B - with on-time maintenance and real-time measurement solutions. The ΔPoF_i is the difference of the PoF_i based on the functions A and B at time t

The decrease in the PoF_i and subsequently, in the RoF_i, is achieved using CBM. This is related to the specific cost components; mainly, the cost of measurement solutions ($CoMS_i$). Therefore, the availability and the $CoMS_i$ has an impact on the potential implementation of the risk reduction.

In order to determine the risk reduction efficiency, it is necessary to analyze it from the cost perspective. For that, the cost-efficiency of the risk reduction ($EoRR_i$) in (43) can be used. The $CoRR_i$ represents the cost of the risk reduction, which in this case is the $CoMS_i$.

$$EoRR_i = \frac{\Delta RoF_i}{CoRR_i} = \frac{RoF_{i(actual)} - RoF_{i(CBM)}}{CoRR_i} \tag{43}$$

The $EoRR_i$ makes it possible to analyze, which equipment risk is the most cost-efficient to decrease. If the risk reduction is achieved using the CBM, then the $EoRR_i$, $CoRR_i$ and ΔRoF_i depend on:

- The cost of measurement solutions ($CoMS_i$)
- The ability of measurement solutions to decrease the PoF_i
- The achievable ΔPoF_i

Each of these parameters are important for risk reduction cost-efficiency. If the value of the $CoMS_i$ is higher, then the $EoRR_i$ is lower. If the measurement solutions are incapable of detecting the change in equipment condition, then a sufficient decrease in the PoF_i can not be achieved. The ΔPoF_i are also related to the accuracy and the usability of the measurement solutions.

Therefore, these parameters depend on the complexity of the monitored equipment. For power transformers and circuit breakers, different types of measurement solutions are needed. In the case of disconnectors and earthing switches, more simple units can be used. Therefore, the $CoMS_i$ is assumed to be higher, if the equipment is considered relatively complex.

Another factor is the measurement solution's ability to decrease the PoF_i. To obtain higher efficiency in condition monitoring, relatively accurate measurement solutions need to be used. In addition, the equipment parameters that indicate condition the best should be measured. Usually, more accurate measurement solutions also have a higher cost. Today, research focuses on developing more affordable options, but these are often less accurate. Therefore, the preset $PoF_{i(CBM)}$ should be higher due to delayed detection of changes in the equipment condition. As a result, the ΔPoF_i is assumed to be lower as well.

The availability of measurement solutions is another factor. This depends mainly on the equipment group. For specific equipment groups, suitable units might not exist or their costs are quite high. An alternative approach is to use other types of measurement solutions that provide an overview of the equipment condition from a distance or estimate it based on indirect parameters.

Without a more extensive analysis of the link between the measurement solution's accuracy, its capability to detect occurred defects and its usability for maintaining the preset condition level of the equipment, an assumption needs to be made. Therefore, determining the achievable decrease in the ΔPoF_i and the $PoF_{i(CBM)}$ can also be a relatively complicated task. If the measurement solutions are capable of detecting the change in equipment condition relatively accurately, then in theory, the PoF_i value can be maintained over a longer time period. For that, it is necessary to keep the condition of the equipment at a good level through timely maintenance.

In method A, decreasing the PoF_i, the risk of equipment is reduced by using condition-based asset management. This means, the condition of the equipment is monitored in real-time or relatively frequently. As a result, defects in equipment leading to failure are detected earlier. Therefore, their probability of failure (PoF) and, subsequently, the RoF_i are decreased. For that, measurement solutions or condition inspections can be used. The cost perspective of condition monitoring is represented by the cost of condition-based management ($CoCBM$). The $CAPEX$ related $CoCBM$ includes the cost of measurement solutions ($CoMS$) and the cost of condition inspections (CoI), expressed by (44).

$$CoCBM = CoMS + CoI \tag{44}$$

Method A is implemented individually for each selected piece of equipment. Thus, the risk reduction is equipment-specific. This also means the $CoCBM_i$ related to it can be different. Nevertheless, the total cost of risk reduction should meet the condition in the (45). If the $CoCBM$ for each piece of equipment is the same, the potential amount of equipment (N_D) included in the condition-based method (CBM) depends on the (46).

$$\sum_{i=1}^{n} CoCBM_i(T) < (CAPEX_{lim}(T)) \tag{45}$$

$$N_D = \frac{(CAPEX_{lim}(T))}{CoCBM_i} \tag{46}$$

The total cost of risk reduction ($CoRR$) based on method A for individual equipment is equal to the $CoCBM_i$. For a group of similar equipment, it is expressed by (47).

$$CoRR(A) = N_D \cdot CoCBM_i \tag{47}$$

3.3.2 Risk Reduction by Decreasing Replacement Time (Method B)

If the cost of equipment replacement (repair) is relatively small and affordable measurement solutions are unavailable, then an alternative method is to arrange spare equipment in the substation or a group of substations. This makes it possible to decrease the time of equipment repair or replacement. By arranging spare equipment, the risk can be decreased for multiple pieces of equipment in the same substation or nearby substations.

Thus, this option can be more efficient in certain cases and with specific equipment types than method A.

Therefore, in method B, the risk of equipment is reduced by reducing their replacement or repair time ($MTTR$) after the occurred failure. Subsequently, this decreases the cost of load curtailment ($CoLC$) and therefore the risk. The $MTTR$ consists of:

- Stage 1 - Determining the location and the type of the failed equipment
- Stage 2 - Preparation time of the maintenance team
- Stage 3 - Getting the spare equipment
- Stage 4 - Bringing the spare equipment to the substation where the failed equipment is located
- Stage 5 - Replacing the failed equipment

Each stage in the $MTTR$ has its significant purpose and their duration depends on various factors. Therefore, no stage can not be fully removed from the sequence or it would be difficult to reduce their scale in the the $MTTR_i$. Nevertheless, it is possible to discard stage 3 and 4 from the replacement process by arranging for spare equipment in the substation beforehand. Thus, there is no need to bring the replacement equipment to the substation reducing the $MTTR$. However, the maintenance team still needs to get to the failed equipment. Therefore, the reduction of $MTTR$ depends on the distance between the location of the maintenance team, the spare equipment and the destination substation. In method B, the cost related to $CAPEX$ is the cost of replacement (CoR) required to acquire a spare equipment.

Method B can be implemented on all similar pieces of equipment in the same or nearby substations. This means the spare equipment for an equipment group k (equipment with the same purpose and functionality) is located at the chosen substation. After the failure of equipment, it is replaced with the spare equipment. Then, the next spare equipment is brought to the substation. Thus, it is possible to reduce the risk of all similar equipment in the same or a cluster of multiple substations. The maximum number of spare equipment (N_S) depends on (48).

$$N_S = \frac{(CAPEX_{lim}(T))}{CoR_i} \tag{48}$$

The main advantage of method B compared to method A is the possibility to reduce the risk of all similar pieces of equipment in multiple substations. The disadvantage is the missing data about the condition of equipment that is obtained using method A. Also, occurred defects can be detected only during inspections. Therefore, method B is considered a partially preventive method. Method B may be preferable, if the equipment has a lower CoR and suitable (low cost) measurement solutions or frequent inspections are unavailable. The cost of risk reduction based on method B for equipment group k equals CoR. The total cost of method B is obtained by (49).

$$CoRR(B) = N_S \cdot CoR_i \tag{49}$$

3.3.3 Risk Reduction Process

To determine a cost-efficient option for equipment risk reduction, methods A and B need to be used individually or combined in a dedicated risk reduction process. In both methods, the achievable ΔRoF_i after the risk reduction is evaluated from the cost ($CoRR$) perspective. It is expressed by the efficiency of the risk reduction ($EoRR$) and is obtained for method A by (50) and for method B by (51).

$$EoRR(A)_i = \frac{\Delta RoF_i}{CoRR(A)_i} \tag{50}$$

$$EoRR(B)_k = \frac{\sum_{i=1}^{k} \Delta RoF_i}{CoRR(B)_k} \tag{51}$$

The difference between the $EoRR$ of methods A and B for multiple similar pieces of equipment (in group k) is assessed by (52). The cost-efficiency of method A increases, if the $CoCBM_i$ or the N_S decreases. For method B to be preferable, the $CoCBM_i$ or the N_S should increase. The total change of ΔRoF_i also has a significant impact on the method's efficiency.

$$\frac{\sum_{i=1}^{N_D} \Delta RoF_i(A)}{N_D \cdot CoCBM_i} = \frac{\sum_{i=1}^{k} \Delta RoF_i(B)}{N_S \cdot CoR_i} \tag{52}$$

The risk reduction methods A and B are used in an iterative process for reducing the risk cost-efficiently. The main process is shown in Fig. 30. Initially, group C is formed with the chosen equipment i included in the risk reduction. The group C can be also used for excluding specific equipment i or equipment groups from risk reduction process.

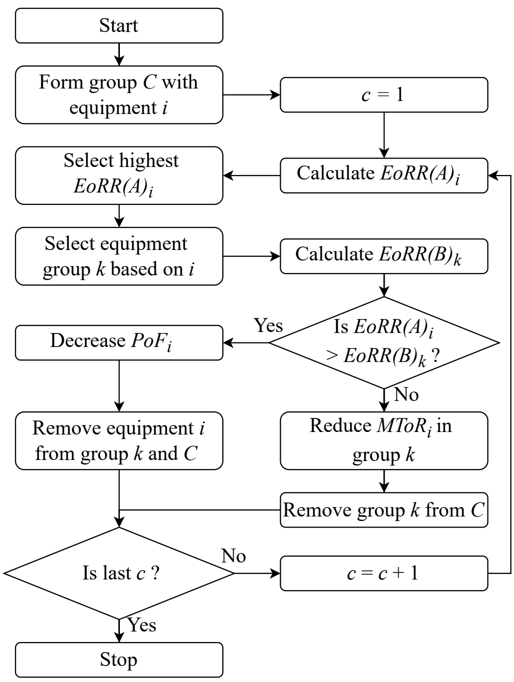

Figure 30: Main process of risk reduction based on $EoRR$ obtained by method A and B [104]

In each iteration c, the equipment with the highest $EoRR(A)_i$ is chosen. Next, the equipment group k of that equipment i is obtained, and the $EoRR(B)_k$ is calculated. If the $EoRR(A)_i$ is higher than $EoRR(B)_k$, then the PoF_i of that equipment is decreased (measurement solutions are added). Otherwise, the $MTTR_i$ of the equipment in group k

is reduced (spare equipment is arranged). After the iteration, the individual equipment i or the equipment group k is removed from the C. Then the next iteration begins.

In each iteration, the $CoRR(A)_i$ and $CoRR(B)_k$ are compared to the available funds $r(CAPEX)$. The latter decreases after the exclusion of $CoRR(A)_i$ or $CoRR(B)_k$ from the $(CAPEX_{lim}(T))$ in the iteration. In addition, if the $CoRR(A)_i$ or $CoRR(B)_k$ is higher than $r(CAPEX)$ in each iteration, then either method A or B is skipped. The process stops, if the $CoRR$ of both methods is higher than $r(CAPEX)$. This means that all the available funds for risk reduction have been used.

The risk reduction process also indicates the distribution of equipment between asset management methods. If the $EoRR$ value is relatively high, then the equipment should be included in the CBM. Otherwise, the TBM may be preferred. If the $EoRR$ value is relatively low, then the cost of risk reduction is higher which means that less equipment can be included in risk reduction and in the CBM within the available funds. Thus, the values of asset management cost components can change the implementation of risk reduction. Therefore, it is necessary to analyze the cost-related limits of the RoF_i reduction.

3.4 Asset Management Cost Estimation

3.4.1 Cost Limits of Risk Reduction

An important factor in risk reduction is the optimal amount of equipment included in the CBM. This factor also determines risk reduction scale and extent. It depends on multiple parameters, which are combined in asset management decision-making. Fig. 31 provides an overview of these parameters. The RoF_i indicates the equipment's importance or rank in the power system and can be used to determine the sequence of risk reductions. For determining the amount of equipment for which the TBM, the CBM, and the run-to-failure approach are to be used, the CoI_i, the $CoMS_i$ and the CoF_i are included besides the risk value. The CoI_i also depends on the condition inspection frequency. In addition, the availability and usability of measurement solutions are important factors. If suitable measurement solutions are unavailable, the CBM can not be used with that equipment until alternative options are developed. Secondly, their usability needs to also be assessed. Foremost, the measurement solutions should give a good indication on equipment condition to determine its HI relatively accurately.

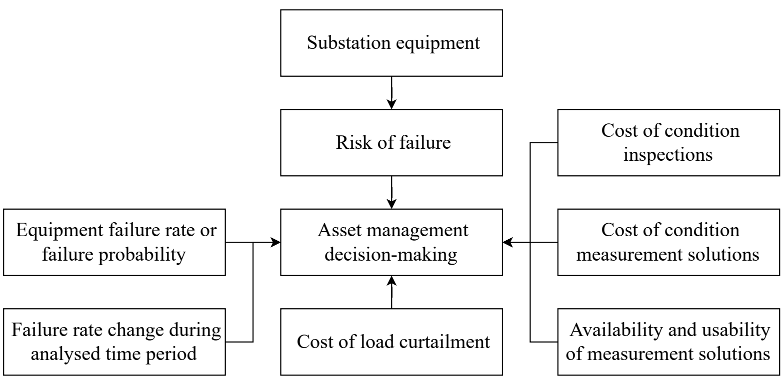

Figure 31: Overview of the parameters related to asset management decision-making

It is also necessary to determine, how many equipment failures could potentially occur during the analyzed time period. The PoF_i partially expresses that value. If the average PoF_i is relatively small, then the number of potential failures is also smaller. Nevertheless, it is relatively complicated to obtain the actual number of equipment failures for a specific time period. it is even more difficult to estimate the necessary amount of equipment maintenance. Overall, optimizing asset management and increasing its cost-efficiency depends on multiple parameters, their accuracy, and the potential means of their obtainment.

In the asset management decision-making process, the majority of parameters are cost components. These determine mainly the amount of equipment included in risk reduction. In addition, different types of equipment have a different impact on risk reduction cost. Thus, the risk reduction process consists of multiple factors. Initially, the sequence of the equipment for the most cost-efficient risk reduction can be obtained based on the $EoRR_i$. Secondly, it is necessary to analyze the potential amount of equipment, whose risk can be decreased. It depends on the funds available or intended for risk reduction. Usually, these are related to the $CAPEX$. Therefore, the total $CoRR_i$ needs to be lower than the planned $CAPEX_{limit}$ during the time period t (53).

$$\sum_{i=1}^{n} CoRR_i(t) < CAPEX_{limit}(t) \tag{53}$$

On the other hand, the inclusion of equipment in the risk reduction changes the asset management method and its cost components. Commonly, instead of the TBM and the CoI_i, the CBM and the $CoMS_i$ is used. Subsequently, this changes the $OPEX$ as well. Without considering the CoF_i, the increase in the $CAPEX$ and the decrease in the $OPEX$ in the time period t is equal, if the (54) applies. If the CoF_i is also included, then the decrease in the $OPEX$ could be bigger. This is because of the higher number of potentially avoided equipment failures when using the CBM.

$$\sum_{i=1}^{m} CoMS_i(t) = \sum_{i=1}^{n} CoI_i(t) \tag{54}$$

The $CoMS_i$ can be related to the CoF_i or the CoR_i as well. In most cases, it could be unreasonable to use measurement solutions with higher costs than the equipment replacement or repair costs. Therefore, the (55) applies.

$$CoMS_i < CoR_i \tag{55}$$

In addition, the measurement solutions provide an earlier indication on the upcoming equipment failure. This makes it possible to prevent equipment failures and can be beneficial in the case of higher CoF_i. Therefore, the (56) could be used instead.

$$CoMS_i < CoR_i + CoLC_i \tag{56}$$

However, the latter approach has two disadvantages. Firstly, the $CoLC_i$ is usually significantly higher than the CoR_i. This can make the condition in (56) always true. Secondly, it is unlikely to have all or the majority of the equipment failures within an analyzed time period. Of course, the length of that time period can have an impact on that. On the other hand, an exception could occur with quite aged equipment. Then again, instead of using measurement solutions, their replacement or maintenance should be scheduled. If the substation equipment is assumed to have a relatively good condition, their failure probability is lower and a potentially small number of failures could occur in the analyzed time period. Also, in a larger equipment group, it is uncertain which individual equipment can cause a failure. In order to know this more precisely, the CBM needs to be used. This would most likely increase asset management costs. In addition, it is necessary to know the equipment's exact condition beforehand, so there needs to be enough data on the equipment condition. As a result, including the $CoLC_i$ in (56) for each equipment can be unreasonable.

For including a higher amount of equipment in the CBM, the condition in (57) should apply. Otherwise, the $CAPEX$ in time period t increases. In the case of (58), adding a lower amount of equipment to the CBM is justified due to the significantly higher $CoMS_i$ compared to the CoI_i. The asset management cost related to the equipment inclusion in the CBM can be evened out over a longer time period, though. For example, if multiple condition inspections are used compared to adding measurement solutions.

$$\sum_{i=1}^{n} CoMS_i(t) < \sum_{i=1}^{n} CoI_i(t) \tag{57}$$

$$\sum_{i=1}^{n} CoMS_i(t) >> \sum_{i=1}^{n} CoI_i(t) \tag{58}$$

The cost of asset management methods ($CoMM_i$) is another factor in determining the amount of equipment included in risk reduction and their distribution between management methods. This makes it also necessary to consider the risk reduction impact on management method costs besides the upper limit of the total $CoRR$ based on the $CAPEX$. If the risk reduction increases the overall cost of asset management, it can be unjustified. Still, the decrease in assumable risk lowers that cost due to the avoided equipment failures. This requires an additional risk and cost related analysis.

To determine the extent and impact of the risk reduction, the cost of different management methods for the equipment should be analyzed. Because of the commonly used TBM, its cost is compared mainly with the cost of CBM (59), for higher reliability and risk reduction. For the full use of the CBM, the total $CoCBM$ needs to be below the total $CoTBM$ for the same equipment. Otherwise, only specific pieces of equipment should be included in the CBM, which makes using the RBM necessary. In this case, the (60) needs to apply.

$$\sum_{i=1}^{n} CoCBM_i(t) < \sum_{i=1}^{n} CoTBM_i(t) \tag{59}$$

$$\sum_{i=1}^{n} CoRBM(t) < (\sum_{i=1}^{n} CoTBM(t), \sum_{i=1}^{n} CoCBM(t), \sum_{i=1}^{n} CoRtF(t)) \tag{60}$$

Overall, the cost of the management method in time period t depends on the method used, the number of equipment failures, and the difference between the $CoMS_i$ and the CoI_i. The latter can be acquired relatively accurately with the available data. It is more difficult to determine the number of equipment failures in the time period t. If the condition of the equipment and the PoF_i are known relatively accurately, it is possible to determine which equipment could potentially fail. On the other hand, if the average failure probability ($P\bar{o}F_i$) estimation is used, then the exact PoF_i of equipment can not be determined exactly. Therefore, the $P\bar{o}F_i$ indicates the probability of having a failure within a specific equipment group, but it does not indicate the exact equipment that could have that failure. For example, if an equipment group includes 1000 of equipment and the $P\bar{o}F_i$ is 0.01, and it is known that 10 of these could have a failure in the time period t, then each of them has 0.01 probability to be the one with the failure.

Therefore, for the estimation of the number of equipment failures and maintenances, two parameter values need to be known. These are the failure rate, which can be expressed by the PoF_i, and its change during the analyzed time period. The parameters are mainly determined based on the statistical data. The number of maintenances is also expected to follow the change in the failure rate. If equipment condition degradation has a higher probability, it will be detected more during inspections or by measurement solutions.

If the statistical data is limited or absent, the uncertainty in these parameters increases. One option is to analyze different scenarios to determine the upper and lower limits of asset management method costs, as well as the increase in the method costs after the change in the parameter values. Overall, this is less accurate compared to using higher quality statistical data. On the other hand, in the case of limited or absent data, it can still indicate the specific trends and break-even values of asset management methods. In addition, it assists in determining the amount of equipment distributed between different methods for the RBM.

3.4.2 Failure Cost Estimation

An option for assessing the cost of different asset management methods is to estimate its values during a preset time period. The total cost of a management method ($CoMM$) consists of the method-related cost components described in Chapter 1. Overall, the function to determine the $CoMM$ in a time period T is expressed by (61). Besides the management method, it also includes specific cost components, such as the CoF, $CoMS$, CoI, and $CoMA$.

$$CoMM(T) = f(Method, \sum_{i=1}^{n} CoF_i, CoMS_i, CoI_i) \tag{61}$$

If some of the cost components are not included in the asset management method, their values are at 0. The total value of the $CoMM$ is based on the summarized values of the cost components. The specific cost fo each asset management method can be calculated. This makes it possible to compare them to determine the most cost-efficient management strategy. For example, if the CBM is estimated to be more affordable due to a relatively low value of the $CoMS$ and avoided CoF compared to the TBM, then using measurement solutions for equipment condition monitoring instead of time-based condition inspections is justified. On the other hand, if the $CoMS$ is relatively high, implementing the CBM on all equipment is not cost-efficient. In the case of the RBM, the optimal distribution between the TBM and the CBM is necessary to obtain based on the equipment's ranking and importance in the power system.

The summarized CoI and $CoMS$ values depend on the amount of equipment, for which condition inspection is carried out and measurement solutions are implemented. It is more difficult to evaluate the total $CoMA$ within that time period. Mainly, it depends on the degradation level of equipment at the time of its condition measurement. Due to irregular degradation characteristics, its pace from an individual equipment perspective can be different. Thus, estimating the $CoMA$ requires relatively complex approaches. This task becomes even more challenging if the actual equipment condition is unknown and related data are limited.

Similarly, there are some limitations in the case of the total CoF estimation. On the one hand, it is possible to estimate the number of equipment failures during a specific time period with data on failure rate, failure probability, and equipment age. On the other hand, these parameters represent a statistically bigger equipment group. Therefore, they are less accurate from an individual equipment perspective. In addition, the lack or limited amount of statistical data makes that estimation more complex. Nevertheless, the total CoF during a specified time period is necessary to obtain in order to determine the extent of the risk reduction. Subsequently, as part of the RBM, the equipment distribution between the TBM, the CBM and the Run-to-Failure approach is indicated. In this circumstance, using alternative CoF evaluation approaches is needed.

Another aspect is related to choosing the length of time period T for asset management cost estimation. Moreover, it should follow the change in failure rate or the PoF_i. Therefore, the change in these parameters needs to be relatively small within T. Still, in the case of the limited or no statistical data, the relatively exact length of that time period can be difficult to determine. Similarly, it is hard to estimate the increase in failure rate or the PoF_i between time periods. Subsequently, this also makes it more difficult to estimate the change between the $CoMM(T)$ and $CoMM(T+1)$ (management cost in the next time period). The latter largely depends on the increase in PoF_i values. Thus, the PoF_i calculation or estimation is needed as an input for asset management cost estimation.

Furthermore, determining the CoF_i values used in asset management is also needed. In the power system, each equipment failure causes a certain amount of CoF_i. It depends on the location of the equipment in the substation and the redundancy of paths between demand and supply. If load curtailment after equipment failure does not occur, the CoR_i is still present. The total CoF_i value for a specific time period depends on the number of equipment failures. Nevertheless, the exact equipment with that potential failure can be difficult to determine, especially if the their exact condition data is absent and the PoF_i is estimated.

For example, the equipment group S consists of 100 pieces of equipment. If the $P\bar{o}F_i$ is 0.01, then one equipment out of 100 could fail within a year. Therefore, it is relatively complicated to estimate potentially failed equipment without having its actual condition data. The total CoF_i, and subsequently, the $CoMM(T)$ could vary significantly depending on the location of those pieces of equipment. Thus, in the presence of limited condition data for a larger equipment group, their highest CoF_i values need to be considered in asset management cost evaluation. The likelihood of having a combined failure of two pieces of equipment in the group S in the same year is 0.001, which is relatively small value meaning a low occurrence probability of two simultaneous failures.

If the $P\bar{o}F_i$ value decreases to 0.001, representing unused equipment, the amount of potential equipment failures in a year can only be above 0 in larger equipment groups. Understandably, if the $P\bar{o}F_i$ increases, the number of failures also increases. For example, the $P\bar{o}F_i$ value 0.1 raises potential equipment failures to 10 in a year for the same group S. This probability is relatively high indicating significant deterioration of the equipment. Therefore, the likelihood of having two simultaneous equipment failures in the same group is 0.01, theoretically meaning that one failure out of 10 potential equipment failures could be a combined failure with another piece of equipment. Still, the actual equipment in that combination could be unknown. The $P\bar{o}F_i$ value 0.5 indicates very high failure probability. This equipment should be replaced very quickly in the case of higher risk. Also, the amount of failures in a year increases, if the amount of equipment in group S increases and the $P\bar{o}F_i$ remains the same. Similarly, the probability of having simultaneous equipment failures also increases.

Subsequently, the difference between a single failure or combined failure event changes the CoF_i values. This is mainly caused by the disconnection of multiple paths increasing the $CoLC_i$. Usually, the $CoLC_i$ in N-2 contingencies is higher, but its likelihood is also lower. Therefore, it may more relevant to consider it in asset management cost evaluation when PoF_i values are higher and the probability of having combined failure events increases. In the case of lower PoF_i, the CoF_i can be assumed based on N-1 contingencies. Based on the risk calculations described in Chapter 2, use of the $CoLC_{i(N-1)}$ or $CoLC_{ij(N-2)}$ depends on the ratio between them and also between the PoF of a single or combined failure event.

For example, the $CoLC_{i(N-1)}$ is 10 MW and the $CoLC_{ij(N-2)}$ is 100 MW. Therefore, to consider the $CoLC_i ij(N-2)$ in risk calculations, the ratio between the PoF values in the N-1 and N-2 contingencies needs to be over 10. This means, if the PoF_i value is 0.1, then the PoF_j value is higher than 0.1 in a combined failure event. If the difference between the $CoLC_{i(N-1)}$ and the $CoLC_{ij(N-2)}$ increases, the ratio between the PoF_i values in single and combined failure events needs to increase as well. Therefore, in the case of a significantly higher $CoLC_{i(N-1)}$ value compared to the $CoLC_{ij(N-2)}$ value, the CoF_i in N-2 contingencies is used, if the failure event includes equipment with a higher PoF_i value.

In the presence of condition data uncertainty, the PoF_i for equipment group S is estimated. If the awareness of actual equipment condition is limited for the majority of equipment in substations or the power system, implementing the CoF_i in the N-1 contingency instead of N-2 contingencies needs to be justified. Foremost, it depends on the individual equipment PoF_i and the amount of equipment in the power system with the potentially higher PoF_i values. If the exact condition state of most equipment is unknown, then the CoF_i in N-1 contingencies should be initially avoided. Afterwards, the prevention of CoF_i in N-2 contingencies is analyzed.

3.4.3 The Process of Estimating Asset Management Cost

A dedicated process is proposed in order to estimate the cost of different asset management methods in the case of condition data uncertainty. Its results can be used in management decision-making to determine the amount of equipment included in the CBM as part of the RBM. The principle of the estimated process is illustrated in Fig. 32. It is assumed that in time period T, the $CoMM$ can be expressed by their mean value. If an accurate PoF_i is unknown, this principle makes it possible to assess the costs of different management methods based on their cost components. In the next time periods $T+1$ and $T+2$, the mean value of $CoMM$ is expected to increase due to the potential degradation of equipment condition.

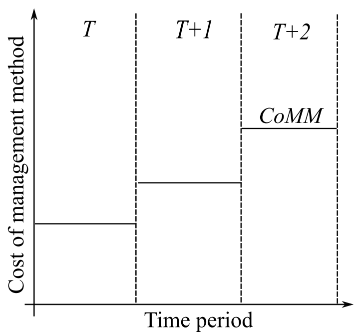

Figure 32: Principle of proposed method for evaluating the cost of asset management [105]

The cost components of different management methods is described in Chapter 1. For asset management cost evaluation, the cost of management methods is compared to determine the potentially achievable decrease in total management costs through optimization. It is assumed that within the major equipment types, the TBM is commonly used. Therefore, it is necessary to compare it to other management methods. These are the CBM, RBM, and the Run-to-Failure approach. The latter, though, can be discarded when increasing overall power system reliability. In the case of the CBM, equipment failures can likely be prevented using real-time or relatively frequent condition monitoring. Therefore, the $CoCBM$ calculation for a time period T does not include the CoF_i component. On the other hand, the CoF_i is present in the $CoTBM(T)$ and $CoRBM(T)$.

It is also assumed that in a time period T, a certain number of failures occur. If the PoF_i in group C are relatively similar, then the CoF is the main component determining their priority. In the case of lower failure probability, only a few failures could occur in equipment group C. In addition, the exact equipment i from group C that will fail is unknown.

Therefore, the $CoTBM(T)$ is expressed by (62). It uses the mean value of all CoF_i values in the group C. The parameter z is used for the threshold value, simulating the increase in failure probability and its rate. In the initial time period, its value can be 1.

$$CoTBM(T) = \sum_{i=1}^{n}(CoI_i + CoMA_i) + \frac{\sum_{i=1}^{n} CoF_i}{n} \cdot z \tag{62}$$

In accordance with (62), the $CoRBM(T)$ is expressed by (63). The k represents the equipment that has been prioritized, the m represents the equipment that has not been prioritized, and the n represents all the equipment in the group C. After prioritization, the equipment is removed from m and included in k. Thus, the respective cost components of prioritized equipment i change. This mean the CoI_i and CoR_i are replaced by the $CoMS_i$.

$$\begin{aligned} CoRBM(T) = \sum_{i=1}^{k}(CoMS_i + CoMA_i) + \sum_{i=1}^{m}(CoI_i + CoMA_i) + \frac{\sum_{i=1}^{n} CoF_i}{n} \cdot z - \\ - \frac{\sum_{i=1}^{n} CoF_i}{n} \cdot \left(1 - \frac{\sum_{i=1}^{n} CoF_i}{n} \cdot \frac{1}{CoF_{ImCoF_{c=1}} - CoF_{ImCoF_c}}\right) \end{aligned} \tag{63}$$

In (63), the CoF is included separately for all of the equipment in k and m, indicated by n. This is due to the use of the mean value of all CoF_i values in group C. The threshold z is used to describe increased probability caused by equipment degradation. For simulating the impact of prioritization on the $CoRBM(T)$, the mean value of CoF is multiplied by the ratio between the mean value of CoF and the difference between the maximum CoF_i and the CoF_i of equipment prioritized (included in k). Because of the iterative process of prioritization, the equipment is added to k after each iteration c. Therefore, at the end of the iteration the potential CoF value decrease. This makes it possible to avoid failure consequences and increase overall reliability as well. The prioritized equipment i is determined based on the highest value of $imCoF_i$ expressed by (64). After prioritization, the $imCoF_i$ and CoF_i values used in iteration c are removed from the selection in decreasing order.

$$ImCoF_i = \frac{CoF_i}{\sum_{i=1}^{n} CoF_i} \cdot n \tag{64}$$

The asset management cost estimation is based on an iterative process that includes multiple stages. In the initial stage, the $CoTBM(T)$ and $CoCBM(T)$ are acquired. In the second stage, the amount of prioritized equipment k in RBM is obtained. It is assumed that the cost of RBM ($CoRBM$) should be lower than the cost of TBM and CBM over time period T. For this, it is necessary to compare the $CoTBM(T)$ and $CoCBM(T)$. If the $CoCBM(T)$ is lower than $CoTBM(T)$, then k can be equal to n. Subsequently, it is more cost-efficient to include all of the equipment in group C in the CBM. If the $CoCBM(T)$ is higher than the $CoTBM(T)$, the value of k needs to be smaller.

The iterative process is shown in Figure 33. In methodology, the value of k is increased by 1 in each iteration c. During iteration c, the $CoTBM(T)$ is compared to $CoRBM(T)$. If the $CoRBM(T)$ is lower than $CoTBM(T)$, the next iteration begins. The iterative process stops when the $CoRBM$ is higher than the $CoTBM$. The previous iteration determines the value of k. The process also stops when all of the equipment in group C is added to k (included in the CBM).

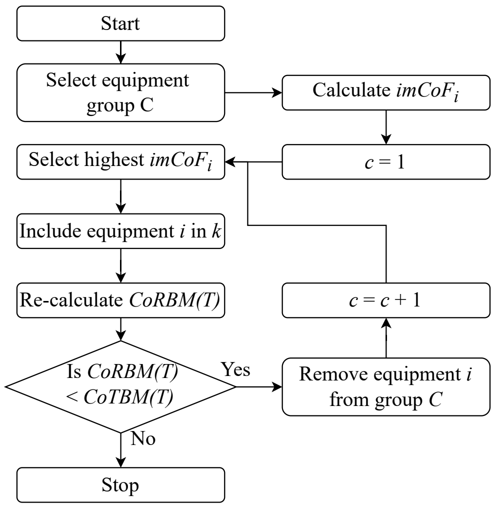

Figure 33: Iterative process for evaluating the cost of asset management [105]

In order to simulate the degradation of equipment during sequential time periods (from T to Tn) and its impact on the cost of asset management ($CoMM$), the threshold value z in (62) and (63) can be increased. The threshold z in the initial time period T is set to 1. In the next time period $T+1$, the z value is increased. A similar pattern is used in $T+2$ until Tn. As a result, it is possible to evaluate the change in the cost of asset management over a longer time period.

For each following time period, separate iterative process needs to be used. Its principles are the same as in the initial time period T. The pieces of equipment already included in k during previous time periods are skipped in the iterative process.

3.5 Case Study

3.5.1 Failure Risk Estimation

Results in this case study are based on publication II. Initially, the IEEE 39-bus power system, given in Fig.22 in Chapter 2, is modeled in PSS/E for contingency analysis. This makes it possible to obtain the LC and the CoF_i values. The risk calculation process is implemented in Python and described in 2.

The analyzed pieces of equipment are instrument transformers indicated as group S. Based on the assumption, a current and voltage transformer is located in each substation bay and voltage transformers are also connected to substation section busbars. This means that there are 320 units in group S. The assumed size of group K is 32, and subsequently, the size of group M is 288. The unknown HI_i values in M are estimated based on the HI_i values in K. Afterwards, the fictive condition inspections, such as measuring partial discharges, dielectric losses and moisture in electrical insulation, magnetization characteristics, saturation behavior, transformation ratio and its accuracy, polarity, load, winding resistance, and withstand voltage, are implemented to detect equipment in M with HI_i values 4 and 5. The difference between the total cost of inspecting the equipment's condition with or without using a predetermined sequence indicates the efficiency of the proposed process. In the three cases considered, the CoI_i compared to the CoR_i is 5% in Case A, 2.5% in Case B, and 0.5% in Case C. The CoR_i is assumed to be 20 k€.

The results of the proposed failure risk estimation and use of the condition inspection sequence are presented in the following. Initially, the best fit distribution function is obtained based on the HI_i values of group K, indicated in Fig. 34. Next, the distribution with the lowest SSE is selected to calculate the PoF_i mean value of equipment in the group M using the Monte Carlo simulation. This is necessary for calculating the failure risk (RoF_i) and estimating the HI_i values for equipment in M.

In Table 1, the PoF_i mean value and confidence intervals for 95 % are presented in accordance to Z-distribution and bootstrap methods. The estimated RoF_i values are shown in Fig. 35 for the whole group S. The majority of the equipment has a RoF_i of around 250, indicating relatively similar maximum LC values in N-2 contingencies. Nevertheless, some equipment in group S have higher RoF_i values due to potentially higher CoF_i.

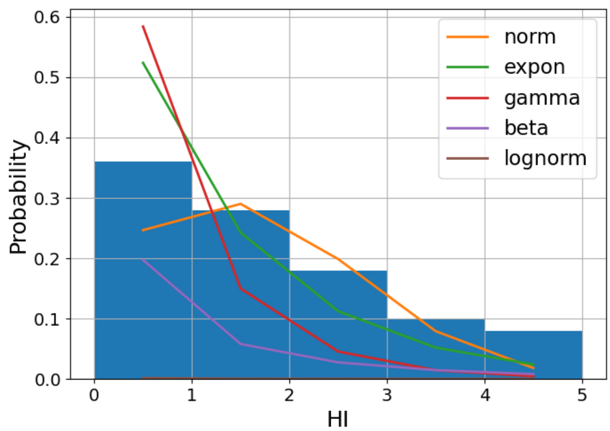

Figure 34: Proportional distribution of known HI values of equipment group K and fitted likelihood functions [106]

Table 2 presents the estimated HI_i values for group M. In accordance to the $\sum_{i=1}^{p}(HI_i = 4,5)$, potentially 12 out of 288 instrument transformers in the group M could fail in the upcoming time-frame and 23 additional pieces of equipment could fail over a longer time-frame. Thus, their CoF_i needs to be minimized and for that, the proposed process is an efficient option. The risk values in Fig. 35 can be used to determine potential order of equipment condition inspections. On the other hand, assuming that the failures do not occur in the same time-frame, the CoF_i in N-1 contingencies are used instead. Overall, when the majority of equipment PoF_i is estimated and the RoF_i calculations are based on its mean value, the CoF_i in N-1 contingencies follow the same pattern as the RoF_i in N-1 contingencies.

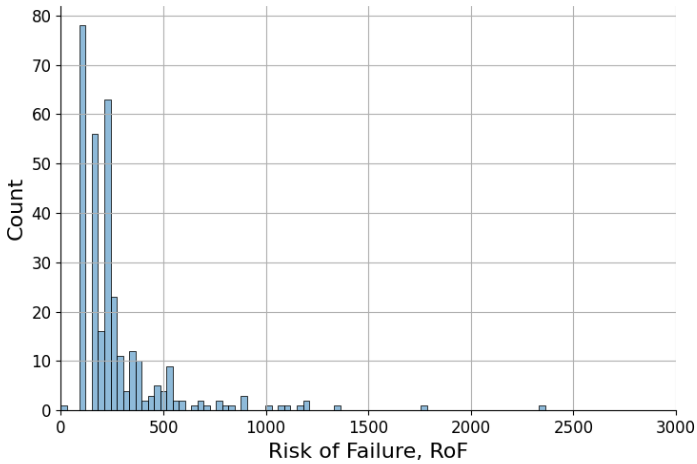

Figure 35: Amount of equipment related to RoF_i values in group S after condition estimation [106]

Table 1: Sum of squared error (SSE) values based fitting distribution functions to HI_i values in K

	Mean	CI(Z-value)	CI(Bootstrap)
PoF_i	0,285	[0,268 0, 302]	[0,260 0,304]

Fig. 36 shows the difference between the total inspection cost ($\sum_{i=1}^{m} CoI_i$) needed to inspect equipment condition in M and the highest CoF_i avoided in each iteration (amount of equipment inspected). As shown, equipment with the highest CoF_i is chosen iteration-wise, which decreases the maximum equipment CoF_i in the following iterations. At iteration 44 (number of inspections done), the remaining $\sum_{i=1}^{m} CoI_i$ exceeds the potentially avoided CoF_i, indicating the lower cost-efficiency of inspecting the remaining equipment (244 in this case). Therefore, the initial $\sum_{i=1}^{m} CoI_i$ is reduced from 288 k€ (randomly inspecting all equipment) to 44 k€. In addition, implementing this process makes it possible to gather the condition data of equipment with higher CoF_i. The difference between Cases A, B, and C has a significant impact to the asset management costs after iteration 44. Nevertheless, the significance of avoiding the CoF_i before iteration 44 weighs over the change in the CoI_i. After iteration 44, the change in the CoI_i, especially in Case C, decreases the remaining $\sum_{i=1}^{m} CoI_i$. Thus, it can be more justified to inspect the condition of the remaining equipment in group M.

If multiple failure events occur within a relatively short time-frame, the related CoF_i can be considerably higher. However, without knowing the exact equipment that will fail, it is similarly quite complicated to take preventive measures. Still, multiple equipment failures could increase the total CoF_i, which changes the difference with the $\sum_{i=1}^{m} CoI_i$. As a result, inspecting the condition of all equipment in M from a cost perspective can be more justified. On the other hand, the proposed process yields higher cost-efficiency in the case of fewer failure events in a longer time-frame, such as 10 years.

Table 2: The number of estimated HI_i values for the equipment in M

	HI = 1	HI = 2	HI = 3	HI = 4	HI = 5
Total	117	81	55	23	12

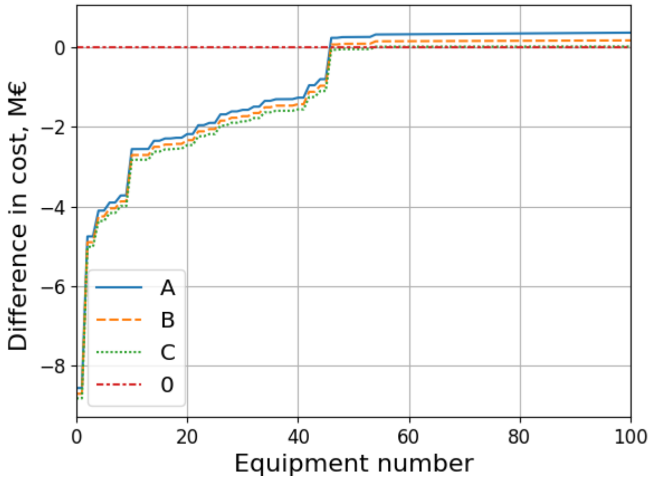

Figure 36: Difference in the summarized inspection cost and the potentially avoided failure cost at the inspection for each iteration (equipment number). Line 0 indicates threshold, when the cost of inspecting the remaining elements becomes higher then the cost of avoided equipment failure. Lines A, B, and C indicates corresponding cases [106]

3.5.2 Cost-Efficient Risk Reduction

The results this case study are based on publication III. They are obtained using a power system with three substations, shown in Fig. 37, where the TS denotes the transmission system side, and the DS denotes the distribution system side. The generation units are connected to substation S1 and a combined load of 30 MW is connected to substations S2 and S3. The power transformers are rated 50 MVA (S1), 16 MVA (S2) and 25 MVA (S3).

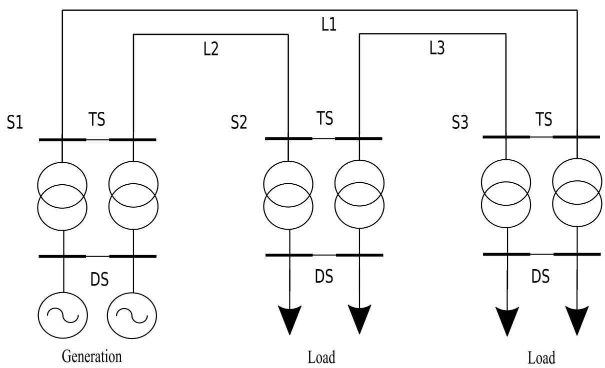

Figure 37: Principle schematic of a transmission system used in the case study

Table 3 indicates the LC values after the disconnection of substation connections represented by transmission lines. The $MTTR$ values are assumed to be 24 hours for PT and 8 hours for other equipment. The disconnection time of substation bays by disconnectors after failure is 2 hours. The included equipment in the calculation process are indicated in 2 with a description of the substation schematics.

Table 3: Potential Curtailment of Loads

Disconnected element	Overloaded element	Load curtailment, MW
L1	L2	7.25
L2	L1	8.7
PT(E3) (S2)	PT(E4) (S2)	9.75
PT(E4) (S2)	PT(E3) (S2)	9.75
L1 + (PT(E3 or E4) (S2))	L2 + (PT(E3 or E4) (S2))	9.75
L2 + (PT(E3 or E4) (S2))	L1 + (PT(E3 or E4) (S2))	10.2
S1 or (S2 and S3)		60
S2 and S3		30
S3 and (PT(E3 or E4) (S2))		39.75

The assumed CoR_i is: C - 30 k€, D - 10 k€, B - 5 k€, VT - 20 k€, CT - 20 k€, CA - 10 k€, ES - 2 k€, SA - 1 k€, IS - 1 k€, PT - (16 MVA) 200 k€, (25 MVA) 300 k€, (50 MVA) 500 k€. The $CoCBM_i$ is taken as 0.25% of the CoR_i. The PoF_i values are generated randomly in each of the 1000 simulations by uniform distribution between 0.1 and 0.5 (assuming older equipment) in order to simulate the differences in equipment conditions. In method A, the failure probability of equipment (PoF_i) is reduced to 0.01 as a result of using the CBM. In method B, the $MTTR_i$ is reduced by 3 hours as a result of arranging a spare unit in the substation. Based on this assumption, the $MTTR_i$ reduction affects equipment in substations S1, S2 and S3 as a cluster. The $(CAPEX_{lim}(T))$ is set to 100 k€. The two cases are analyzed to determine the efficiency of using preventive or corrective management approaches in a combined sequence. In Case 1, the proposed failure risk reduction process including method A and B is used. In Case 2, the failure risk is reduced by the common method - applying the CBM in accordance with the highest ΔRoF_i in each iteration. All the equipment types mentioned in Chapter 2, besides B and PT, are included in the simulation.

The efficiency of risk reduction ($EoRR$) based on Case 1 (indicated in black) and Case 2 (indicated in red) is presented in Fig. 38. It can be concluded, that the proposed RoF_i reduction process (Case 1) has higher $EoRR$ values compared to Case 2. The difference in Case 1 and Case 2 is especially large within the initial 10 iterations. Also, the variability of $EoRR$ from its mean value in Case 2 is also bigger, indicating its inefficiency from a cost perspective.

The inefficiency of failure risk reduction in Case 2 is caused by the related costs ($CoRR$ not being considered. This means, the higher decrease in the RoF_i could also be based on the higher $CoRR$. Subsequently, a smaller amount of equipment is included in the failure risk reduction resulting in overall lower reliability. Instead, the efficiency of failure risk reduction needs to be maximized. The proposed process in Case 1 includes the $CoRR$ being able to achieve a higher $EoRR$ within the same limited funds. In addition, this reduces the failure risk of a higher amount of equipment.

The cost of risk reduction ($CoRR$) based on the Case 1 (indicated in black) and Case 2 (indicated in red) is shown in Fig. 39. Similarly, the proposed risk reduction process (Case 1) has lower $CoRR$ values compared to Case 2. This pattern is seen throughout the iterations. In addition, the variability of $CoRR$ is also larger in Case 2. This indicates that

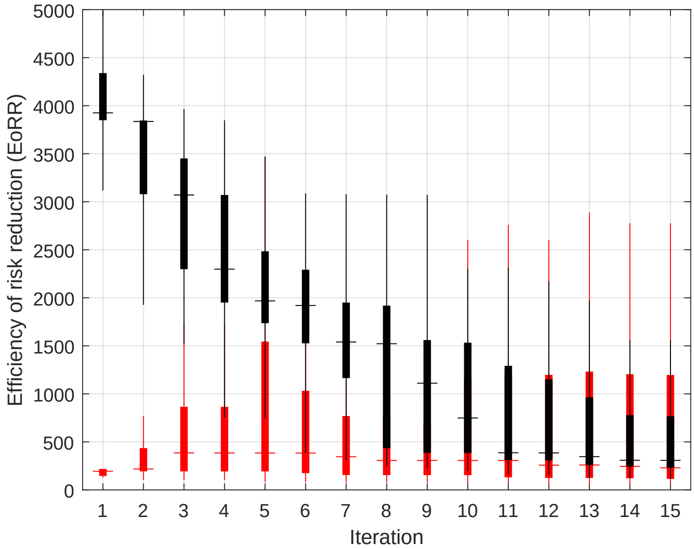

Figure 38: The efficiency of risk reduction ($EoRR$) based on the Case 1 (indicated in black) and Case 2 (indicated in red) [104]

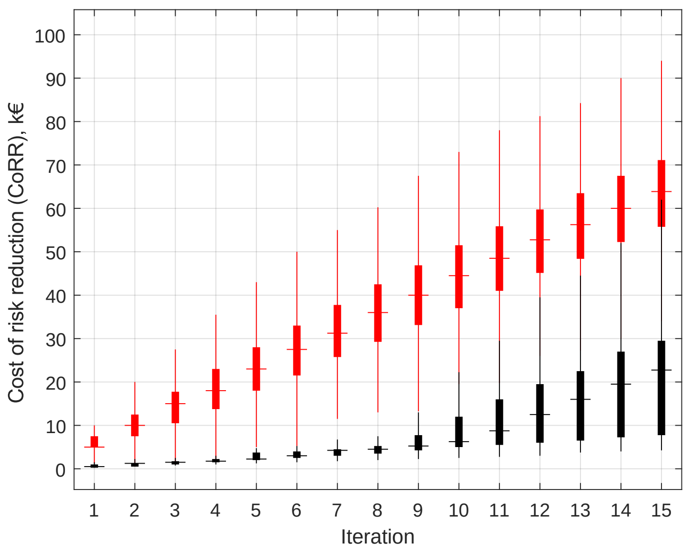

Figure 39: The cumulative cost of risk reduction ($CoRR$) based on the Case 1 (indicated in black) and Case 2 (indicated in red) [104]

choosing the equipment based on the ΔRoF_i results with a lower $EoRR$.

Furthermore, the spread of cumulative cost of risk reduction in iterations 1 to 4 is relatively small. This means that decreasing the RoF_i of certain types of equipment is more cost-efficient. This is foremost related to the difference between the $CoCBM_i$, the CoR_i, the N_D and the N_S. As a result, it is possible to increase the $EoRR$ by arranging spare equipment for a similar type of equipment group instead of decreasing the single equipment PoF_i within the same funds.

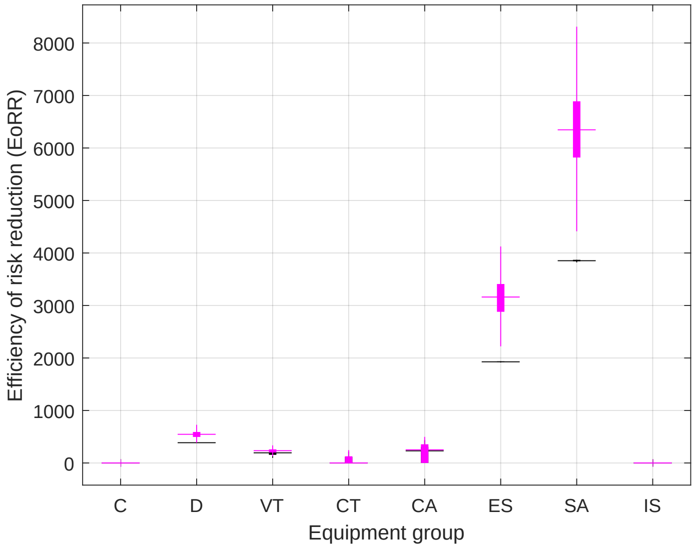

Figure 40: The efficiency of risk reduction ($EoRR$), when method B is chosen instead of method A, for each equipment group used. The $EoRR(A)$ is indicated in black and the $EoRR(B)$ is indicated in magenta [104]

Fig. 40 shows the efficiency of risk reduction ($EoRR$), when method B is preferred over method A. The $EoRR(A)_i$ is indicated in black and the $EoRR(B)_k$ is in magenta. Based on the results, the $EoRR(B)_k$ values are higher than the $EoRR(A)_i$ values with specific equipment groups (D, VT, CA, ES, SA). Therefore, implementing method B for these equipment groups achieves higher risk reduction cost-efficiency ($EoRR$) than method A. The latter means using condition monitoring solutions as a part of the CBM. Equipment groups ES and SA have the highest $EoRR$ values, due to the number of equipment in the substation schematic used. In addition, the $CoCBM_i$ and the CoR_i have a high impact on the $EoRR$ value as well. Subsequently, the difference in the input values of risk reduction process determines the decision to arrange for spare equipment instead of using condition monitoring or inspections.

The results of the proposed process are case dependent, though. This means it can suggest a different failure risk reduction sequence based on the corresponding power system structure. Nevertheless, it has higher failure risk reduction cost-efficiency compared to distributing available funds based on the highest ΔRoF_i. Moreover, the proposed process is useful for assessing the use of preventive or corrective asset management approaches from a cost and reliability perspective.

3.5.3 Asset Management Cost Estimation

The results in this case study are based on publication IV, and use the same power system in Fig. 37. In order to estimate asset management costs over a longer time period, three cases are analyzed. These are Case A - power system lines and transformers could overload after failures in the substations; Case B - similar to Case A, but with a 3 times higher ($CoLC_i$); and Case C - similar to Case A, but with a 3 times lower ($CoLC_i$). The LC values are similarly indicated in Table 3. The $MTTR_i$ values are assumed to be 24 hours for PT and 8 hours for other equipment. The disconnection period of substation connections by disconnectors after failure is 2 hours. The equipment included in group C is circuit breakers. The $CoMS_i$ as a part of the CBM is assumed to be 15 k€ and the CoI_i as part of the TBM is assumed to be 2.5 k€. The $CENS$ is assumed to be 1 k€/MWh. Three time periods (T, $T+1$ and $T+2$) are used for simulating change in the cost of asset management methods ($CoMM$). In the initial time period T, the threshold z is set to 1. It is increased to 1.25 in $T+1$ and to 1.5 in $T+2$.

An example of the results based on Case A is presented in Fig. 41 and Fig. 42. The modeled time periods include the following x-axis values: T - 1...10; $T+1$ - 11...20; $T+2$ - 21...30. In each time period, the threshold value z multiplied by the mean of the total CoF_i is increased. This makes it possible to simulate the change in the failure probability. Also, the inspection of equipment condition is used in each time period, which has an impact on the $CoTBM$. In time period $T+2$, the replacement of measurement solutions is carried out increasing the $CoCBM$.

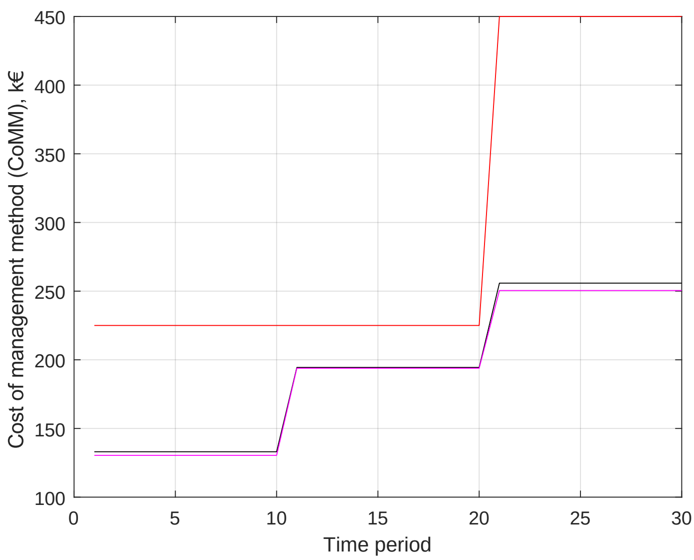

Figure 41: Cumulative cost of management method ($CoMM$ in Case A: black - TBM; red - CBM; magenta - RBM) [105]

According to Fig. 41, the $CoCBM$ in the initial time period is higher than the $CoTBM$. This indicates that using the CBM with all equipment in the group C increases the total $CoMM$. Therefore, an extensive and more frequent preventive management method is inefficient from a cost perspective. Thus, only a certain amount of equipment needs to be included in the CBM. This means that the remaining ones are left in the TBM or considered alternatively using the corrective approach. In order to achieve overall lower management costs and increase the power system's reliability, the RBM is preferred. The obtained results indicate that the proposed process makes it possible to keep the $CoRBM$ below the $CoTBM$ by prioritizing equipment with a higher CoF_i. Subsequently, the selected equipment is included in the CBM in each time period. Out of 15 pieces of equipment in the group C, 2 are prioritized in T, 6 are prioritized in $T+1$ and 3 are prioritized in $T+2$. This means that higher cost-efficiency of asset management is achieved by gradually increasing the number of equipment in a preventive approach.

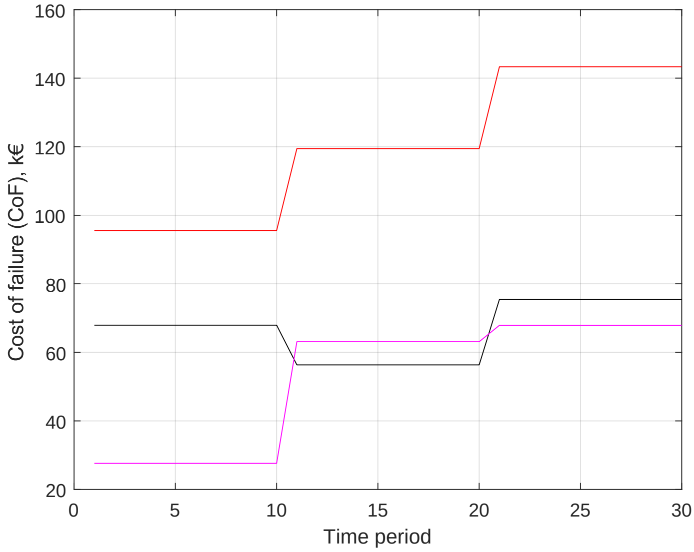

Figure 42: Cost of failure (CoF in Case A: black - RBM; red - TBM; magenta - difference between TBM and RBM) [105]

The total related CoF of using the TBM, the RBM, and their difference is depicted in Fig. 42. This indicates that the total CoF in the case of RBM increases noticeably less compared to the TBM. Furthermore, the proposed process maintains the total CoF in the case of RBM at a similar level by iteratively prioritizing pieces of equipment with a higher CoF and including them in the CBM. As a result, the difference between the total CoF in the case of the TBM and the RBM increases.

In a longer perspective, the $CoTBM$ in $T+2$ becomes higher than the $CoCBM$ in $T+1$. This means that without replacing the measurement solutions in $T+2$, the $CoCBM$ is lower than the $CoTBM$. Therefore, all equipment can be included in the CBM at the end of $T+1$. This may be enough to justify the initial inclusion of all equipment in group C in the CBM. There is a noticeable cost related to it, but on the other hand, it could potentially prevent all failures. Nevertheless, in the case of limited funds, initial inclusion of all equipment in the CBM is restricted.

Conclusions and Future Work

Conclusions

Power networks are crucial for linking electricity demand and supply. Maintaining their functionality depends on asset management decision-making procedures used by power system operators. These procedures include multiple factors related to power system equipment, such as equipment condition data and the cost of potential failure consequences. Based on the equipment condition and the topology of the power system, different management decisions are taken. Their main difference whether they use a preventive or corrective approach. If implementing a preventive approach, equipment condition inspections or real-time condition monitoring solutions are used to avoid equipment failures. If using a corrective approach instead, equipment is replaced or repaired after failure. Subsequently, these have an impact on the overall cost of the asset management method, making one of them more cost-efficient than the others.

Thus, an important part of modern day asset management is to improve decision-making. This requires increasing management cost-efficiency and the power system's reliability. In order to achieve that, it is necessary to overcome various challenges related to asset management. The first challenge is to tackle aging substations. Equipment condition can be still relatively good even after reaching its life expectancy. This means that there is no need for replacement and it is possible to maximize equipment usage. On the other hand, some pieces of equipment may degrade before reaching life expectancy. Therefore, it is necessary to determine the condition of each individual piece of equipment separately and relatively frequently. This increases asset management costs, which power system operators are trying to avoid.

The second challenge is partially related to the previous one and requires an awareness of equipment condition. Related data can be used to calculate equipment failure risk and assess its importance in the power system. Based on this, it is possible to justify the preventive replacement of equipment before reaching life expectancy or maximize its use and implement corrective replacement instead. Due to the various types of equipment in a substation and their potentially similar impacts on the power system reliability, each individual failure risk needs to be determined. This makes it possible to gain general overview of failure risk levels throughout the substations and in the power system.

The third challenge is related to different asset management methods and their associated costs. After obtaining an overview of equipment with higher failure risk values, it is necessary to prevent and avoid potential failures. Otherwise, the cost of equipment failures can increase the overall cost of asset management significantly. However, preventive measures like measurement solutions and condition inspections have their own specific costs, limiting their extensive implementation. Thus, it is necessary to assess the cost components of different asset management methods to determine an optimal and cost-efficient distribution of equipment between them.

The fourth challenge is to obtain sufficient data on equipment condition. This is necessary in order to determine equipment condition and failure risk. For some equipment types, statistical data is available, but there may also be equipment types that have limited or even absent condition data available. In this case, an estimation of their condition is necessary. This makes it possible to evaluate the amount of equipment in the power system with potentially higher degradation levels. In addition, it is possible to obtain their failure risk in the case of data uncertainty. This data is used when choosing the appropriate methods for avoiding potential equipment failures and optimizing asset management.

After determining the failure risk of equipment and the cost components of asset management, the fifth challenge is related to choosing cost-efficient methods to decrease equipment failure risk. Without this, more resources are used to reduce the failure risk of less equipment. In addition, the costs related to it are distributed between equipment inefficiently. The optimal risk reduction method also depends on the equipment's location in the substation and its type. For some equipment, a preventive approach is more justified, and for others, a corrective approach is preferred. Subsequently, this has an impact on asset management costs and the distribution of equipment between management methods.

This thesis focuses on all of the aforementioned challenges and proposes solutions to them. Due to similar aspects between these challenges, it is possible to solve some of them within the same method. In addition, certain challenges require overcoming other ones to achieve the required input parameters or initial conditions. Therefore, in order to determine the justified approach to increase asset management efficiency from a cost and reliability perspective, it is necessary to overcome all of them. However, some of these challenges are relatively complex to provide complete answers to, and therefore, the solutions proposed in this thesis need to be improved further in future research.

One of the main tasks of the thesis is to provide a solution related to determining individual equipment failure risk. For this purpose, a hybrid calculation method of maximum failure risk was developed, which includes each piece of equipment and all the equipment types on the substation's primary side. In the method, the N-1 contingency is the failure of a single piece of equipment and the N-2 contingency is the combined failure event of two pieces of equipment. This makes it possible to obtain a full overview of equipment failure risk levels throughout the substation from the perspective of an individual piece of equipment. As a result, it is possible to determine which equipment's failure would result in a higher impact on the power system's functionality.

The results of the case study in Chapter 2 proved by addressing the **RQ1**, that it is possible to calculate the risk of failure for each individual equipment on the substation primary side. In the developed risk calculation process, all common substation equipment types were included. Therefore, their maximum RoF value based on a single and multiple combined failure events can be obtained and mapped all over the power system. In addition, it is possible to analyze the change in risk of failure based on the location of equipment in the power system, the configuration of substation, and the number of equipment included in the failure event (N-1 or N-2 contingencies). It also proved that it is possible to differentiate various types of equipment, including the "low-cost" ones, in the risk calculations. In addition, these units with higher RoF can be detected from a larger group of similar equipment. Therefore, confirming the **RQ1** subsequently means that the hypothesis **Hs1** is valid. If only focusing on the "bigger" and more expensive equipment, the "smaller" and less expensive equipment with higher RoF can remain undetected. As a result, the perspective of overall risk analysis is extended.

In order to obtain the failure risk values of equipment in the case of condition data uncertainty, a method incorporating the available condition data and estimation approaches of unknown condition data is used. It is assumed that the distribution of the equipment's Health Index values based on the available condition data represent the overall Health Index distribution of the whole group of similar equipment types. Thus, using a likelihood function and numerical simulations, an estimated condition state of the equipment is determined. This is implemented in equipment failure risk calculations. As a result, the importance of equipment with unknown condition data in the power system can be evaluated.

For choosing the failure risk reduction method of an individual piece of substation equipment from an asset management cost perspective, a process of determining an equipment inspection sequence is proposed. It considers the cost of equipment failure and inspection as part of the preventive and corrective asset management approaches. Based on the potential cost of equipment failure, their priority in the power system is obtained. Next, the total cost of equipment condition inspections is compared to the potential maximum cost of equipment failure. In the iterative inclusion of equipment in preventive asset management, the potential maximum cost of equipment failure is reduced sequentially. At a specific threshold, the total cost of equipment inspection exceeds the potential maximum cost of equipment failure. This marks one of the decision factors of choosing corrective asset management instead of a preventive approach.

The case study results in Chapter 3 indicated by addressing the **RQ2** that it is possible to estimate the equipment risk of failure if having limited data about their condition. It can be considered enough to detect the equipment with higher RoF_i from the overall group. Thereon, additional asset management activities are used in order to increase the awareness about the condition of that equipment. The case study results also confirmed by addressing **RQ4** that it is possible to increase the asset management cost-efficiency if having limited data of equipment condition. Using dedicated procedures enables to focus on equipment with higher RoF_i and implement preventive measures despite restricted information. On the other hand, equipment with lower risk of failure values can be included in the corrective management approach. This optimization of management methods subsequently decreases the related cost. Therefore, the hypothesis **Hs2** is valid from that perspective.

To overcome the challenges associated with the reduction of equipment failure risk, a failure risk reduction method is proposed that incorporates both preventive and corrective asset management approaches and determines the justified option. The proposed method also considers the cost of decreasing failure risk and the achievable decrease in failure risk. Based on these parameters, the efficiency of failure risk reduction is determined. The risk reduction method includes two options that decrease either the failure risk of individual pieces of equipment or the failure risk of equipment types in the substation. Therefore, it makes it possible to justify using either preventive or corrective asset management.

Addressing the **RQ3**, the case study results in Chapter 3 indicate that it is possible to determine a cost-efficient risk reduction process (sequence) to distribute equipment between preventive and corrective asset management, including all substation equipment on the primary side. Using the efficiency of risk reduction as an indicator enables to achieve a more cost-efficient decrease in equipment RoF_i. The dedicated procedure also includes all common equipment types in the substation, making it possible to decrease the risk all over the substation. Thus, the "smaller" and less expensive equipment besides the "bigger" and more expensive ones are additionally considered in that process. Thereon, all equipment can be distributed between preventive and corrective asset management methods more cost-efficiently. This means that the hypothesis **Hs3** is valid in that regard.

Therefore, each of the developed and proposed approaches and processes also corresponds to the specific research question of the thesis, and as a result, confirms the related hypothesis. Combining the proposed methods makes it possible to evaluate the change in the currently implemented asset management strategy if preventive or corrective failure risk reduction were implemented on various pieces of equipment. In addition, the cost of different asset management approaches is determined. This makes it possible to compare these approaches in order to determine an optimal distribution of equipment between them. It also allows one to analyze the amount of equipment included in a specific management method without exceeding the one currently in use.

From the perspective of power system operators, the proposed methods provide options to increase the efficiency of substation asset management. Firstly, a full overview of failure risk values of substation equipment can be obtained. These values also represent the maximum failure risk considering all possible combined failure events of the different pieces of equipment. Secondly, it is possible to estimate the failure risk of equipment if its exact condition state is not known. This makes it possible to analyze the equipment's importance in the power system for further risk-related asset management decisions. Thirdly, the methods can be used to determine a justified distribution of equipment between preventive and corrective asset management approaches. For example, it is possible to evaluate how much equipment should be included in time-based, condition-based, or run-to-failure management. The distribution scale is assessed based on the cost of equipment failure, the cost of equipment condition inspection or monitoring, and the failure probability. When combined, the proposed methods form a risk-based substation equipment asset management methodology.

Future Work

In further research, various additional aspects can be added to the proposed methods. For example, the risk calculation method could include voltage control equipment as well. Nowadays, renewable energy facilities are spreading at a fast pace, creating a need for more extensive voltage control throughout the power grid. In addition, considering the link between equipment on the primary and secondary sides also makes it possible to improve the failure risk calculation process. It is reasonable to combine a failure risk estimation method with various determining approaches of equipment Health Index values. This makes it possible to obtain more exact functions of condition-related data for different equipment types. The availability of condition assessment solutions and their measurement accuracy can also be incorporated in the failure risk reduction method. In addition, considering with the location of the substation in the power system as part of optimal arrangement of spare equipment could increase the failure risk reduction efficiency as well. Moreover, if data on the change of equipment condition over a longer time period is available, the threshold values of equipment distribution between asset management methods can be made more accurate. Overall, the proposed methods are the main pillars of improving asset management decision-making, gathering more equipment related data, and increasing its cost-efficiency.

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References

[1] “Options for the design of european electricity markets in 2030,” *ENTSO-E*, 2021.

[2] “Risk preparedness: Short-term and seasonal adequacy assessments methodology methodology to identify regional electricity crisis scenarios,” *ENTSO-E*, 2019.

[3] “Risk preparedness: Methodology to identify regional electricity crisis scenarios,” *ENTSO-E*, 2019.

[4] “Facing the replacement wave,” *ENTSO-E*, 2015.

[5] “Research, development and innovation roadmap 2020 – 2030,” *ENTSO-E*, 2020.

[6] “ISO 55000:2014, asset management - overview, principles and terminology,” International Organisation for Standardization, Tech. Rep., 2014.

[7] “ISO 55001:2014, asset management. management systems. requirements,” *International Organisation for Standardization*, 2014.

[8] “ISO 55002:2014, asset management. management systems. guidelines for the application of ISO 55001,” *International Organisation for Standardization*, 2014.

[9] “PAS 55:2008-1, specification for the optimised management of physical assets,” *British Standards Institution*, 2008.

[10] “PAS 55:2008-2, guidelines for tha application of PAS 55-1,” *British Standards Institution*, 2008.

[11] S. R. Khuntia, J. L. Rueda, S. Bouwman, and M. A. M. M. van der Meijden, “A literature survey on asset management in electrical power transmission and distribution system,” *International Transactions on Electrical Energy Systems*, vol. 26, no. 10, pp. 2123–2133, feb 2016.

[12] J. Schneider, A. J. Gaul, C. Neumann, J. Hográfer, W. Wellßow, M. Schwan, and A. Schnettler, “Asset management techniques,” *International Journal of Electrical Power & Energy Systems*, vol. 28, no. 9, pp. 643–654, nov 2006.

[13] P. Dehghanian, M. Fotuhi-Firuzabad, F. Aminifar, and R. Billinton, “A comprehensive scheme for reliability centered maintenance in power distribution systems - part i: Methodology,” *IEEE Transactions on Power Delivery*, vol. 28, no. 2, pp. 761–770, apr 2013.

[14] R. Dashti and S. Yousefi, “Reliability based asset assessment in electrical distribution systems,” *Reliability Engineering and System Safety*, vol. 112, pp. 129–136, apr 2013.

[15] L. Belak, R. Marusa, R. Ferlic, and J. Pihler, “Strategic maintenance of 400-kv switching substations,” *IEEE Transactions on Power Delivery*, vol. 28, no. 1, pp. 394–401, Jan 2013.

[16] S. Raghavan and B. Chowdhury, “State diagram-based life cycle management plans for power plant components,” *IEEE Transactions on Smart Grid*, vol. 6, no. 2, pp. 965–972, March 2015.

[17] R. Ross, “Reliability analysis for asset management of electric power grids,” 2019.

[18] L. Bertling, P. Bangalore, and L. A. Tuan, “On the use of reliability test systems: A literature survey,” in *2011 IEEE Power and Energy Society General Meeting*, July 2011, pp. 1–9.

[19] C. J. WallnerströM, P. Hilber, and J. G. Travi, “Implementation and evaluation of commonly used risk analysis methods applied to a regional power distribution system,” in *22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013)*, June 2013, pp. 1–4.

[20] M. Papic, O. A. Ciniglio, and S. K. Agarwal, “Reliability assessment of multiple substations in idaho system using a node-breaker model,” in *2016 IEEE Power and Energy Society General Meeting (PESGM)*, July 2016, pp. 1–5.

[21] L. Cheng, M. Liu, C. Ye, Q. Li, and Q. Zhao, “An extended minimal cut set algorithm applied into overall power system reliability assessment,” in *2014 International Conference on Power System Technology*, Oct 2014, pp. 368–373.

[22] W. Nathasri, N. Keawlumyai, and S. Chaitusaney, “Reliability evaluation of substation bus configurations with consideration of switching device operation and load growth,” in *2015 12th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, June 2015, pp. 1–5.

[23] E. Coster, D. Boender, and B. Staarink, “Evaluation of substation configurations and distribution automation with the aid of reliability calculations,” in *2015 IEEE Eindhoven PowerTech*, June 2015, pp. 1–6.

[24] Z. Dong, D. Koval, and J. Propst, “Reliability of various industrial substations,” *IEEE Transactions on Industry Applications*, vol. 40, no. 4, pp. 989–994, July 2004.

[25] L. Zhenyi and F. Yunxin, “Reliability assessment of 500kv substation based on fault tree analysis,” in *2021 6th International Conference on Power and Renewable Energy (ICPRE)*, Sep. 2021, pp. 227–232.

[26] J. H. Jürgensen, L. Nordström, and P. Hilber, “Individual failure rates for transformers within a population based on diagnostic measures,” *Electric Power Systems Research*, vol. 141, pp. 354–362, Dec. 2016.

[27] N. Mitsuhiro, T. Shigeyuki, N. Masao, and M. Kouji, “Approach to asset management of substation equipment in japan,” in *2020 International Symposium on Electrical Insulating Materials (ISEIM)*, Sep. 2020, pp. 68–71.

[28] Z. Wu, B. Liu, Z. Wang, S. Ma, and G. Ni, “Research on condition-based maintenance approach of power system considering equipment imperfect maintenance model,” in *2017 Chinese Automation Congress (CAC)*, Oct 2017, pp. 3695–3700.

[29] R. D. Medina, D. A. Zaldivar, A. A. Romero, J. Zuñiga, and E. E. Mombello, “A fuzzy inference-based approach for estimating power transformers risk index,” *Electric Power Systems Research*, vol. 209, p. 108004, Aug. 2022.

[30] Y. Suzuki, H. Kojima, N. Hayakawa, F. Endo, and H. Okubo, “Optimization of asset management in high voltage substation based on equipment monitoring and power system operation,” in *2010 IEEE International Symposium on Electrical Insulation*, June 2010, pp. 1–5.

[31] H. Ge, J. Hou, and S. Asgarpoor, "Multiperspective risk analysis for aging asset fleet management," in *2012 IEEE Power and Energy Society General Meeting*, July 2012, pp. 1–6.

[32] S. Natti and M. Kezunovic, "A risk-based decision approach for maintenance scheduling strategies for transmission system equipment," in *Proceedings of the 10th International Conference on Probablistic Methods Applied to Power Systems*, May 2008, pp. 1–6.

[33] X. Xu, F. Dong, L. Huang, and B. P. Lam, "Modeling and simulation of substation-related outages in power flow analysis," in *2010 International Conference on Power System Technology*, Oct 2010, pp. 1–5.

[34] G. C. Montanari, P. Seri, and R. Hebner, "A scheme for the health index and residual life of cables based on measurement and monitoring of diagnostic quantities," in *2018 IEEE Power & Energy Society General Meeting (PESGM)*. IEEE, Aug. 2018.

[35] Y. Li, X. Han, B. Xu, and Y. Wang, "A condition-based maintenance approach to an optimal maintenance strategy considering equipment imperfect maintenance model," in *2015 5th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT)*, Nov 2015, pp. 1466–1471.

[36] M. Vermeer, J. Schuddebeurs, and M. Wetzer, "The application of health- and risk indices as a decision-support tool for utilities," in *Asset Management Conference (AM 2016)*. Institution of Engineering and Technology, 2016.

[37] W. Li and J. Lu, "Risk evaluation of combinative transmission network and substation configurations and its application in substation planning," *IEEE Transactions on Power Systems*, vol. 20, no. 2, pp. 1144–1150, May 2005.

[38] Z. Wang, K. Zhang, H. Li, F. Xiao, Y. Chen, and T. Wang, "Evaluation method of substation weak link based on power grid risk severity indexs," in *2021 IEEE 5th Information Technology,Networking,Electronic and Automation Control Conference (ITNEC)*, vol. 5, Oct 2021, pp. 1109–1115.

[39] S. Fattaheian-Dehkordi, M. Fotuhi-Firuzabad, and R. Ghorani, "Transmission system critical component identification considering full substations configuration and protection systems," *IEEE Transactions on Power Systems*, vol. 33, no. 5, pp. 5365–5373, Sep. 2018.

[40] K. Boakye-Boateng, A. A. Ghorbani, and A. H. Lashkari, "Riskism: A risk assessment tool for substations," in *2021 IEEE 9th International Conference on Smart City and Informatization (iSCI)*, Oct 2021, pp. 23–30.

[41] R. Bulbul, C.-W. Ten, and A. Ginter, "Risk evaluation for hypothesized multiple busbar outages," in *2014 IEEE PES General Meeting*, July 2014, pp. 1–7.

[42] A. Leal and J. F. Botero, "Defining a reliable network topology in software-defined power substations," *IEEE Access*, vol. 7, pp. 14 323–14 339, 2019.

[43] J. Endrenyi and G. Anders, "Aging, maintenance, and reliability - approaches to preserving equipment health and extending equipment life," *IEEE Power and Energy Magazine*, vol. 4, no. 3, pp. 59–67, May 2006.

[44] M. Shahidehpour and R. Ferrero, "Time management for assets: chronological strategies for power system asset management," *IEEE Power and Energy Magazine*, vol. 3, no. 3, pp. 32–38, May 2005.

[45] I. Jeromin, G. Balzer, J. Backes, and R. Huber, "Life cycle cost analysis of transmission and distribution systems," in *2009 IEEE Bucharest PowerTech*, June 2009, pp. 1–6.

[46] S. Laohanan and D. Banjerdpongchai, "Dynamic programming approach to optimal maintenance scheduling of substation equipment considering life cycle cost and reliability," in *2018 15th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, July 2018, pp. 388–391.

[47] C. Trentini, W. de Oliveira Guedes, L. W. de Oliveira, B. H. Dias, and V. H. Ferreira, "Maintenance planning of electric distribution systems - a review," *Journal of Control, Automation and Electrical Systems*, vol. 32, no. 1, pp. 186–202, nov 2020.

[48] H. Mirsaeedi, A. Fereidunian, S. M. Mohammadi-Hosseininejad, and H. Lesani, "Electricity distribution system maintenance budgeting: A reliability-centered approach," *IEEE Transactions on Power Delivery*, vol. 33, no. 4, pp. 1599–1610, aug 2018.

[49] E. Shayesteh and P. Hilber, "Reliability-centered asset management using component reliability importance," in *2016 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*. IEEE, oct 2016.

[50] H. A. Koksal and A. Ozdemir, "Determination of optimal component maintenance process for RCAM of power transmission system using TOPSIS method," in *2016 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*. IEEE, oct 2016.

[51] B. Xu, S. Xu, and Y. Zhang, "Determining optimal inspection rates of power equipment considering opportunistic maintenance strategy," in *2019 IEEE 3rd International Conference on Green Energy and Applications (ICGEA)*, March 2019, pp. 51–55.

[52] N. A. Bakar and A. Abu-Siada, "Fuzzy logic approach for transformer remnant life prediction and asset management decision," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 23, no. 5, pp. 3199–3208, Oct. 2016.

[53] J. Foros and M. Istad, "Health index, risk and remaining lifetime estimation of power transformers," *IEEE Transactions on Power Delivery*, vol. 35, no. 6, pp. 2612–2620, Dec. 2020.

[54] A. Crespo Márquez, J. Serra Parajes, A. de la Fuente Carmona, and A. Sola Rosique, "Integrating complex asset health modelling techniques with continuous time simulation modelling: A practical tool for maintenance and capital investments analysis," *Computers in Industry*, vol. 133, p. 103507, Dec. 2021.

[55] H. Wang, D. Lin, J. Qiu, L. Ao, Z. Du, and B. He, "Research on multiobjective group decision-making in condition-based maintenance for transmission and transformation equipment based on d-s evidence theory," *IEEE Transactions on Smart Grid*, vol. 6, no. 2, pp. 1035–1045, March 2015.

[56] J. Zhong, W. Li, R. Billinton, and J. Yu, "Incorporating a condition monitoring based aging failure model of a circuit breaker in substation reliability assessment," *IEEE Transactions on Power Systems*, vol. 30, no. 6, pp. 3407–3415, Nov 2015.

[57] A. A. Razi-Kazemi and M. Shariatnasab, "A new approach on prioritization of the circuit breakers for installation of online monitoring systems," *IEEE Transactions on Power Delivery*, vol. 34, no. 4, pp. 1569–1577, Aug 2019.

[58] D. Huang and B. Bagen, "System reliability risk model and its application to station breaker replacement," in *2020 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*, Aug 2020, pp. 1–6.

[59] 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. 17, no. 9, pp. 1972–1984, Mar. 2023.

[60] A. P. Shishavan and A. Razi-Kazemi, "A practical knowledge-based ranking approach to identify critical circuit breakers in large power systems," *Knowledge-Based Systems*, vol. 227, p. 107237, sep 2021.

[61] J. H. Jurgensen, L. Nordstrom, P. Hilber, E. Andreasson, and A. L. Brodersson, "Assessment of explanatory variables on the failure rate of circuit breakers using the proportional hazard model," in *2018 Power Systems Computation Conference (PSCC)*. IEEE, jun 2018.

[62] S. R. Khuntia and B. Heling, "Assessment of different health index aggregation techniques for electric utilities," in *2023 IEEE PES GTD International Conference and Exposition (GTD)*. IEEE, May 2023.

[63] A. Underbrink, "Risk analysis in distribution and transmission networks," in *2006 International Conference on Probabilistic Methods Applied to Power Systems*, June 2006, pp. 1–4.

[64] T. M. Welte, "Using state diagrams for modeling maintenance of deteriorating systems," *IEEE Transactions on Power Systems*, vol. 24, no. 1, pp. 58–66, Feb 2009.

[65] H. Ge, S. Asgarpoor, and J. Hou, "Aging equipment maintainability assessment for management of critical utility assets," in *2011 IEEE Power and Energy Society General Meeting*, July 2011, pp. 1–7.

[66] S. Raghavan and B. Chowdhury, "Developing life cycle management plans for power plant components," in *2012 North American Power Symposium (NAPS)*, Sep. 2012, pp. 1–6.

[67] F. Fayaz and G. Pahuja, "Reliability modeling and criticality ranking of power substation," in *2019 3rd International conference on Electronics, Communication and Aerospace Technology (ICECA)*, June 2019, pp. 1141–1145.

[68] A. Purnomoadi, I. M. Sari, J. Anna Maria, D. B. Fiddiansyah, N. E. Saputro, and M. Sofan Hadi, "A method to quantify data quality in asset health indices model," in *2023 4th International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*. IEEE, Aug. 2023.

[69] Y. Fan and D. Zhang, “Reliability evaluation of power systems incorporating maintenance policy with partial information,” in *2016 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*, Oct 2016, pp. 1–5.

[70] R. A. Prasojo, Suwarno, and A. Abu-Siada, “Dealing with data uncertainty for transformer insulation system health index,” *IEEE Access*, vol. 9, pp. 74 703–74 712, 2021.

[71] D. Zhang, Z. Chu, Q. Gui, F. Wu, H. Yang, Y. Ma, and W. Tao, “Transformer maintenance decision based on condition monitoring and fuzzy probability hybrid reliability assessment,” *IET Generation, Transmission & Distribution*, vol. 17, no. 4, pp. 976–992, Dec. 2022.

[72] S. Li, H. Ma, T. Saha, and G. Wu, “Bayesian information fusion for probabilistic health index of power transformer,” *IET Generation, Transmission & Distribution*, vol. 12, no. 2, pp. 279–287, Oct. 2017.

[73] J. Aizpurua, B. Stewart, S. McArthur, B. Lambert, J. Cross, and V. Catterson, “Improved power transformer condition monitoring under uncertainty through soft computing and probabilistic health index,” *Applied Soft Computing*, vol. 85, p. 105530, Dec. 2019.

[74] 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, Jan. 2024.

[75] H. Ge and S. Asgarpoor, “Reliability evaluation of equipment and substations with fuzzy markov processes,” *IEEE Transactions on Power Systems*, vol. 25, no. 3, pp. 1319–1328, Aug 2010.

[76] H. Kim and C. Singh, “Reliability modeling and simulation in power systems with aging characteristics,” *IEEE Transactions on Power Systems*, vol. 25, no. 1, pp. 21–28, Feb 2010.

[77] M. H. Firouz and N. Ghadimi, “Optimal preventive maintenance policy for electric power distribution systems based on the fuzzy AHP methods,” *Complexity*, vol. 21, no. 6, pp. 70–88, mar 2015.

[78] A. Alizadeh, A. Fereidunian, M. Moghimi, and H. Lesani, “Reliability-centered maintenance scheduling considering failure rates uncertainty: A two-stage robust model,” *IEEE Transactions on Power Delivery*, vol. 37, no. 3, pp. 1941–1951, jun 2022.

[79] M. Dong, W. Li, and A. B. Nassif, “Long-term health index prediction for power asset classes based on sequence learning,” *IEEE Transactions on Power Delivery*, vol. 37, no. 1, pp. 197–207, Feb. 2022.

[80] G. J. Anders, “Ranking of substations based on past historical performance,” in *2010 IEEE 11th International Conference on Probabilistic Methods Applied to Power Systems*, June 2010, pp. 308–313.

[81] H. N. Bhandari, V. Vittal, G. T. Heydt, F. L. Quintanilla, and W. B. Knuth, “Ranking of bulk transmission assets for maintenance decisions,” in *2019 North American Power Symposium (NAPS)*, Oct 2019, pp. 1–6.

[82] D. Karlsson, L. Wallin, H.-E. Olovsson, and C.-E. Solver, “Reliability and life cycle cost estimates of 400 kv substation layouts,” *IEEE Transactions on Power Delivery*, vol. 12, no. 4, pp. 1486–1492, Oct 1997.

[83] Z. Cramer, M. Y. Vaziri, and M. Zarghami, “Distribution substation bus design for optimal reliability and economics,” in *2015 IEEE Power & Energy Society General Meeting*, July 2015, pp. 1–5.

[84] M. B. Stevens and S. Santoso, “Improving the reliability of breaker-and-a-half substations using sectionalized busbars,” in *2013 IEEE Power and Energy Society General Meeting*, July 2013, pp. 1–5.

[85] W. Li, R. Billinton, and A. Tache, “Reliability evaluation of multiple substations with distribution networks,” in *2014 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*, July 2014, pp. 1–6.

[86] F. Dong and L. Fan, “Power system reliability assessment with full topology model,” in *2017 IEEE Power and Energy Society General Meeting*, July 2017, pp. 1–5.

[87] A. H. Chowdhury, P. S. Sarker, K. R. Islam, and S. T. Tanjil, “Effect of intermediate substation configurations on reliability of power transmission corridor,” in *8th International Conference on Electrical and Computer Engineering*, Dec 2014, pp. 639–642.

[88] T. Xu, Z. Lu, Y. Huang, R. Huang, and A. Pang, “Reliability assessment of multiple-voltage regional transmission and distribution system considering substation interior failure,” in *2016 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*, Oct 2016, pp. 1–6.

[89] D.-L. Duan, X.-Y. Wu, and H.-Z. Deng, “Reliability evaluation in substations considering operating conditions and failure modes,” *IEEE Transactions on Power Delivery*, vol. 27, no. 1, pp. 309–316, Jan 2012.

[90] M. Heidarifar and H. Ghasemi, “A network topology optimization model based on substation and node-breaker modeling,” *IEEE Transactions on Power Systems*, vol. 31, no. 1, pp. 247–255, Jan 2016.

[91] X. Wu, J. Zhang, and Q. Chen, “Probability analysis model and risk assessment of n-k contingency based on condition-based maintenance,” in *2011 4th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT)*, July 2011, pp. 968–973.

[92] Y.-T. Byeon, K. Kwon, and J.-O. Kim, “Reliability analysis of power substation with common cause failure,” in *2009 International Conference on Power Engineering, Energy and Electrical Drives*, March 2009, pp. 467–472.

[93] Z. Liu, B. Wang, H. Jia, Y. Zeng, T. Xu, J. Liu, D. Chen, and Y. Lu, “Hierarchical risk assessment of transmission network considering the influence of micro-grid,” in *2013 IEEE Power and Energy Society General Meeting*, July 2013, pp. 1–6.

[94] K. Zhang, Z. Du, F. Xiao, T. Wang, and L. Zhang, “Improved sequential monte carlo method approach to substation connection reliability assessment,” in *2020 IEEE 4th Conference on Energy Internet and Energy System Integration (EI2)*, Oct 2020, pp. 2357–2362.

[95] D. Clements and P. Mancarella, “Systemic modelling and integrated assessment of asset management strategies and staff constraints on distribution network reliability,” *Electric Power Systems Research*, vol. 155, pp. 164–171, feb 2018.

[96] W. Maia, P. Ekel, D. A. Gomes Vieira, E. Antônio de Castro, M. A. Dorna de Oliveira, I. M. Reis, and K. M. G. Dos Santos, “Evaluation of operational risk in power substations and its rational reduction on the basis of multicriteria allocating resources,” *IEEE Access*, vol. 9, pp. 149 383–149 397, 2021.

[97] H. Gao, L. Miao, J. Liu, K. Dong, and X. Lin, “Inspection pattern for smart substations based on risk analysis,” in *2019 IEEE 8th International Conference on Advanced Power System Automation and Protection (APAP)*, Oct 2019, pp. 229–234.

[98] H. A. R. Ardabili, M.-R. Haghifam, and S. M. Abedi, “A stochastic markov model for maintenance scheduling in the presence of online monitoring system,” *IEEE Transactions on Power Delivery*, vol. 37, no. 4, pp. 2831–2842, aug 2022.

[99] C. Wang, Y. Hou, Z. Qin, C. Peng, and H. Zhou, “Dynamic coordinated condition-based maintenance for multiple components with external conditions,” *IEEE Transactions on Power Delivery*, vol. 30, no. 5, pp. 2362–2370, oct 2015.

[100] G. Hamoud and C. Yiu, “A new reliability strategy for managing assets of customer delivery systems,” *IEEE Transactions on Power Delivery*, vol. 36, no. 2, pp. 890–898, April 2021.

[101] G. Andreesen, M. Leinakse, J. Kilter, and M. Landsberg, “Maximum risk calculation process for individual substation equipment in primary side,” in *ISGT Europe 2024*. IEEE, oct 2024, pp. 1–5.

[102] MatPower, “Power flow data for 39 bus New England system,” 2024.

[103] H. Manninen, “Data-driven asset management and condition assessment methodology for transmission overhead lines,” *PhD Dissertation*, 2022.

[104] G. Andreesen, M. Leinakse, J. Kilter, and M. Landsberg, “Cost-efficient improvement of power system’s reliability within limited funds,” in *RTUCON 2024*. IEEE, oct 2024, pp. 1–6.

[105] G. Andreesen, M. Leinakse, J. Kilter and M. Landsberg, “Methodology for forecasting the cost of substation asset management in upcoming future,” in *PECON 2024*. IEEE, nov 2024, pp. 1–5.

[106] G. Andreesen, M. Leinakse, J. Kilter and M. Landsberg , “Determining cost-efficient sequence of condition inspection based on estimated condition data,” in *ISGT Europe 2024*. IEEE, oct 2024, pp. 1–5.

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Abstract

Development of a Substation Risk-Based Asset Management Decision-Making Process in the Case of Insufficient Information

The majority of power system substations were constructed more than 30 years ago, meaning that the expected lifespan of their equipment has been reached or will soon be reached. This means the TSO's and DSO's have to start replacing aged equipment, resulting in significantly increased asset management costs. However, the aging characteristics of similar types of equipment are different, resulting in situations where the replaced equipment could have maintained its proper functionality. Thus, it is more efficient to maximize equipment lifespan instead of replacing everything at the end of its life expectancy. On the other hand, some equipment might degrade faster, resulting in their failure before the planned replacement. The condition of most equipment is assessed periodically, which makes preventing rapidly developed failures complicated. On top of that, the available statistical data for determining the optimal period for equipment replacement might be limited or absent. Especially considering that "smaller" and less "expensive" units can cause an extent of failure consequences similar to "bigger" and more "expensive" ones. Furthermore, the funds for determining actual equipment condition is also limited, resulting in the need for an efficient sequence of equipment inspection. Subsequently, there is significant cause for estimating equipment failure risk while considering the uncertainty component in order to increase the efficiency of management decision-making.

The focus of this thesis is to tackle challenges associated with failure risk calculation of substation equipment, estimating equipment failure risk in the case of input data uncertainty, and determine an efficient failure risk reduction sequence from a management cost perspective. Thus, it is initially necessary to have an appropriate method for calculating equipment maximum failure risk including all substation equipment on the primary side. For this, a hybrid calculation process is developed that can determine failure risk from an individual equipment perspective. This makes it possible to pinpoint all of the pieces of equipment in the power system within different equipment types that can cause large-scale failure consequences. Secondly, it is necessary to obtain input data related to equipment condition to calculate its failure risk, especially in the case of data uncertainty. For this purpose, a method for estimating the condition of equipment with the limited data is proposed and used to determine an efficient equipment inspection sequence from a cost perspective. This can justify the need to use preventive measures with specific equipment or maximize the asset and include it in a corrective approach. Thirdly, higher failure risk needs to be reduced in order to prevent equipment failures resulting in serious consequences. For this purpose, a method of determining risk reduction efficiency from a cost perspective considering individual equipment or similar equipment types is proposed. It assists in determining whether a preventive or corrective approach would be more appropriate while considering the achievable extent of risk reduction and the associated cost. Lastly, a method for estimating management costs in the case of input data uncertainty is proposed. This makes it possible to determine the extent of using either preventive or corrective measures as part of risk reduction.

The proposed methods were tested in a case study. In the case of the developed risk calculation process, the results indicated that it is possible to detect all pieces of equipment in substations that have a higher failure risk and consequences. This increases the overall integrity of the risk analysis and makes it possible to focus on failure prevention more directly on each link in the transmission chain. In the case of equipment condition data estimation and its use in determining a condition inspection sequence, the results indicated a relationship between estimated data, related costs, and the limits of a preventive management approach. Therefore, it can justify a delay in equipment replacement or an increase in its priority. When using the risk reduction process, the results indicated the sequence of equipment inclusion individually or type-wise in preventive or corrective methods. This provides an overall perspective of substation asset failure risk reduction options to decrease total failure risk from a cost perspective. The results of implementing the method of asset management cost estimation additionally provides potential threshold values for determining how much preventive measures should be used on equipment. Combining these methods makes it possible to increase the efficiency of the asset management decision-making process with a decrease in the associated costs and also considers the uncertainty factor related to input data. In addition, they can be included in the existing substation asset management method to tackle multiple challenges related to it and improve its optimality.

Keywords: Asset management, Decision-making process, Failure risk, Management cost- efficiency, Management cost optimization, Power system reliability, Risk analysis, Risk reduction, Substation equipment condition

Kokkuvõte

Alajaama riskipõhise varahalduse otsustusprotsessi arendamine ebapiisava sisendteabe tingimustes

Enamik alajaamu on ehitatud rohkem kui 30 aastat tagasi. Seetõttu on nendes asuvate seadmete eeldatav kasutusaeg juba ületatud või see ületatakse lähiajal. Nõnda peavad elektrisüsteemi haldajad hakkama vananenud seadmeid välja vahetama, mille tulemuseks on oluliselt suurenenud varahalduskulud. Samas, sarnaste seadmete vananemine võib olla erinev, mille tõttu võidakse asendada veel korralikult toimiv seade. Selle asemel on tõhusam maksimeerida seadmete tööaega ning vahetada neid välja lähtuvalt vajadusest. Teisest küljest aga võivad mõned seadmed jällegi kiiremini vananeda ja põhjustada rikke enne kavandatud asendamist. Lisaks hinnatakse enamiku seadmete seisukorda perioodiliselt, mis muudab kiiresti arenevate rikete vältimise keeruliseks. Muuhulgas võib ka saadaolev statistika olla piiratud või hoopiski puududa, et määrata kindlaks optimaalne seadmete väljavahetamise periood. Eriti kui arvestada "väiksemate"ja vähem "kallimate"seadmetega, mis põhjustavad samasuguse rikke tagajärje, kui "suuremad"ja "kallimad". Lisaks on veel seadmete tegeliku seisukorra välja selgitmaiseks mõeldud rahalised vahendid piiratud, mistõttu tuleb tõsta seadmete ülevaatuse tõhusust ja optimeerida selle järjekorda. Seetõttu on oluline seadmete rikkeriski määramisel võtta arvesse määramatuse komponenti, et suurendada juhtimisotsuste tegemise tõhusust.

Käesolev doktoritöö keskendubki väljakutsetele, mis seonduvad alajaama seadmete rikkeriski arvutamisega, seadmete rikkeriski hindamisega sisendandmete ebatäpsuse korral ja tõhusa rikkeriski vähendamise järjestuse määramisega halduskulude vaatenurgast. Seega on esmaselt vaja sobivat meetodit seadmete maksimaalse rikkeriski arvutamiseks hõlmates kõiki primaarpoole alajaama seadmeid. Selleks töötati välja hübriidarvutusprotsess, mis võimaldab määrata iga üksiku seadme rikkeriski. Nõnda on täpselt leitavad kõik elektrisüsteemis asetsevad erinevad seadmed, millede rike võib põhjustada tõsiseid tagajärgi. Teiseks on rikkeriski arvutamiseks vaja määrata seadme seisukorda iseloomustavad sisendandmed võttes arvesse ka nende puudumist või ebatäpsust. Sellel eesmärgil töötati välja meetod hindamaks seadmete seisukorda piiratud andmete korral, mida kasutatakse seadmete ülevaatuse järjestuse kulutõhususe suurendamisel. Nõnda on võimalik põhjendada rikke ennetusmeetmete või korrigeeriva lähenemisviisi kasutamise vajadust seadmepõhiselt ja maksimeerida seadmete kasutusaega. Kolmandaks on vaja kõrgemat rikkeriski vähendada, et vältida tõsiste tagajärgedega seadmete rikkeid. Sellel eesmärgil töötati välja meetod rikkeriski vähendamise kulutõhususe määramiseks võttes arvesse üksikuid seadmeid ja sarnaseid seadmetüüpe. Samuti aitab see põhjendada valikut ennetava ja korrigeeriva haldusmetoodika vahel ning näitab riski vähendamise saavutatavat ulatust koos kaasnevate kuludega. Lisaks töötati välja meetod alajaamade halduskulude arvutamiseks sisendandmete ebatäpsuse korral. See võimaldab hinnata ennetavate või korrigeerivate meetmete kasutamise ulatust riski vähendamise osana.

Välja töötatud meetodeid kontrolliti simulatsioonide põhjal. Maksimaalse rikkeriski arvutamise protsessi puhul näitasid tulemused, et alajaamades on võimalik avastada kõiki suurema rikkeriski ja tagajärgedega seadmeid. Seega suurendab see riskianalüüsi üldist terviklikkust ja võimaldab rikete ennetamiseks keskenduda otsesemalt igale üksikseadmele. Seadmete seisundteabe estimeerimisel ja edasisel kasutamisel seisukorra kontrollimise järjestuse määramisel näitasid tulemused eeldatavate andmete, sellega kaasnevate kulude ja ennetava haldusmetoodika tasuvuspunkti omavahelist seost. Nõnda on võimalik põhjendada seadmete asendusega viivitamist või nende prioriteetsuse tõstmist. Rikkeriskide vähendamise protsessi kasutamise korral andsid tulemused seadmetele ennetava või korrigeeriva haldusmetoodika valimise järjestuse individuaalselt või tüübiti. Selle põhjal on võimalik põhjendada alajaamade seadmete rikkeriski vähendamise otsuseid ja tõsta üldist elektrisüsteemi töökindlust kulutõhusalt. Varahalduskulude arvutamise meetodi rakendamise tulemused annavad aga potentsiaalsed läviväärtused ennetava või korrigeeriva haldusmetoodika kasutamise ulatuse määramiseks. Nende välja töötatud meetodite kombineerimine võimaldab tõsta varahalduse otsustusprotsessi efektiivsust koos sellega kaasnevate kulude vähendamisega arvestades sealjuures sisendandmete võimaliku ebatäpsusega. Lisaks saab neid rakendada alajaama varahalduses, et lahendada mitmeid selles olevaid küsimusi.

Märksõnad: Alajaama seadmete seisukord, Elektrisüsteemi töökindlus, Otsustusprotsess, Rikke risk, Riskianalüüs, Riski vähendamine, Varahaldus, Varahalduse kulutõhusus, Varahalduse kulude optimeerimine

Appendix 1

I

G. Andreesen, M. Leinakse, J. Kilter, and M. Landsberg, “Maximum risk calculation process for individual substation equipment in primary side,” in *ISGT Europe 2024*. IEEE, oct 2024, pp. 1–5

Maximum Risk Calculation Process for Individual Substation Equipment in Primary Side

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***Abstract*—Commonly, the risk is obtained for specific equipment groups in the substations. Yet, there are many other equipment groups, which can also have higher risk. This paper presents the hybrid solution to calculate the maximum risk of all the individual equipment on the substation primary side. It combines the power flow with contingency analysis done in PSSE and dedicated risk calculation logic developed in Python. In PSSE, load curtailment values are obtained in accordance with the contingency descriptions. These represent a part of the equipment failure consequences. The main risk calculation logic is in Python. It uses the power system data and contingency analysis results to combine them with individual substation equipment. It also includes inputs for failure probability, replacement times, replacement costs, load curtailment cost, and substation types. It is tested on the IEEE 39-bus power system. The results indicated the different impact on the equipment risk based on the changes in inputs. Based on that, it is possible to determine the parameters sensitivity to individual equipment and adjust the asset management decisions accordingly.**

***Index Terms*—Asset management, Failure probability, Load curtailment, Risk assessment, Substation reliability**

I. Introduction

The aging of the substations creates many challenges for power system owners. To avoid equipment failures with significant consequences, the failure risk of substation equipment needs to be calculated. Due to the variety of different equipment in substations, the risk needs to be obtained for all of them. Focusing on the bigger and more expensive equipment can not avoid the failure of other equipment in the substations. For that, a dedicated methodology is needed to calculate the risk of all substation equipment on the primary side.

In the literature, the risk of failure is calculated for specific equipment groups, such as power transformers and circuit breakers. In [1], [2], methods to identify the equipment of higher risk value based on an example of circuit breakers are presented. A method to rank power transformers based on their risk is proposed in [3]. Similarly, in [4] and [5], the inspection rates are optimized for a specific equipment group.

The reliability of substations is evaluated based on the perspective of the disconnection of the transmission lines. A couple of approaches are described in [6], [7], where load restrictions after the failures in substation connections were considered as an important parameter. This is supported by the methodology presented in [8], also including switching equipment operations. From the same perspective, in [9] and [10] are determined the important equipment in selected groups in the power system.

The risk itself is used in asset management procedures. A methodology for allocating the available funds for the management of higher risk equipment is presented in [11]. The implementation of condition monitoring solutions applied on circuit breakers for improving the condition awareness and the substation reliability is analysed in [12], [13]. The risk values are also a part of stochastic processes for maintenance scheduling in an approach proposed in [14].

Despite the extensive coverage, there is a lack of risk calculation methodology allowing to obtain the maximum risk for all the equipment on the substation primary side. Also, the risk in N-1 or N-2 contingencies from an equipment perspective. Discarding these equipment and aspects can alter the overall management decisions.

This paper presents the methodology for that purpose. It is based on the hybrid solutions, combining the contingency analysis in PSSE and the risk calculation of equipment in Python. The risk calculation logic is developed to obtain the maximum risk in N-1 and N-2 situations from equipment perspective. It has multiple inputs, such as failure probability, replacement times and cost, load curtailment cost, and substation type. As a result, the methodology allows to calculate the maximum risk of equipment in accordance with all possible failure combinations with other equipment and pinpoint their importance in the power system. It also allows to detect the combinations of equipment failures causing the higher risk. It can be used for determining the risk of every equipment in the substation and analyse its sensitivity to input parameters.

II. Methodology

A. Risk of Failure

Risk of failure (RoF_i) is used in the power system to indicate the equipment's importance based on failure consequences and probability. It consist of multiple components, such as the cost of load curtailment ($CoLC$), the cost of repair (CoR) and the probability of failure (PoF). The $CoLC$ includes the value of lost load ($VoLL$) at time interval t and mean time to repair equipment ($MTTR$). Commonly, the failures in the power system cause N-1 (failure of equipment i) and N-2 (combined failure event between equipment i and j) contingencies. The (1) and (2) is used to compute the risk value in N-1 and N-2 contingencies, and the maximum risk is obtained by (6). The acquirement of $VOLL$ is expressed by (7), where $CoL_i(t)$ the cost of load i, $LF_i(t)$ is a load factor for load i, and $LC_i(t)$ is load i curtailment.

$$RoF_{i(N-1)} = ((VOLL_i(t) \cdot MTTR_i) + CoR_i) \cdot PoF_i = (CoLC_i + CoR_i) \cdot PoF_i \quad (1)$$

$$RoF_{ij(N-2)} = (CoLC_{ij} + CoR_i + CoR_j) \cdot PoF_i \cdot PoF_j \quad (2)$$

$$CoLC_{ij} = \begin{cases} MTTR_i > MTTR_j, \ use \ (4) \\ MTTR_i = MTTR_j, \ VOLL_{ij}(t) \cdot MTTR_i \\ MTTR_i < MTTR_j, \ use \ (5) \end{cases} \quad (3)$$

$$VOLL_{ij}(t) \cdot MTTR_j + VOLL_i(t) \cdot (MTTR_i - MTTR_j) \quad (4)$$

$$VOLL_{ij}(t) \cdot MTTR_i + VOLL_j(t) \cdot (MTTR_j - MTTR_i) \quad (5)$$

$$RoF_i = max(RoF_{i(N-1)}, RoF_{ij(N-2)}) \quad (6)$$

$$VOLL_i(t) = \sum_{i=1}^{n} CoL_i(t) \cdot LC_i(t) \cdot LF_i(t) \quad (7)$$

B. Load Curtailment

The consequences of the equipment failures (contingencies) depend on the restrictions applied based on the limits in the power system elements. Commonly, contingencies cause voltage violations at the busbars and overload in the elements. In the case of contingencies, the occurrence of the voltage violations at busbars and overload in branches or power transformers is checked. If these occur, then an option is to reduce the load until the conditions are met. This means load curtailment at a specific bus (LC_i), which increases the cost of failure and risk. It is also possible to use generation control, power transformers tap changers and shunts for voltage and overload control. If these options are allowed, then the LC_i value is smaller.

In contingency analysis, LC_i values are based on either the disconnection of the load or the corrective measures implemented to maintain the voltage between limits or reduce the overload. The corrective measures in the contingencies without the disconnection of load, indicate the LC_i needed to maintain the power system's operational state without violations. The LC_i needs to be calculated for each contingencies and linked to individual equipment.

C. Concept of Risk Calculation Process of Individual Substation Equipment

The overall concept of the risk calculation procedure is given in Fig. 1, and is divided into separate modules. Firstly, the power system is modelled in the software used in power system analysis, which in this case is PSSE. It allows to obtain the LC_i values by considering also the dynamics of the power system. Next, the contingency analysis is done for obtaining the LC_i values based on individual contingencies. In the second module, these values are processed in the statistical or mathematical software, which in this case is Python. In that, the dedicated logic is developed to link the LC_i values with individual substation equipment. It is part of the overall risk calculation process using multiple inputs. At the end of the process, the risk for individual equipment is calculated.

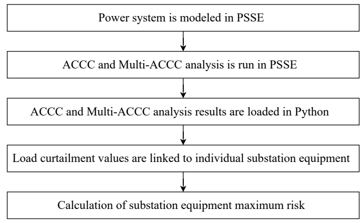

Fig. 1. Principle concept of the risk calculation of substation equipment

In PSSE, the LC_i values are obtained based on the ACCC (AC Contingency Analysis) and Multi-ACCC analysis. For that, the contingency descriptions need to be generated. These are based on the location of the equipment in the substation and the power system. It determines, which branches or substation bays are disconnected after the equipment failure. In that, the reliability of the substation schematic has an important factor.

D. Logic of Risk Calculation Process

The main logic of the risk calculation process is given in Fig. 2. Firstly, the data files are loaded from the outputs of PSSE and the power system description. These include the results of the ACCC and Multi-ACCC analysis in .acc files and the power system decription data in .raw file. Next, that data is linked to specific power system busbars. In the developed concept, busbars are considered fictive substations. Another task of the logic process is to link the LC_i to individual substation equipment located at its bays. The dedicated matrices are used for that purpose, containing the description of equipment for each substation. Before the main risk calculation, additional data related to equipment is included in the process. These include following parameters: $VOLL_i(t)$, CoR, $MTTR$,PoF, type the substation schematic, power transformer side of the branch, and substation section numbers with connected bays.

Next, the substation schematic types are considered, and the link between the LC_i and the equipment is adjusted accordingly. The LC_i are combined with other parameter values in the parts of the N-1 and N-2 calculations. In the N-2 calculations, the risk is obtained for all possible combinations between two equipment failures. Based on the maximum risk value in N-1 and N-2 contingencies, the maximum risk is acquired for the equipment.

E. Linking Substation Equipment to Busbars

The main part of the risk calculation logic is the link between individual substation equipment and power system

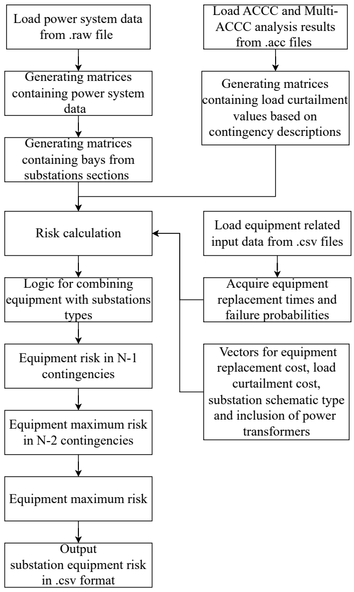

Fig. 2. Main logic of the hybrid risk calculation process

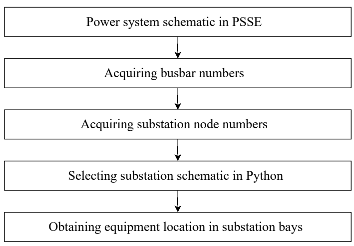

Fig. 3. Principle logic to link power system data individual substation equipment

busbars. In Fig. 3 is given the procedure of that process. Similarly to load curtailment, the data is extracted from the file describing the power system schematic. From that, the busbar numbers and the substation node numbers are acquired. These represent the fictional substations. The node numbers are used to link the branches and other connections to specific substation sections (bus). The principle of using node numbers is expressed by Fig. 4. As the results, the equipment is linked to the specific substation bay.

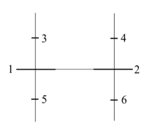

Fig. 4. Principle of using substation node numbers 3....6 to identify the bays (connections) to substation sections 1 and 2

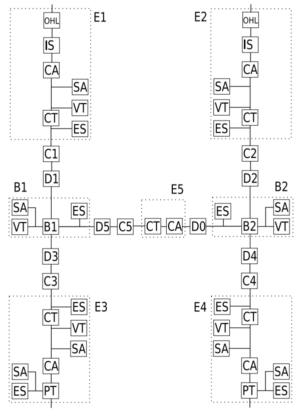

Fig. 5. Schematic of a substation with single-breaker single-disconnector configuration (type 1). Indices E1. . . E4 are substation bays and E5 is connection between substation section 1 (indicated by B1) and section 2 (indicated by B2). Other indices are C (CB) – circuit breaker, D (DC) – disconnector, VT – voltage transformer, CT – current transformer, CA – cable, ES – earthing switch, SA – surge arrester, PT – power transformer, IS – insulator chain.

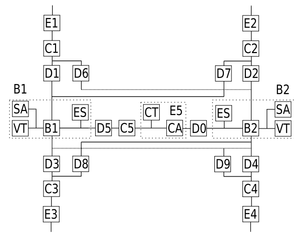

Fig. 6. Schematic of a substation with double-bus single-breaker configuration (type 2)

F. Implementation of Substation Schematic Type

The individual equipment is linked to power system branches, generation units, loads, or other connections based on the substation node numbers and substation type. The implemented schematic types are: 1- single circuit breaker and single disconnector with branch (also known as H-schematic), 2 - single circuit breaker and double disconnector with branch, 3 - double circuit breaker and double disconnector with branch. These schematics are given in Fig. 5, 6 and 7. In Fig. 6 and 7, the E1. . . E4 includes the same equipment as in Fig. 5. It is assumed, that E1 is connected to node 3 in. 4, E2 to node 4, E3 to node 5 and E4 to node 6.

G. Risk Calculation Based on Substations Types

The values of the LC_i are linked to the equipment by the following principles. If the equipment is in E1. . . E4, then its failure causes the disconnection of a single branch. If the equipment is directly connected to busbars (sections B1 and B2), then its failure can cause either the disconnection of all branches (bays) connected to that busbar or its specific section

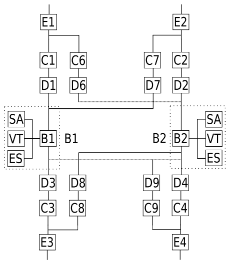

Fig. 7. Schematic of a substation with double-bus double-breaker configuration (type 3)

or disconnect only the specific section. This is related to the substation schematic used and can include equipment VT(B), ES(B), SA(B), CB and DC. The third case is related to the equipment in E5.

In N-1 contingencies, that principle is implemented in accordance with a single substation schematic. In N-2 contingencies, different combinations between substation schematics are considered. This procedure is described in 8. For that, the location of both equipment with failure (indicated by i and j) is obtained. If equipment i or j are not in E1…E4, then the combinations considering substation type are analyzed. It is initially checked, are equipment i and j in the same substation. If not, then the next conditions in the sequence are followed. This means also, that equipment i and equipment j are in different substations.

Therefore, the cases are considered: inclusion of the equipment i and j in E1…E4, the type of the schematic of substations, if the equipment i and j are not in E1…E4, inclusion of the equipment i and j in E5, and inclusion of the equipment i and j at the same substation.

III. Case Study

The IEEE 39-bus power system, given in Fig.9, is used to test the proposed methodology. For that, the initial parameters are changed individually to evaluate their impact on the risk. In addition, to analyse the difference of the change based on individual equipment. In the initial case, the PoF_i for all of the equipment is set to 0.1 for sensitivity analysis. The all substation types are set to 3. For testing the risk calculation process, four cases are used. These cases are: 1 - initial, 2 - PoF_i is set from 0.1 to 0.2, 3 - $MTTR_i$ is set from 8 hours to 10 hours, 4 - substation type is set from 3 to 1 (schematic in Fig. 7 is changed to schematic in Fig. 5).

IV. Results

The results in Figs. 10 and 11 show the impact of input parameters based on the load curtailment values for couple of equipment in the power system. These are VT1 (branch 8 at busbar 7) and VT2 (branch 21 at busbar 19) in Fig. 10, and DC1 and DC2 (branch 20 at busbar 4) in Fig. 11.

In Fig. 10 is given the risk (RoF_i) for the equipment VT1 and VT2. These values are based on the risk in N-1 contingency and its maximum value in N-1 and N-2 contingencies. It

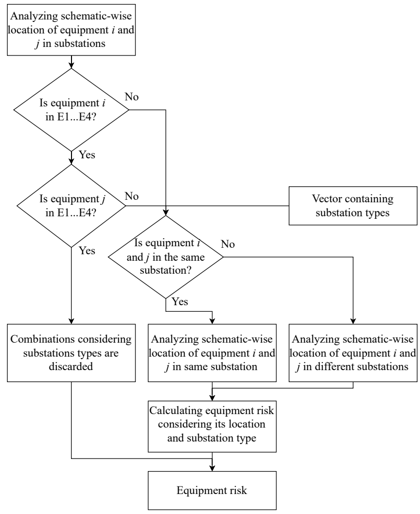

Fig. 8. Process of linking the load curtailment to equipment location in different substation schematics

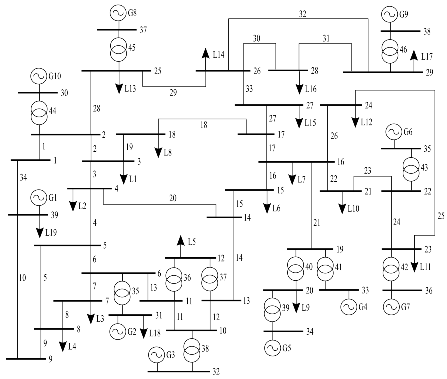

Fig. 9. Schematic of the IEEE 39-bus power system used in the risk calculations

can be seen, that increasing the PoF_i to 0.2 (case 2) increases the risk as well (compared to case 1). The increase in $MTTR_i$ also increases the risk (case 3 compared to case 1). Although, the change in case 3 is smaller than in case 2. Therefore, the increase of $MTTR_i$ by 2 hours has less impact on risk compared to the change in PoF_i from 0.1 to 0.2.

It can also be noticed that the risk of VT1 is lower in N-1 contingencies than its maximum value. It means that the maximum risk is obtained in N-2 contingencies. In the case of VT2, the maximum risk is based on N-2 contingencies. The change in the substation type does not have an impact on risk, mainly due to the location in a branch (E1 in Fig. 5).

In Fig. 11 is given the risk for equipment DC1 and DC2.

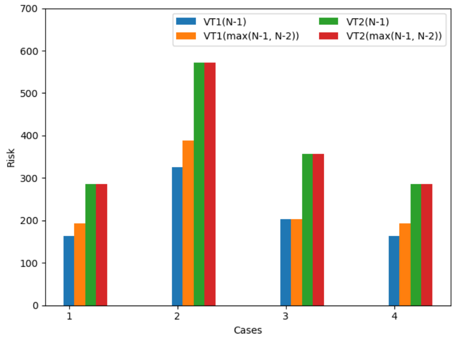

Fig. 10. Risk of substation equipment (VT1 and VT2) based on cases: 1 - initial, 2 - PoF_i is increased to 0.2, 3 - $MTTR$ is increased to 10, 4 - substation type is changed to 1

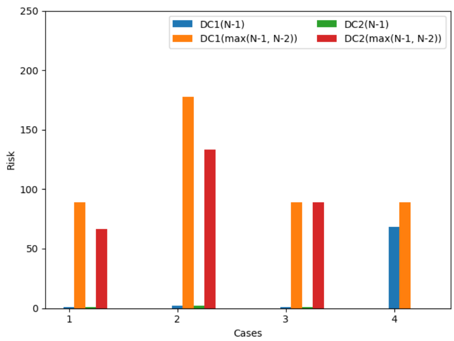

Fig. 11. Risk of substation equipment (DC1 and DC2) based cases: 1 - initial, 2 - PoF_i is increased to 0.2, 3 - $MTTR$ is increased to 10, 4 - substation type is changed to 1

It can be noticed the similar pattern in case 2, where the risk increased due to the increase in the PoF_i. The increase in the $MTTR_i$ has an impact on DC2 maximum risk. Although, compared to case 2, that impact is smaller. In case 4, the RoF_i of DC1 in N-1 increases from near 0 to 70 compared to case 1. Although, the maximum risk is the same. The RoF_i of DC2 is absent in case 4, because of the usage of a simpler substation schematic without two disconnectors with connection (the schematic in Fig. 7 is changed to Fig. 5).

In accordance with the results, the change in risk after the change of PoF_i or $MTTR_i$ is different based on equipment location and its type. A similar pattern is with the risk in N-1 contingency and the maximum risk based on N-1 and all the failure combinations in N-2 contingencies. It allows to determine with higher accuracy the equipment importance, the cause of the higher risk, and options to reduce the risk.

V. Conclusion

The methodology to obtain the maximum risk of substation equipment is proposed in this paper. It allows to calculate the risk for all the equipment on the substation's primary side. It implements the hybrid concept, combining contingency analysis in dedicated power system software and the risk calculation logic developed in computational software. The methodology uses dedicated processes to link individual substation equipment to power system data and load curtailment values. It also allows to adjust the input parameters and change substation schematics to assess the sensitivity of input values to risk. The methodology is tested on an IEEE 39-bus power system. The methodology can be useful tool for power system owners for calculating the risk of all substation equipment and evaluating management decisions accordingly.

References

[1] D. Huang and B. Bagen, "System reliability risk model and its application to station breaker replacement," in *2020 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*, Aug 2020, pp. 1–6.

[2] A. P. Shishavan and A. Razi-Kazemi, "A practical knowledge-based ranking approach to identify critical circuit breakers in large power systems," *Knowledge-Based Systems*, vol. 227, p. 107237, sep 2021.

[3] R. D. Medina, D. A. Zaldivar, A. A. Romero, J. Zuñiga, and E. E. Mombello, "A fuzzy inference-based approach for estimating power transformers risk index," *Electric Power Systems Research*, vol. 209, p. 108004, aug 2022.

[4] Z. Wu, B. Liu, Z. Wang, S. Ma, and G. Ni, "Research on condition-based maintenance approach of power system considering equipment imperfect maintenance model," in *2017 Chinese Automation Congress (CAC)*, Oct 2017, pp. 3695–3700.

[5] B. Xu, S. Xu, and Y. Zhang, "Determining optimal inspection rates of power equipment considering opportunistic maintenance strategy," in *2019 IEEE 3rd International Conference on Green Energy and Applications (ICGEA)*, March 2019, pp. 51–55.

[6] Z. Cramer, M. Y. Vaziri, and M. Zarghami, "Distribution substation bus design for optimal reliability and economics," in *2015 IEEE Power Energy Society General Meeting*, July 2015, pp. 1–5.

[7] M. Papic, O. A. Ciniglio, and S. K. Agarwal, "Reliability assessment of multiple substations in idaho system using a node-breaker model," in *2016 IEEE Power and Energy Society General Meeting (PESGM)*, July 2016, pp. 1–5.

[8] F. Dong and L. Fan, "Power system reliability assessment with full topology model," in *2017 IEEE Power Energy Society General Meeting*, July 2017, pp. 1–5.

[9] W. Maia, P. Ekel, D. A. Gomes Vieira, E. Antônio de Castro, M. A. Dorna de Oliveira, I. M. Reis, and K. M. G. Dos Santos, "Evaluation of operational risk in power substations and its rational reduction on the basis of multicriteria allocating resources," *IEEE Access*, vol. 9, pp. 149 383–149 397, 2021.

[10] Z. Wang, K. Zhang, H. Li, F. Xiao, Y. Chen, and T. Wang, "Evaluation method of substation weak link based on power grid risk severity index," in *2021 IEEE 5th Information Technology,Networking,Electronic and Automation Control Conference (ITNEC)*, vol. 5, Oct 2021, pp. 1109–1115.

[11] H. Mirsaeedi, A. Fereidunian, S. M. Mohammadi-Hosseininejad, and H. Lesani, "Electricity distribution system maintenance budgeting: A reliability-centered approach," *IEEE Transactions on Power Delivery*, vol. 33, no. 4, pp. 1599–1610, aug 2018.

[12] J. Zhong, W. Li, R. Billinton, and J. Yu, "Incorporating a condition monitoring based aging failure model of a circuit breaker in substation reliability assessment," *IEEE Transactions on Power Systems*, vol. 30, no. 6, pp. 3407–3415, Nov 2015.

[13] A. A. Razi-Kazemi and M. Shariatnasab, "A new approach on prioritization of the circuit breakers for installation of online monitoring systems," *IEEE Transactions on Power Delivery*, vol. 34, no. 4, pp. 1569–1577, Aug 2019.

[14] H. A. R. Ardabili, M.-R. Haghifam, and S. M. Abedi, "A stochastic markov model for maintenance scheduling in the presence of online monitoring system," *IEEE Transactions on Power Delivery*, vol. 37, no. 4, pp. 2831–2842, aug 2022.

Appendix 2

II

G. Andreesen, M. Leinakse, J. Kilter and M. Landsberg , “Determining cost-efficient sequence of condition inspection based on estimated condition data,” in *ISGT Europe 2024*. IEEE, oct 2024, pp. 1–5

Determining Cost-Efficient Sequence of Condition Inspection Based on Estimated Condition Data

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***Abstract*—This paper presents a methodology to determine the cost-efficient sequence of substation equipment inspections. It is mainly intended for cases when having limited or absent data about equipment condition. The methodology is based on the usage of known condition data to estimate the condition of equipment with unknown data. It is estimated by fitting the likelihood function to the distribution of known Health Index values of equipment. The estimation values are implemented as an input to determine the cost-efficient sequence of equipment inspections. As a result, the process allows to decrease the uncertainty in condition data, avoid costly failures, and reduce total inspection cost. The methodology is tested on the IEEE 39-bus power system. The obtained results indicated the reduction of inspection cost by 80 % in the example case and avoiding failures with higher cost. The process can assist in risk reduction when having equipment with unknown or limited condition data.**

***Index Terms*—Asset management, Failure probability, Non-parametric estimation, Risk assessment, Substation reliability**

I. Introduction

Access to electricity is important for industries, the functionality of services, and regular consumers. Therefore, it is crucial to avoid extensive shortages of electricity caused by the failures of equipment in the power system. For that, maintaining the good condition of substation equipment is a crucial task for the power system owners. To determine the equipment needing higher attention, awareness about their condition is needed. This can be a complicated task if the data for the majority of equipment is absent. In addition, insufficient data makes asset management less cost-efficient.

In the literature, the relationship between substation equipment condition, expressed by Health Index (HI), and subsequent risk is analysed from multiple perspectives. The overall importance of using HI values and the options to increase their accuracy is discussed in [1]. Implementing health diagnostics is a common method to acquire the HI for all of the equipment. This approach to obtain the HI for power transformers is presented in [2]. Condition assessment of the equipment is also considered as the main factor for obtaining accurate HI in methods presented in [3] and [4].

The quality of data and its relation to uncertainty of HI is discussed in [5], and the impact of data uncertainty to HI is analysed in [6]. An methodology for obtaining the failure probability from the HI with selected degrees of uncertainty is proposed in [7], and implemented on circuit breakers. Overall, estimating the condition of the equipment allows to reduce uncertainty.

More complex estimation of the HI and risk based on the condition of equipment is given in [8], and with the implementation of stochastic processes in [9]. Fuzzy logic-based uncertainty is also incorporated in [10] and [11] for risk estimation. A method for obtaining the HI values through the equipment condition estimation with uncertainty factor is presented in [12] by combining statistical approaches. A similar estimation of the risk in a longer time period based on predictable patterns is used in [13]. The time parameter is also implemented in [14] to estimate the change in equipment condition and HI. Their main objective is to reduce the cost of potential failures.

Overall, the existing methodologies concentrate on specific equipment groups and relay on the available statistics. In the case of less analysed equipment, such as instrument transformers, disconnectors, and insulators, they lack the necessary functionality to obtain their risk. Especially if having limited or absent statistical data about the equipment condition. In addition, the procedures describing the cost-efficient sequence of equipment inspection in the presence of limited data.

This paper addresses these aspects. Its essence is to use known HI_i values to estimate the unknown HI_i values. Based on the estimation, the number of equipment with potentially higher HI_i values is obtained. By implementing the proposed process, the cost-efficient sequence of equipment inspections to detect the equipment with a higher HI_i is determined. The process focuses on equipment with a higher cost of failure, allowing to avoid it and also reducing the overall inspection cost. The proposed methodology is tested on an IEEE 39-bus power system with all primary side equipment implemented in a dedicated logic developed in Python. The methodology is intended to be used on equipment with limited or absent data.

II. Methodology

A. Risk of Failure

Risk of failure (RoF_i) is used in the power system to indicate the equipment importance based on failure consequences and probability. It consist of multiple components, such as the cost of load curtailment ($CoLC$), the cost of repair (CoR) and probability of failure (PoF). The $CoLC$ includes the value of lost load ($VoLL$) at time interval t and mean time to repair

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equipment ($MTTR$). Commonly, the failures in the power system causes N-1 (failure of equipment i) and N-2 (combined failure event between equipment i and j) contingencies. The (1) and (2) can be used to compute the risk value in N-1 and N-2 contingencies, and the maximum risk is obtained by (6). The cost of failure (CoF) combines the $CoLC$ and the CoR.

$$RoF_{i(N-1)} = ((VOLL_i(t) \cdot MTTR_i) + CoR_i) \cdot PoF_i = (CoLC_i + CoR_i) \cdot PoF_i \quad (1)$$

$$RoF_{ij(N-2)} = (CoLC_{ij} + CoR_i + CoR_j) \cdot PoF_i \cdot PoF_j \quad (2)$$

$$CoLC_{ij} = \begin{cases} MTTR_i > MTTR_j, & use\ (4) \\ MTTR_i = MTTR_j, & VOLL_{ij}(t) \cdot MTTR_i \\ MTTR_i < MTTR_j, & use\ (5) \end{cases} \quad (3)$$

$$VOLL_{ij}(t) \cdot MTTR_j + VOLL_i(t) \cdot (MTTR_i - MTTR_j) \quad (4)$$

$$VOLL_{ij}(t) \cdot MTTR_i + VOLL_j(t) \cdot (MTTR_j - MTTR_i) \quad (5)$$

$$RoF_i = max(RoF_{i(N-1)}, RoF_{ij(N-2)}) \quad (6)$$

B. Health Index Based Equipment Condition Indexing

The equipment HI_i can be obtained by grading its specific components or parameters within preset limits. Commonly used HI_i values are between 1 and 5. The HI_i value 1 means that the equipment is in a good condition, and HI_i value 5 indicates the need for equipment (partial) replacement. An option of determining the overall HI_i based on the condition of individual equipment components ($HI_{i(c1...cn)}$) is described by (7).

$$HI_i = max(HI_{i(c1)}, HI_{i(c2)}, ..., HI_{i(cn)}) \quad (7)$$

It is also necessary to implement the HI_i value in the risk calculation process by converting the HI_i into PoF_i. This allows to use it in optimization processes and for analysing the uncertainty impact in the case of stochastic or absent data.

C. Usage of Known Data for Estimation of Unknown Data

The estimation of HI_i or PoF_i based on unknown data requires having samples of known data. Latter is obtained from known HI_i values. For that, the group S with analysed equipment i needs to be chosen. Next, the group S is divided into group K including the equipment i with available data, and group M without available data (8).

$$S = K + M \quad (8)$$

The known HI_i from K are distributed based on their values. Next, that distribution is fitted to probability functions, such as exponential, beta, weibull, and normal. The goodness-of-fit of the chosen distributions is evaluated to determine the function with the best fit. For evaluating the fit of probabilistic characteristics, the sum of squared error (SSE) is used.

In accordance with the characteristic with the best fit, the HI_i values for the group M are estimated. For that, the Monte Carlo method is used to generate random values based on chosen distribution function. The generated values are linked to each HI_i value. The obtained distribution represents the estimated HI_i values for group M. From these, the PoF_i for the equipment is calculated by using the (9), where v_i is the randomly generated value based on the distribution functions.

$$PoF_i = \frac{v_i}{max(v_i)} \quad (9)$$

Based on the estimated PoF_i, the risk of equipment in M is calculated. For the PoF_i and the RoF_i values, the confidence interval is also obtained. In asset management procedures, the maximum value is used to lower the change of under-estimation. Compared to the uncertainty of the equipment RoF_i without the data of their conditions, the estimation process decreases that uncertainty level. Without the risk estimation, the confidence interval of RoF_i could not be determined. Therefore, these equipment are incomparable with the equipment having known risk values.

D. Implementation of Estimated Data in Asset Management

The estimated HI_i and PoF_i (subsequently RoF_i) are used for determining the amount of specific HI_i values in the group M. These are HI_i value 4 ($HI_i = 4$), meaning the need for maintenance to avoid further condition deterioration, and the HI_i value 5 ($HI_i = 5$), meaning extensive condition deterioration, and expected failure. Another use of the estimated values is to evaluate the importance of the equipment in M at the same base value as the equipment in K. Obtained data are combined for asset management.

The objective of asset management is to decrease the failure probability in the case of higher risk equipment. For that, the PoF_i, RoF_i, and HI_i need to be linked to individual equipment. In the case of K, due to the knowledge of the exact equipment with specific HI_i value, it is possible to directly focus on that equipment and arrange maintenance or schedule replacement. It is also known the potential consequences of the equipment failure. Therefore, the asset management can be addressed based on individual equipment. In the case of M, due to the estimation of HI_i for the whole group, it is not directly known the equipment, which has that specific higher HI_i value. Therefore, addressing that equipment is difficult.

An option is to assess the condition of each equipment in M, but this can be time-consuming and with a higher cost. On the opposite, the HI_i value 4 can lead to HI_i value 5 without on-time maintenance, which subsequently causes equipment failure. From an asset management perspective, both options are not preferred. Therefore, additional parameters are necessary to use to locate the potential equipment, whose failures could have higher consequences.

For that, the significance of the additional parameters indicating their combined weight (W_i) is implemented. The W_i (10) is a vector representing individual weight parameters w_i.

In this case, the w_1 is a cost related parameter and the w_2 is a risk related parameter.

$$W_i = f(w_1, w_2) \tag{10}$$

According to the W_i and its parameter w_1, the HI_i is linked based on their related tasks and consequences to specific cost components, indicated in (11) and (12).

$$(HI_i = 4) \longrightarrow (HI_i = 5), if\ \ i \in M \tag{11}$$

$$(HI_i = 5) = CoF_i, if\ \ i \in M \tag{12}$$

The cost function CoP_a for the group M is determined by (13). It represents the cost of not reacting to the individual equipment p with HI_i values 4 and 5 in the case of M.

$$CoP_a(HI_i = 4 \longrightarrow 5, 5) = \sum_{i=1}^{p} CoF_i, if\ \ i \in M \tag{13}$$

Another factor to be considered is the cost of reacting the opposite way to higher HI_i values. In the case of M, it means using the condition inspections to determine the exact equipment, which can have the HI_i values 4 and 5. For that, the condition and HI_i of each equipment m in M need to be assessed. This task is expressed by the cost function CoP_b in (14), where CoI_i is the cost of equipment inspection.

$$CoP_b(HI_i = 4, 5) = \sum_{i=1}^{m} CoI_i, if\ \ i \in M \tag{14}$$

Due to the different options of reacting to higher HI_i values and their related cost functions, the equilibrium in (15) need to be evaluated. It is expressed by cost function in (16).

$$CoP_a(HI_i = 4, 5) = CoP_b(HI_i = 4, 5) \tag{15}$$

$$\sum_{i=1}^{m} CoI_i = \sum_{i=1}^{p} CoF_i, if\ \ i \in M \tag{16}$$

In accordance with the objective of the asset management, the overall CoI_i and the CoF_i need to be minimised to meet the condition in (16) if the equipment is in M. Other ways, the cost-efficiency of asset management decreases. Based on the cost functions CoP_a, CoP_b, the weight vector W_i and the condition in (16), the minimisation function (17) is obtained.

$$F(CoP_a, CoP_b, W_i) = \min(\sum_{i=1}^{m} CoI_i, \sum_{i=1}^{p} CoF_i), if\ \ i \in M \tag{17}$$

In this case, it is reasonable to make an assumption, that failures of equipment in group M does not occur at the same time-frame. This simplifies the obtainment of CoF_i, which equals the CoF_i in N-1 contingencies (18).

$$\sum_{i=1}^{p} CoF_i \longrightarrow CoF_{ij(N-1)}, if\ \ i \in M \tag{18}$$

The minimisation function (17) is used in the process to determine the sequence of condition inspections of the equipment in the group M. This allows to avoid potential failures with higher cost and optimise the overall asset management cost.

E. Process of Choosing the Equipment for Condition Inspections

In accordance with the estimated knowledge of having HI_i values 4 and 5 in the group M, the cost-efficient sequence of the equipment condition inspection needs to be determined. This is decided based on the weight of additional parameters in W of the equipment in group M and the minimisation function. By the principle of the process, the highest CoF_i is avoided by inspecting the equipment condition and implementing necessary measures, such as condition maintenance or replacement. Therefore, in each iteration (actual inspections), the potentially highest CoF_i is reduced in a sequence. This is done until the highest CoF_i is lower than the $\sum_{i=1}^{m} CoI_i$ for remaining equipment in the group M.

Initially, it is necessary to summarize the equipment p in M with estimated HI_i values 4 and 5, indicated by $\sum_{i=1}^{p}(HI_I = 4, 5)$. Next, the process in the following is used. The process consists of a sequence of tasks and conditions, described as:

- Step 1 - Selecting the equipment with highest CoF_i in N-1 contingencies.
- Step 2 - Inspecting the condition of the selected equipment and removing its CoF_i from iterations.
- Step 3 - If obtained HI_i is rated as 4 or 5, then the $\sum_{i=1}^{p}(HI_i = 4, 5)$ is reduced by 1.
- Step 4 - the $\sum_{i=1}^{m} CoI_i$ is reduced by the CoI_i.
- Step 5 - checking the condition in (16) to meet the minimization objective (17).
- Step 6 - if the potential CoF_i in N-1 contingencies is higher than the $\sum_{i=1}^{m} CoI_i$ and if the $\sum_{i=1}^{p}(HI_i = 4, 5)$ is above 1, then the next iteration starts.
- Similarly, in Step 1, the equipment with the highest CoF_i in N-1 contingencies is chosen and in Step 2, its condition is inspected.
- The iteration ends with Steps 3, 4 and 5.
- If the conditions in Steps 5 and 6 are not met, then the process stops.

The end of the process means that the overall cost of condition inspection of the remaining equipment in the group M, to detect the equipment with HI_i values 4 and 5, costs more than the potential equipment failure CoF_i.

The proposed methodology allows to step from the total uncertainty about the condition of these equipment to the decreased uncertainty due to estimated conditions. Secondly, the equipment failures can be avoided by inspecting them in sequence based on the described process above. Thirdly, this allows to reduce the total inspection and asset management costs. Lastly, the awareness about equipment conditions in group M increases due to the inspections.

III. CASE STUDY

The IEEE 39-bus power system, given in Fig.1, is modeled in PSSE for contingency analysis. This allows to obtain the amount of load curtailment after equipment failures. From that, the CoF_i is obtained. The risk calculations are implemented in Python as a dedicated logic process. In that, the CoF_i

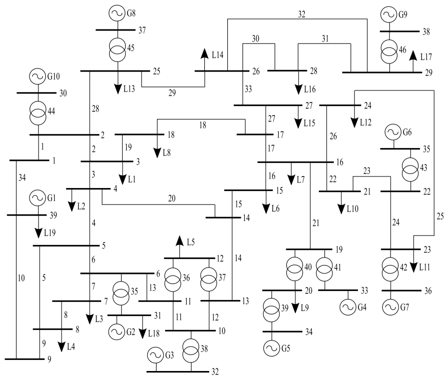

Fig. 1. Schematic of the IEEE 39-bus power system used in the risk calculations. Power system data is available in [15].

is linked to individual equipment, and its risk is calculated. Each substation equipment on the primary side existing in real power systems is included in the risk calculation logic.

The chosen equipment group is instrument transformers, which forms group S. It is assumed, that in each substation bay, a current and voltage transformer is located. In addition, voltage transformers are also in substation section busbars. Therefore, the overall size of group S is 320. The assumed size of group K is 32 and the size of group M is 288. The objective is to estimate the unknown HI_i values in M based on the HI_i in K. Next, the fictive condition inspections, such as measuring partial discharges, dielectric losses and moisture in electrical insulation, magnetization characteristic, saturation behavior, transformation ratio and its accuracy, polarity, load, winding resistance, and withstand voltage, is used to detect the equipment in M with HI_i values 4 and 5. The efficiency of proposed process is compared to the cost of inspecting equipment's condition without predetermined sequence. Three cases are considered. The CoI_i compared to the CoR_i is 5% in Case A, 2.5% in Case B, and 0.5% in Case C. The CoR_i is assumed to be 20 k€.

IV. Results

The results of the proposed methodology are presented in the following. Firstly, the HI_i values of the equipment in group K with the known data are used to obtain the best fit distribution function, represented in Fig. 2. Next, the distribution with the lowest SSE is chosen, and the PoF_i mean value of the equipment in the group M is obtained. The Monte Carlo simulation is used based on the characteristic parameters of the distribution function with the best fit. Subsequently, the risk (RoF_i) for these equipment is calculated. In addition, the HI_i values for the equipment in M are estimated.

In the Table I is given the PoF_i mean value and confidence intervals for 95 % in accordance to Z-distribution and bootstrap methods. It can be noticed, that the lower and upper limits are relatively near to mean value of the PoF_i. In the Fig. 3 is given the risk values (RoF_i) for the whole group S based on the estimation. It can be noticed, that the risk of the majority of equipment is around 250. This is due to having similar maximum failure consequences in N-2 situations. Certain equipment in group have risk values above 500 indicating higher importance and potentially higher CoF_i.

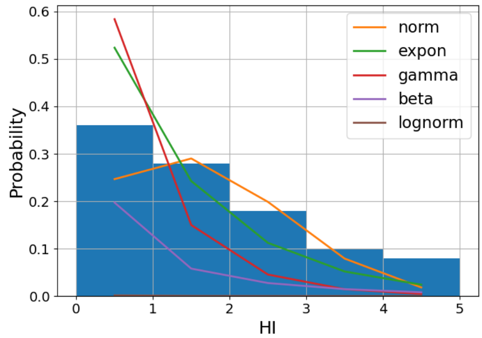

Fig. 2. Proportional distribution of known HI values of equipment group K and fitted likelihood functions

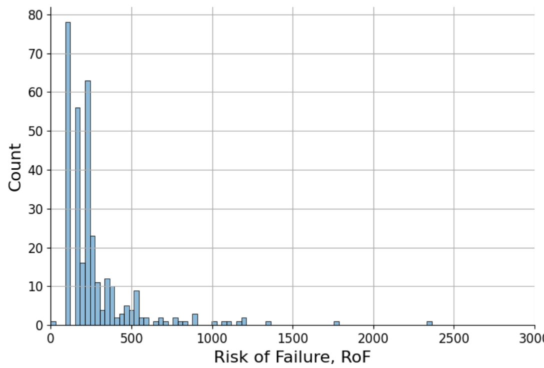

Fig. 3. Risk values of the equipment in group S after condition estimation

In the Table II is given the estimated number of HI_i values for the group M. It can be noticed, that the total $\sum_{i=1}^{p}(HI_i = 4,5)$ value is 35. Therefore, from the 288 instrument transformers in the group M, potentially 12 could have failure in the upcoming time-frame. In the longer time-frame, 23 additional equipment could have failure. Based on that knowledge of the potential equipment with higher HI_i values in the group M, the cost of their failures needs to be minimised. The risk values in Fig. 3 can be used for that purpose representing the maximum risk in the case of N-1 and N-2 contingencies. Due to the assumption that the failures do not occur at the same time-frame, the CoF_i in N-1 contingencies are used instead. Overall, they follow the same pattern as the risk value.

In Fig. 4 is given the result of using the proposed process, where the difference between the $\sum_{i=1}^{m} CoI_i$ and the highest CoF_i for each iteration (number of equipment inspected) is

TABLE I
SUM OF SQUARED ERROR (SSE) VALUES BASED FITTING DISTRIBUTION FUNCTIONS TO HI_i VALUES IN K

	Mean	CI(Z-value)	CI(Bootstrap)
PoF_i	0,285	[0,268 0, 302]	[0,260 0,304]

TABLE II
THE NUMBER OF ESTIMATED HI_i VALUES FOR THE EQUIPMENT IN M

	HI = 1	HI = 2	HI = 3	HI = 4	HI = 5
Total	117	81	55	23	12

presented. It can be noticed, that initially the equipment with the highest CoF_i is chosen. In the following iterations, the maximum equipment CoF_i decreases. At iteration 44 (number of inspections done), the remaining $\sum_{i=1}^{m} CoI_i$ is higher than the potentially avoided CoF_i at that iteration. It indicates the inefficiency to inspect remaining equipment (244 in this case) from a cost perspective. Therefore, the initial total CoI_i is reduced from 288 k€ (inspecting randomly all equipment) to 44 k€, and the data about the condition of equipment with higher CoF_i is obtained. The difference between Cases A, B, and C is noticed after iteration 44. In Case C, inspecting remaining 244 equipment do not increase the cost difference significantly.

If assuming the occurrence of multiple failures within the relatively narrow time-frame, then the overall CoF_i can be considerably higher, increasing the difference to the total CoI_i. Subsequently, it is reasonable to inspect the condition of all equipment in M from a cost perspective. Nevertheless, if the time-frame is relatively wide, such as 10 years, then the proposed process can be preferred.

V. CONCLUSION

This paper presents a process to determine the cost-efficient inspection sequence of equipment without exact condition data. It is based on the usage of known HI_i values to estimate the unknown HI_i values. If the estimated HI_i includes higher values, the process allows for direct condition inspections to the equipment with a higher failure cost. This decreases the needed inspection cost, which are other ways used to inspect all of the equipment. The process reduces the uncertainty in equipment data, allows to avoid failures with higher cost, and increases the proportion of known HI_i data. The results indicated the reduction of needed inspection cost by 80 % with a decrease in potential failures with higher costs. The proposed process is mainly intended for equipment with limited data.

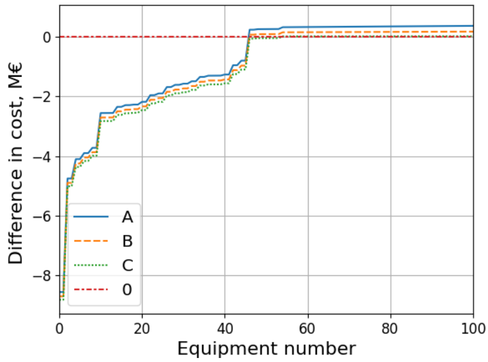

Fig. 4. Difference in the summarized inspection cost and the potentially avoided failure cost at the inspection for each iteration (equipment number). Line 0 indicates threshold, when the cost of inspecting the remaining elements becomes higher then the cost of avoided equipment failure. Lines A, B, and C indicates corresponding cases.

REFERENCES

[1] S. R. Khuntia and B. Heling, "Assessment of different health index aggregation techniques for electric utilities," in *2023 IEEE PES GTD International Conference and Exposition (GTD)*. IEEE, May 2023.

[2] J. H. Jürgensen, L. Nordström, and P. Hilber, "Individual failure rates for transformers within a population based on diagnostic measures," *Electric Power Systems Research*, vol. 141, pp. 354–362, Dec. 2016.

[3] 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. 17, no. 9, pp. 1972–1984, Mar. 2023.

[4] G. C. Montanari, P. Seri, and R. Hebner, "A scheme for the health index and residual life of cables based on measurement and monitoring of diagnostic quantities," in *2018 IEEE Power & Energy Society General Meeting (PESGM)*. IEEE, Aug. 2018.

[5] A. Purnomoadi, I. M. Sari, J. Anna Maria, D. B. Fiddiansyah, N. E. Saputro, and M. Sofan Hadi, "A method to quantify data quality in asset health indices model," in *2023 4th International Conference on High Voltage Engineering and Power Systems (ICHVEPS)*. IEEE, Aug. 2023.

[6] R. A. Prasojo, Suwarno, and A. Abu-Siada, "Dealing with data uncertainty for transformer insulation system health index," *IEEE Access*, vol. 9, pp. 74 703–74 712, 2021.

[7] 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, Jan. 2024.

[8] J. Foros and M. Istad, "Health index, risk and remaining lifetime estimation of power transformers," *IEEE Transactions on Power Delivery*, vol. 35, no. 6, pp. 2612–2620, Dec. 2020.

[9] D. Zhang, Z. Chu, Q. Gui, F. Wu, H. Yang, Y. Ma, and W. Tao, "Transformer maintenance decision based on condition monitoring and fuzzy probability hybrid reliability assessment," *IET Generation, Transmission & Distribution*, vol. 17, no. 4, pp. 976–992, Dec. 2022.

[10] R. D. Medina, D. A. Zaldivar, A. A. Romero, J. Zuñiga, and E. E. Mombello, "A fuzzy inference-based approach for estimating power transformers risk index," *Electric Power Systems Research*, vol. 209, p. 108004, Aug. 2022.

[11] N. A. Bakar and A. Abu-Siada, "Fuzzy logic approach for transformer remnant life prediction and asset management decision," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 23, no. 5, pp. 3199–3208, Oct. 2016.

[12] J. Aizpurua, B. Stewart, S. McArthur, B. Lambert, J. Cross, and V. Catterson, "Improved power transformer condition monitoring under uncertainty through soft computing and probabilistic health index," *Applied Soft Computing*, vol. 85, p. 105530, Dec. 2019.

[13] M. Dong, W. Li, and A. B. Nassif, "Long-term health index prediction for power asset classes based on sequence learning," *IEEE Transactions on Power Delivery*, vol. 37, no. 1, pp. 197–207, Feb. 2022.

[14] A. Crespo Márquez, J. Serra Parajes, A. de la Fuente Carmona, and A. Sola Rosique, "Integrating complex asset health modelling techniques with continuous time simulation modelling: A practical tool for maintenance and capital investments analysis," *Computers in Industry*, vol. 133, p. 103507, Dec. 2021.

[15] MatPower, "Power flow data for 39 bus new england system," 2024.

Appendix 3

III

G. Andreesen, M. Leinakse, J. Kilter, and M. Landsberg, “Cost-efficient improvement of power system’s reliability within limited funds,” in *RTUCON 2024*. IEEE, oct 2024, pp. 1–6

Cost-Efficient Improvement of Power System's Reliability within Limited Funds

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***Abstract*—This paper presents a methodology for the cost-efficient improvement of the power system's reliability. The proposed process combines two risk reduction methods: improving the condition awareness of equipment and reducing the replacement time of equipment. The process assesses risk reduction efficiency based on the achievable decrease in risk and its related cost. At each iteration a part of the limited funds is allocated to the most cost efficient risk reduction method. The methodology can be implemented on all the equipment of substation primary side. The results of a case study are presented to illustrate the proposed methodology. They indicate, that in each iteration the process decreases the risk using the most cost-efficient way. In addition, with certain equipment groups the higher cost-efficiency is achieved by arranging a spare equipment in substation cluster. The methodology can assist network owners and system operators in determining the cost-efficient method to improve the reliability of the power system within the limited funds.**

***Index Terms*—Asset management, Cost-efficient management, Risk assessment, Risk reduction, Substation reliability**

I. INTRODUCTION

The main task of the system operators is to maintain the proper functioning of the power system and improve its reliability in a cost-efficient manner. The available funds for that mainly depend on the capital expenditures ($CAPEX$) planned for upcoming period. Commonly, it is a limited value determining also the limit for the reliability improvement. The system's reliability is based on its equipment's risk of failure. Therefore, an option to increase the reliability is reducing the risk as much as possible within available funds. Thus, these funds need to be directed towards assets, which risk can be reduced with higher cost-efficiency. For that, it is necessary to calculate the achievable risk reduction for each equipment and its cost. Latter depends on the risk reduction measures used.

In [1], [2], methods to identify the equipment of higher risk value based on an example of circuit breakers is presented. A method to rank power transformers based on their risk is proposed in [3]. The reliability of substations is evaluated in [4], [5]. In there, the load restrictions after the failures in substation connections were considered as an important parameter. This is supported by the methodology presented in [6], also including switching equipment operations.

Asset management approaches in a power system are analysed in [7], [8]. It is stated, that improving the condition awareness of equipment allows to increase the system's reliability by decreasing their failure probability. A condition-based asset management methodology for maintaining the functionality of power system's equipment is given in [9]. Similar methodologies are proposed in [10], [11] for reliability focused maintenance and its scheduling based on equipment risk. In there, the asset management procedures is directed towards higher risk assets for achieving the increase in reliability.

A methodology for allocating the available funds for the management of higher risk equipment is presented in [12]. The implementation of condition monitoring solutions for improving the condition awareness and the substations reliability is analysed in [13], [14]. The methodologies are applied on circuit breakers as chosen equipment group. The condition monitoring solutions are also a part of stochastic processes for maintenance scheduling in an approach proposed in [15].

There are various aspects presented in the existing literature, however, some distinctive gaps can be distinguished. Firstly, the description of risk reduction process from cost-efficiency perspective by considering the cost of condition assessment. Secondly, the analysis of risk reduction cost-efficiency from the perspective of arranging a spare equipment in a substation cluster.

This paper addresses these gaps and proposes a methodology for the cost-efficient improvement of the power system's reliability. The objective is to divide the available funds in a cost-efficient manner for risk reduction. It is achieved by either using condition monitoring solutions or inspections to decrease the failure probability of equipment, or arranging a spare equipment in substations. For that, two risk reduction methods are combined in a process. As a result, the limited funds are directed towards equipment or equipment group with highest cost-efficiency of risk reduction. This allows to improve the power system's reliability with higher cost-efficiency of asset management.

II. METHODOLOGY

A. *Value of Risk*

The criticality of the substation equipment in power system is indicated by the risk of failure (RoF_i). The risk consist of multiple components, such as the cost of load curtailment ($CoLC$), the cost of replacement (CoR) and probability of failure (PoF). The $CoLC$ includes the value of lost load

($VoLL$) at time interval t and mean time of equipment repair ($MTTR$). Commonly, the failures in the power system causes N-1 (failure of equipment i) and N-2 (combined failure event between equipment i and j) contingencies. The (1) and (2) can be used to compute the risk value in N-1 and N-2 contingencies, and the maximum risk is obtained by (6).

$$RoF_{i(N-1)} = ((VOLL_i(t) \cdot MTTR_i) + CoR_i) \cdot PoF_i = (CoLC_i + CoR_i) \cdot PoF_i \quad (1)$$

$$RoF_{ij(N-2)} = (CoLC_{ij} + CoR_i + CoR_j) \cdot PoF_i \cdot PoF_j \quad (2)$$

$$CoLC_{ij} = \begin{cases} MTTR_i > MTTR_j, \ use \ (4) \\ MTTR_i = MTTR_j, \ VOLL_{ij}(t) \cdot MTTR_i \\ MTTR_i < MTTR_j, \ use \ (5) \end{cases} \quad (3)$$

$$VOLL_{ij}(t) \cdot MTTR_j + VOLL_i(t) \cdot (MTTR_i - MTTR_j) \quad (4)$$

$$VOLL_{ij}(t) \cdot MTTR_i + VOLL_j(t) \cdot (MTTR_j - MTTR_i) \quad (5)$$

$$RoF_i = max(RoF_{i(N-1)}, RoF_{ij(N-2)}) \quad (6)$$

B. Cost-Efficiency of Risk Reduction

The increase in power system's reliability can be achieved by decreasing the risk of substation equipment. Commonly, the funds needed are taken from the $CAPEX$ planned for the time period T, described as $(CAPEX_{lim}(T))$. Thus, the $CAPEX$ used in risk reduction in time period T should be within the limit of $(CAPEX_{lim}(T))$ as expressed by (7).

$$CAPEX(T) < CAPEX_{lim}(T) \quad (7)$$

The objective is to achieve maximum risk reduction efficiency within available $CAPEX(T)$. The extent of risk reduction is described by the difference of risk value (ΔRoF_i) before the reduction $RoF_{i(Bef)}$ and after the reduction $RoF_{i(Aft)}$, expressed by (8).

$$max(\Delta RoF_i) = max(RoF_{i(Bef)} - RoF_{i(Aft)}) \quad (8)$$

For the risk reduction, specific methods should be used. The risk reduction methods considered in this paper are:

- Method A - reducing the failure probability (PoF) of substation equipment;
- Method B - reducing the replacement time ($MTTR$) of substation equipment.

In method A, the risk of equipment is reduced by using condition-based asset management. It means, that the condition of equipment is monitored in real-time or relatively frequently. As a result, the occurred defects in equipment leading to failure are detected earlier. Therefore, their probability of failure (PoF), and subsequently, the risk is decreased. For that, measurement solutions or condition inspections can be used. The cost perspective of condition monitoring is represented by the cost of condition-based management ($CoCBM$). The $CAPEX$ related $CoCBM$ includes the cost of measurement solutions ($CoMS$) and the cost of condition inspections (CoI), expressed by (9).

$$CoCBM = CoMS + CoI \quad (9)$$

The method A is implemented individually for each selected equipment. Thus, the risk reduction is equipment-specific. It also means, that the $CoCBM_i$ related to it can be different. Nevertheless, the total cost of the risk reduction should meet the condition in the (10). If the $CoCBM$ for each equipment is the same, then the potential number of equipment (N_D) included in condition-based method (CBM) depends on the (11).

$$\sum_{i=1}^{n} CoCBM_i(T) < (CAPEX_{lim}(T)) \quad (10)$$

$$N_D = \frac{(CAPEX_{lim}(T))}{CoCBM_i} \quad (11)$$

The cost of risk reduction ($CoRR$) based on method A for individual equipment equals to the $CoCBM_i$. For the group of similar equipment, it is expressed by (12).

$$CoRR(A) = N_D \cdot CoCBM_i \quad (12)$$

In method B, the risk of equipment is reduced by reducing their replacement time ($MTTR$) after the occurred failure. Subsequently, this decreases the cost of load curtailment ($CoLC$) and therefore the risk. The $MTTR$ consist of:

- Stage 1 - Determining the location and the type of failed equipment;
- Stage 2 - Preparation time of maintenance team;
- Stage 3 - Getting the spare equipment;
- Stage 4 - Bringing the spare equipment to substation, where the failed equipment is located;
- Stage 5 - Replacing the failed equipment.

An option is to beforehand arrange a spare equipment in the substation, which can be used to replace the failed equipment. This makes it possible to discard stage 3 and 4 from the replacement process. Thus, there is no need to bring the replacement equipment to the substation allowing to reduce the $MTTR$. However, the maintenance team still needs to get to the failed equipment. Therefore, the reduction of $MTTR$ depends on the distance between the location of maintenance team, spare equipment and destination substation. In method B, the cost related to $CAPEX$ is the cost of replacement (CoR) required to acquire a spare equipment.

The method B can be implemented on all similar equipment in the same or nearby substation. It means, that the spare equipment for a equipment group k (equipment with the same purpose and functionality) is located at the chosen substation. After the failure of equipment, it is replaced with a spare equipment. Then, the next spare equipment is brought to the substation. Thus, it is possible to reduce the risk of all similar equipment in the same or a cluster of multiple substations. The maximum number of spare equipment (N_S) to locate in substations depends on (13).

$$N_S = \frac{(CAPEX_{lim}(T))}{CoR_i} \quad (13)$$

The main advantage of the method B compared to method A is the possibility to reduce the risk of all similar equipment in the multiple substations. The disadvantage is the missing data about the condition of equipment possible to obtain by using method A. Also, occurred defects can be detected only during inspections. Therefore, the method B is considered as partially preventive method. The method B could be preferred, if the equipment has lower CoR and the suitable (low cost) measurement solutions or frequent inspections are absent. The cost of risk reduction based on method B for a equipment group k equals CoR. The total cost of the method B is obtained by (14).

$$CoRR(B) = N_S \cdot CoR_i \tag{14}$$

In both methods, the achievable ΔRoF_i after the risk reduction is evaluated from the cost ($CoRR$) perspective. It is expressed by the efficiency of the risk reduction ($EoRR$) and is obtained for method A by (15) and for method B by (16).

$$EoRR(A)_i = \frac{\Delta RoF_i}{CoRR(A)_i} \tag{15}$$

$$EoRR(B)_k = \frac{\sum_{i=1}^{k} \Delta RoF_i}{CoRR(B)_k} \tag{16}$$

The difference between the $EoRR$ of method A and B for multiple similar equipment (in group k) is assessed by (17). The cost-efficiency of method A increases, if the $CoCBM_i$ or the N_S decreases. To prefer method B, the $CoCBM_i$ or the N_S should increase. The total change of ΔRoF_i has also significant impact on methods efficiency.

$$\frac{\sum_{i=1}^{N_D} \Delta RoF_i(A)}{N_D \cdot CoCBM_i} = \frac{\sum_{i=1}^{k} \Delta RoF_i(B)}{N_S \cdot CoR_i} \tag{17}$$

C. Process of Cost-Efficient Risk Reduction

The risk reduction methods A and B are used in a iterative process for reducing the risk cost-efficiently. The main process is shown in Fig. 1. Initially, the group C is formed with chosen equipment i included in risk reduction. The group C can be also used for excluding specific equipment i or equipment groups from risk reduction process.

In each iteration c, the equipment with the highest $EoRR(A)_i$ is chosen. Next, the equipment group k of that equipment i is obtained, and the $EoRR(B)_k$ is calculated. If the $EoRR(A)_i$ is higher than $EoRR(B)_k$, then the PoF_i of that equipment is decreased (measurement solutions are added). Other ways, the $MTTR_i$ of the equipment in the group k is reduced (spare equipment is arranged). After the iteration, the individual equipment i or the equipment group k is removed from the C. Next, the following iteration begins.

In each iteration, the $CoRR(A)_i$ and $CoRR(B)_k$ is compared to the available funds $r(CAPEX)$. Latter decreases after the exclusion of $CoRR(A)_i$ or $CoRR(B)_k$ in iteration from the $(CAPEX_{lim}(T))$. In addition, if the $CoRR(A)_i$ or $CoRR(B)_k$ is higher than $r(CAPEX)$ in each iteration,

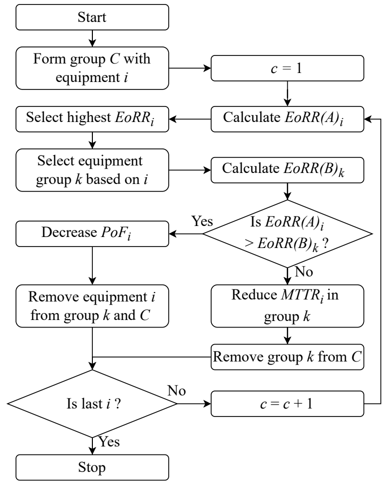

Fig. 1. Main process of risk reduction based on $EoRR$ obtained by method A and B

then either method A or B is skipped. The process stops, if the $CoRR$ of both method is higher than $r(CAPEX)$. This means that all the available funds for risk reduction have been used.

III. Case Study

In the case study a power system with three substations, shown in Fig. 2, is used. The TS denotes the transmission system side of a substation, while the DS denotes the distribution system side. The generation units are connected to substation S1. Substations S2 and S3 have a combined load of 30 MW. The power transformers are rated 50 MVA (S1), 16 MVA (S2) and 25 MVA (S3).

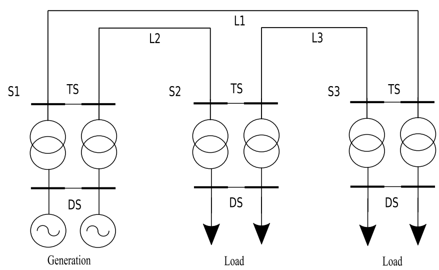

Fig. 2. Principle schematic of a transmission system used in the case study

The substations use the topology illustrated by Fig. 3. All primary side equipment of a substation are included. E1...E5 are sets of series connected equipment. B1 and B2 are sets of equipment, which include busbar and equipment directly linked to the busbar. The schematic connections E1 and E2 are connected to TS and connections E3 and E4 to DS.

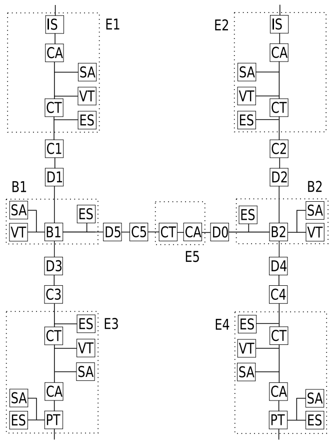

Fig. 3. Schematic of a power system substation with sectionalized bus configuration used in the case study (Equipment in schematic: IS – insulator, CA – cable or over-head line, SA – surge arrester, VT – voltage transformer, CT – current transformer, ES – earthing switch, Ci – circuit breaker i, Di – disconnector i, Bi – busbar i, PT – power transformer. Ei indicates connections)

Table I shows the occurred load curtailment caused by the disconnection of substation connections. The $MTTR$ values for PT is assumed to be 24 hours and 8 hours for other equipment. The disconnection period of substation sections by disconnectors after a failure is 2 hours.

TABLE I
POTENTIAL CURTAILMENT OF LOADS

Disconnected element	Overloaded element	Load curtailment, MW
L1	L2	7.25
L2	L1	8.7
PT(E3) (S2)	PT(E4) (S2)	9.75
PT(E4) (S2)	PT(E3) (S2)	9.75
L1 + (PT(E3 or E4) (S2))	L2 + (PT(E3 or E4) (S2))	9.75
L2 + (PT(E3 or E4) (S2))	L1 + (PT(E3 or E4) (S2))	10.2
S1 or (S2 and S3)		60
S2 and S3		30
S3 and (PT(E3 or E4) (S2))		39.75

The assumed CoR is: C - 30 k€, D - 10 k€, B - 5 k€, VT - 20 k€, CT - 20 k€, CA - 10 k€, ES - 2 k€, SA - 1 k€, IS - 1 k€, PT - (16 MVA) 200 k€, (25 MVA) 300 k€, (50 MVA) 500 k€. The $CoCBM$ is taken as 0.25% from the CoR. The PoF values of equipment is generated randomly by uniform distribution between 0.1 and 0.5 (assuming older equipment) for simulating the differences in devices conditions. 1000 simulations were run. In method A, the failure probability of equipment (PoF_i) is reduced to 0.01 after implementing CBM. In method B, the $MTTR_i$ is reduced by 3 hours. It is assumed, that the reduction of $MTTR_i$ affects equipment in all substations S1, S2 and S3 as a whole cluster. The $(CAPEX_{lim}(T))$ is set to 100 k€. In the case study two cases are analysed. In Case 1, the proposed risk reduction process combining method A and B is used. In Case 2, the risk is reduced by the common method - applying condition-based asset management according to the highest ΔRoF_i in each iteration. All equipment groups seen in Fig. 3, besides B and PT, are included in simulation.

IV. Results

The efficiency of risk reduction ($EoRR$) based on the Case 1 (indicated by black) and Case 2 (indicated by red) is presented in Fig. 4. It can be noticed, that the proposed risk reduction process (Case 1) has higher $EoRR$ values than in Case 2. Especially, during the initial 10 iterations. The variability of $EoRR$ from its mean value in Case B is also bigger. That indicates the inefficiency of risk reduction from cost perspective.

It also indicates that decreasing risk by only considering it change results in inefficient cost distribution. If the cost of risk reduction is not included (Case 2), then the higher decrease in risk could be achieved by a higher cost. This leads into situations where only some of equipment are included in risk reduction within limited funds. Therefore, the cost of risk reduction is not optimised. If using the proposed method (Case 1), where the cost is included, it is possible to achieve higher efficiency of risk reduction within the same funds. Also, it is possible to reduce the risk of more equipment.

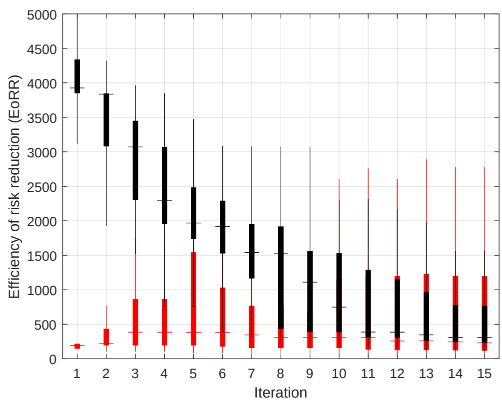

Fig. 4. The efficiency of risk reduction ($EoRR$) based on the Case 1 (indicated by black) and Case 2 (indicated by red)

The cost of risk reduction ($CoRR$) based on the Case 1 (indicated by black) and Case 2 (indicated by red) is shown in Fig. 5. It can be noticed, that the proposed risk reduction process (Case 1) has lower $CoRR$ values than in Case 2. This trend is visible throughout iterations. In addition, the variability of $CoRR$ is also larger in Case 2 indicating the lower $EoRR$ by choosing the equipment by ΔRoF_i.

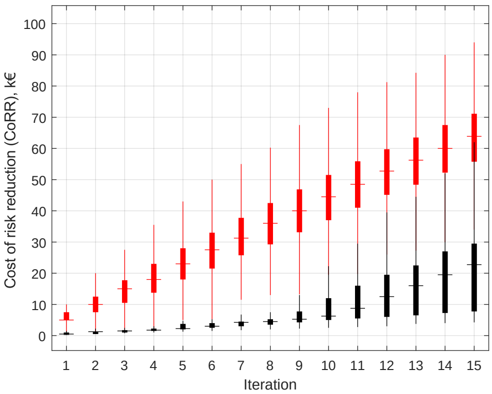

Fig. 5. The cumulative cost of risk reduction ($CoRR_i$) based on the Case 1 (indicated by black) and Case 2 (indicated by red)

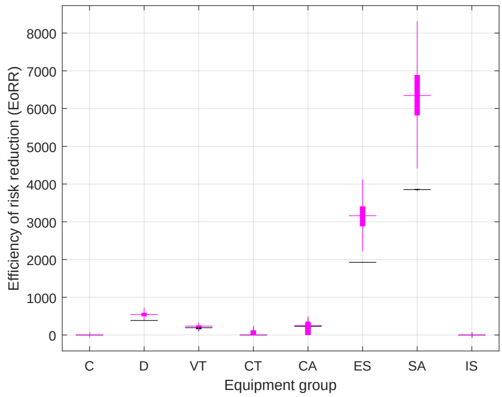

Fig. 6. The efficiency of risk reduction ($EoRR$), when method B is chosen instead of method A, for each equipment group used. The $EoRR(A)$ is indicated by black and the $EoRR(B)$ is indicated by magenta

It can also be noticed that the spread of cumulative cost of risk reduction in iterations 1 to 4 is relatively small. This is caused by the reason that decreasing the risk of some equipment are cost-efficient with a higher range of PoF_i values. It is mainly related to the difference between the $CoCBM_i$, the CoR_i, the N_D and the N_S. Therefore, it is possible to achieve higher risk reduction cost-efficiency, if arranging spare equipment for a group of similar equipment instead of decreasing the risk in one equipment within the same funds.

Efficiency of risk reduction ($EoRR$), when method B is chosen instead of method A is presented in Fig. 6. The $EoRR(A)$ is indicated in black and the $EoRR(B)$ is indicated in magenta. It can be seen, that the $EoRR(B)$ values are higher than $EoRR(A)$ values with most of the equipment groups (D, VT, CA, ES, SA). Thus, arranging a spare equipment for these equipment groups (using method B) can yield higher risk reduction cost-efficiency ($EoRR$) than using condition measurement solutions (method A). The highest $EoRR$ values are with equipment group ES and SA, though. The reason for that lays on the number of equipment in the substation schematic in Fig. 3. Another aspect is also the $CoCBM$ and CoR of equipment SA and ES. As a result, the cost-efficiency of their risk reduction ($EoRR$) is higher than other equipment or equipment groups. Thus, for these equipment it is reasonable to arrange a spare one instead of using condition monitoring or inspections.

The results in Fig. 4, Fig. 5, and Fig. 6 are dependent on the inputs used in a specific case study. Thus, the implementation of the proposed process in other cases can yield different outcomes. Overall, the proposed process allows to achieve higher risk reduction cost-efficiency compared to using available funds only based on the highest ΔRoF_i. It can also be used for evaluating the arrangement of spare equipment at a substation instead of using condition-based asset management from the perspective of risk reduction cost-efficiency.

V. Conclusions

This paper proposes a methodology for cost-efficient improvement of power system's reliability. It uses iterative process combining two risk reduction methods, i.e., the risk of equipment is reduced by using condition-based asset management or the risk of equipment group is reduced by arranging the spare equipment in substation for a cluster of substations. In the process, most cost-efficient approach is chosen. Presented case study indicates that the process decreases the risk of equipment or equipment groups by choosing the highest cost-efficiency value in each iteration. It is also shown that it is more cost-efficient with certain equipment groups to decrease the risk by arranging the spare equipment in substation cluster instead of condition-based asset management. The methodology can be an add-on tool for network owners or system operators to improve the cost-efficiency of their asset management.

References

[1] D. Huang and B. Bagen, "System reliability risk model and its application to station breaker replacement," in *2020 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*, Aug 2020, pp. 1–6.

[2] A. P. Shishavan and A. Razi-Kazemi, "A practical knowledge-based ranking approach to identify critical circuit breakers in large power systems," *Knowledge-Based Systems*, vol. 227, p. 107237, sep 2021.

[3] R. D. Medina, D. A. Zaldivar, A. A. Romero, J. Zuñiga, and E. E. Mombello, "A fuzzy inference-based approach for estimating power transformers risk index," *Electric Power Systems Research*, vol. 209, p. 108004, aug 2022.

[4] Z. Cramer, M. Y. Vaziri, and M. Zarghami, "Distribution substation bus design for optimal reliability and economics," in *2015 IEEE Power & Energy Society General Meeting*, July 2015, pp. 1–5.

[5] M. Papic, O. A. Ciniglio, and S. K. Agarwal, "Reliability assessment of multiple substations in idaho system using a node-breaker model," in *2016 IEEE Power and Energy Society General Meeting (PESGM)*, July 2016, pp. 1–5.

[6] F. Dong and L. Fan, "Power system reliability assessment with full topology model," in *2017 IEEE Power & Energy Society General Meeting*, July 2017, pp. 1–5.

[7] S. R. Khuntia, J. L. Rueda, S. Bouwman, and M. A. M. M. van der Meijden, "A literature survey on asset management in electrical power [transmission and distribution] system," *International Transactions on Electrical Energy Systems*, vol. 26, no. 10, pp. 2123–2133, feb 2016.

[8] D. Clements and P. Mancarella, "Systemic modelling and integrated assessment of asset management strategies and staff constraints on distribution network reliability," *Electric Power Systems Research*, vol. 155, pp. 164–171, feb 2018.

[9] C. Wang, Y. Hou, Z. Qin, C. Peng, and H. Zhou, "Dynamic coordinated condition-based maintenance for multiple components with external conditions," *IEEE Transactions on Power Delivery*, vol. 30, no. 5, pp. 2362–2370, oct 2015.

[10] E. Shayesteh and P. Hilber, "Reliability-centered asset management using component reliability importance," in *2016 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*. IEEE, oct 2016.

[11] A. Alizadeh, A. Fereidunian, M. Moghimi, and H. Lesani, "Reliability-centered maintenance scheduling considering failure rates uncertainty: A two-stage robust model," *IEEE Transactions on Power Delivery*, vol. 37, no. 3, pp. 1941–1951, jun 2022.

[12] H. Mirsaeedi, A. Fereidunian, S. M. Mohammadi-Hosseininejad, and H. Lesani, "Electricity distribution system maintenance budgeting: A reliability-centered approach," *IEEE Transactions on Power Delivery*, vol. 33, no. 4, pp. 1599–1610, aug 2018.

[13] J. Zhong, W. Li, R. Billinton, and J. Yu, "Incorporating a condition monitoring based aging failure model of a circuit breaker in substation reliability assessment," *IEEE Transactions on Power Systems*, vol. 30, no. 6, pp. 3407–3415, Nov 2015.

[14] A. A. Razi-Kazemi and M. Shariatnasab, "A new approach on prioritization of the circuit breakers for installation of online monitoring systems," *IEEE Transactions on Power Delivery*, vol. 34, no. 4, pp. 1569–1577, Aug 2019.

[15] H. A. R. Ardabili, M.-R. Haghifam, and S. M. Abedi, "A stochastic markov model for maintenance scheduling in the presence of online monitoring system," *IEEE Transactions on Power Delivery*, vol. 37, no. 4, pp. 2831–2842, aug 2022.

Appendix 4

IV

G. Andreesen, M. Leinakse, J. Kilter and M. Landsberg, “Methodology for forecasting the cost of substation asset management in upcoming future,” in *PECON 2024*. IEEE, nov 2024, pp. 1–5

Methodology for Forecasting the Cost of Substation Asset Management in Upcoming Future

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***Abstract*—In this paper, the methodology to forecast the cost of substation asset management over longer time periods is proposed. The methodology allows for the simulation of the cost of different management methods based on their cost components. Thus, it can be implemented for a preliminary analysis of the cost related outcomes of management tasks and decisions and in the transition to risk-based management. Firstly, it assists in determining the impact of equipment prioritization on the total management cost. Secondly, for obtaining the optimal number of prioritized equipment. The case study is used to illustrate the methodology. The results indicated that a process kept the cost of the risk-based method below the time- or condition-based method. In according with results, prioritizing all of the equipment in the initial time period has lower cost compared to the cost of the time-based method in the later period.**

***Index Terms*—Asset management, Management cost-efficiency, Risk-based management, Risk reduction, Substation reliability**

I. Introduction

The asset management of substations is important for maintaining the power system's reliability, avoiding failures resulting in great consequences, and dealing with aging equipment. Both of these factors increase the cost of asset management. To achieve higher cost-efficiency, management focus should be directed towards equipment with higher priority. Equipment priority is determined based on their risk. It also determines their order for condition assessment and importance in the power system. A crucial part of that process is the evaluation of the equipment prioritization impact on the cost of asset management and determining the optimal number of prioritized equipment. Thus, a methodology for evaluating the cost of asset management over longer time periods is necessary.

In the existing research, the priority of equipment and its relation to the cost of asset management is analysed from different perspectives. From the focus of prioritization, the methodology for obtaining the rank of equipment in accordance to their risk of failure is presented in [1], [2]. Similarly, the importance of power systems' equipment is acquired in decreasing order based on the proposed approach in [3]. Methods for obtaining the higher risk equipment in the group of circuit breakers are given in [4], [5] and for power transformers in [6]. Thus, acquiring the priority level of equipment is essential for efficient asset management decisions. Although, according to [7], incorrect statistics can have an impact on the calculation of device reliability, overall risk, and asset management cost.

From the focus of prioritization relation to asset management, different management approaches in a power system are analysed in [8], [9]. In accordance with these, improving the condition awareness of equipment allows to increase the system's reliability. In addition, it is decreasing the equipment failure probability and subsequently the potential cost of failure. This is supported by [10], where the condition-based management is considered to provide a needed overview about the equipment's health. The methodologies for maintenance scheduling based on the risk of equipment are given in [11], [12]. These assist in directing the aim of asset management towards the equipment of higher importance in the power system. The methodology for optimal inspection and maintenance is proposed in [13]. It also allows to include the uncertainty factor caused by the equipment condition monitoring. The allocation of asset management funds to equipment with higher risk is described in [14].

Still, some distinctive aspects remain uncovered in the existing research. Firstly, it is necessary to develop a methodology for assessing the cost-efficiency of using a risk-based management method over a longer time period within various levels of equipment prioritization. Secondly, it should allow to analyse the relationship between the potential cost of failure and the number of prioritized equipment. Thirdly, it is necessary to describe the asset management cost evaluation process, when equipment failure probability is unknown.

In this paper, an asset management cost evaluation methodology is proposed. It allows the comparison of the costs of different management methods over a longer period of time. The methodology is based on the cost components of asset management methods and their relation to management tasks and decisions. This can also be useful for determining the achievable cost-efficiency in the presence of uncertainty in condition data. In addition, it assists in obtaining the optimal number of prioritized equipment in the risk-based method and determining the impact of prioritization on the overall cost of asset management.

II. Methodology

A. Cost-efficiency and Cost Components of Asset Management

In order to increase the cost-efficiency of substation asset management, it is necessary to decrease the related $CAPEX$

(Capital expenses) and $OPEX$ (Operational expenses) over time period T. This is expressed by (1).

$$min(CAPEX(T), OPEX(T)) \tag{1}$$

It is assumed, that increasing $CAPEX(T)$ should decrease $OPEX(T)$. Thus, the cost used to increase the reliability of the power system should lower the cost related to equipment failures. The difference between the $CAPEX(T)$ and $OPEX(T)$ depends on the number of equipment included in condition-based management (CBM), time-based management (TBM) and do nothing (run to failure) management (DNM). An option to achieve asset management cost-efficiency is to use risk-based management (RBM). It combines CBM, TBM and DNM, which are used on equipment based on their priority (risk) in the power system. For that, though, it is necessary to determine the optimal number of prioritized equipment. In addition, to the $CAPEX(T)$ and $OPEX(T)$.

The $CAPEX(T)$ includes specific cost components of asset management. Their values are based on the planned asset management tasks. Therefore, the cost of asset management tasks related to $CAPEX(T)$ are cost of planned equipment condition inspection (CoI) and measurement solutions ($CoMS$). Similarly, the $OPEX(T)$ also includes specific cost components of asset management. Their values are based on the occurred asset management outcomes. Subsequently, the cost of asset management outcomes related to $OPEX(T)$ are the cost of equipment maintenance's ($CoMA$), equipment repair (CoR), and the load curtailment ($CoLC$).

The overall cost of management method ($CoMM(T)$) of equipment i depends on the cost of management task (activity) ($CoMT(T)$) and the cost of management outcome ($CoMO(T)$). The $CoMM(T)_i$ can be described by (2). The management cost $CoMM(T)$ of an equipment group is expressed by (3).

$$CoMM(T)_i = \sum_{i=1}^{n} CoMT(T)_i + \sum_{i=1}^{n} CoMO(T)_i \tag{2}$$

$$CoMM(T) = \sum_{i=1}^{n} CoMM(T)_i \tag{3}$$

B. Evaluating Asset Management Cost Over a Longer Time Period

As described by (1), the objective is to decrease the $CoMM(T)$. For that, it is necessary to compare the cost of TBM, CBM, and RBM over T. In order to evaluate the cost of asset management ($CoMM(T)$), it is necessary to obtain the number and the cost of occurred failures of equipment and load curtailments, maintenance activities of equipment, condition inspections used, measurement solutions added to equipment, and measurement solutions replaced or repaired.

The values of planned cost components (mainly related to $CAPEX(T)$) are commonly known. Thus, their impact on overall $CoMM(T)$ can be calculated relatively accurately. As an opposite, the values of cost components related to $OPEX(T)$ are more complex to predict. It is caused by the fact, that $OPEX(T)$ depends on the condition degradation of equipment. Due to the condition degradation of equipment caused by aging, heavy transmission loads, insufficient maintenance, infrequent condition inspections, and environmental factors, their probability of failure increases. Without interference, this eventually leads to failures and possible load curtailments.

In order to increase the cost-efficiency of asset management and the reliability of power systems, the RBM can be the potential approach. The main aim is to decrease the CoR and avoid $CoLC$ by monitoring the condition of higher risk equipment, and decrease the CoI by eliminating unneeded inspections. Although the cost of measurement sensors ($CoMS$) and the number of equipment included in CBM should also be kept lower for decreasing the overall $CoMM$. Thus, the cost of risk-based method ($CoRBM$) depends on the number of equipment included in CBM, TBM, and DNM.

Each of these asset management methods includes specific cost components and can be expressed by (4)...(6). The cost of TBM ($CoTBM$) can include all potential CoF_i values. The cost of CBM ($CoCBM$) includes $CoMS$ allowing to discard CoF_i. The $CoRBM$ is based on the cost components of prioritized equipment k and the cost components of lower priority equipment n.

$$CoTBM = \sum_{i=1}^{n} (CoI_i + CoMA_i + CoR_i + CoLC_i) \tag{4}$$

$$CoCBM = \sum_{i=1}^{k} (CoMS_i + CoMA_i), k = n \tag{5}$$

$$\begin{aligned} CoRBM = &\sum_{i=1}^{k} (CoMS_i + CoMA_i) + \\ &\sum_{i=1}^{n} (CoI_i + CoMA_i + CoR_i + CoLC_i) \end{aligned} \tag{6}$$

In the case of insufficient or inaccurate statistics, the prediction of $OPEX(T)$ is complicated. Subsequently, the number of prioritized equipment k included in RBM can be difficult to estimate. An option is to use a simplified approach to evaluate the potential cost of asset management ($CoMM(T)$)

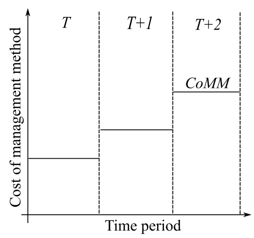

Fig. 1. Principle of proposed method for evaluating the cost of asset management

over a longer period of time to determine the cost related limits of asset management approaches.

The proposed method is illustrated in Fig. 1. It is assumed that in the time period T, the $CoMM$ can be expressed by their mean value. In the case of not knowing the accurate failure probability, this principle allows to assess the cost of different management methods based on their cost components. In the next time periods $T+1$ and $T+2$, the mean value of $CoMM$ is expected to increase due to the potential degradation of equipment condition.

It is also assumed that in time period T, certain number of failures could occur. If the failure probability of equipment within the group C is relatively similar, then the CoF is the main component determining their priority. In the case of lower failure probability, only a few failures could occur in the group C. In addition, it is not known, which equipment i from the group C could have failure. Therefore, the $CoTBM(T)$ can be expressed by (7). It uses the mean value of all CoF_i values in the group C. The CoF_i combines CoR_i and $CoLC_i$. The parameter z is used for the threshold value, simulating the increase in failure probability and its rate. In the initial time period, its value can be 1.

$$CoTBM(T) = \sum_{i=1}^{n}(CoI_i + CoMA_i) + \frac{\sum_{i=1}^{n} CoF_i}{n} \cdot z \quad (7)$$

In accordance with (7), the $CoRBM(T)$ can be expressed by (8). The k represents the equipment, which has been prioritized, the m represents the equipment, which has not been prioritized, and the n represents all the equipment in the group C. After the prioritization, the equipment is removed from m and included in k. Thus, the respective cost components of prioritized equipment i are changed. Meaning that CoI_i and CoR_i is replaced by $CoMS_i$.

$$\begin{aligned} CoRBM(T) = {} & \sum_{i=1}^{k}(CoMS_i + CoMA_i) + \\ & \sum_{i=1}^{m}(CoI_i + CoMA_i) + \frac{\sum_{i=1}^{n} CoF_i}{n} \cdot z - \\ & - \frac{\sum_{i=1}^{n} CoF_i}{n} \cdot \left(1 - \frac{\sum_{i=1}^{n} CoF_i}{n} \cdot \frac{1}{CoF_{ImCoF_{c=1}} - CoF_{ImCoF_c}}\right) \end{aligned} \quad (8)$$

In (8), the CoF is included separately for all of the equipment in k and m, indicated by n. This is due to the usage of the mean value of all CoF_i values in group C. The threshold z is used to describe the increased probability caused by equipment degradation. For simulating the impact of prioritization on the $CoRBM(T)$, the mean value of CoF is multiplied by the ratio between the mean value of CoF and the difference between the maximum CoF_i and the CoF_i of equipment prioritized (included in k). Because of the iterative process of prioritization, the equipment is added in k after each iteration c. Therefore, at the end of iteration the potential CoF value is decreased. This allows to avoid failure consequences and increase overall reliability as well. The prioritized equipment i is determined based on the highest value of $imCoF_i$ expressed by (9). After the prioritization, the $imCoF_i$ and CoF_i values used in iteration c is removed from the selection in decreasing order.

$$ImCoF_i = \frac{CoF_i}{\sum_{i=1}^{n} CoF_i} \cdot n \quad (9)$$

C. Process of Forecasting the Cost of Asset Management

The cost forecast of asset management is based on an iterative process that includes multiple stages. In the initial stage, the $CoTBM(T)$ and $CoCBM(T)$ are acquired. In the second stage, the number of prioritized equipment k in RBM is obtained. It is assumed that the cost of RBM ($CoRBM$) should be lower than the cost of TBM and CBM, over a time period T. For that, it is necessary to compare the $CoTBM(T)$ and $CoCBM(T)$. If the $CoCBM(T)$ is lower than $CoTBM(T)$, then the k can be equal to n. Subsequently, it is more cost-efficient to include all of the equipment in group C in CBM. If the $CoCBM(T)$ is higher than the $CoTBM(T)$, the value of k needs to be smaller.

The iterative process is shown in Figure 2. In methodology, the value of k is increased by 1 in each iteration c. During iteration c, the $CoTBM(T)$ is compared to $CoRBM(T)$. If the $CoRBM(T)$ is lower than $CoTBM(T)$, then the next iteration begins. The iterative process stops, if the $CoRBM$ is higher than $CoTBM$. The previous iteration determines the value of k. The process also stops, if all of the equipment in the group C is added in k (included in CBM).

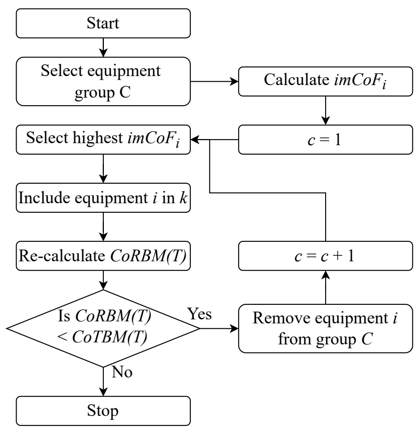

Fig. 2. Iterative process for evaluating the cost of asset management

In order to simulate the degradation of equipment during sequential time periods (from T to Tn) and its impact on the cost of asset management ($CoMM$), the threshold value z in (7) and (8) can be increased. The threshold z in the initial time period T is set to 1. In the next time period $T+1$, the

z value is increased. A similar pattern is used in $T+2$ until Tn. As a result, it is possible to evaluate the change in the cost of asset management over a longer time period.

For each following time period, separate iterative process need to be used. Its principles are the same as in the initial time period T. The equipment already included in k during previous time periods are skipped in the iterative process.

III. Case Study

The proposed methodology is demonstrated based on a case study. The power system with three substations used in the case study is shown in Figure 3. The TS denotes the transmission system side of a substation, while the DS denotes the distribution system side. The generation units are connected to substation A1. Substations A2 and A3 have a combined load of 30 MW. The power transformers are rated 50 MVA (A1), 16 MVA (A2), and 25 MVA (A3).

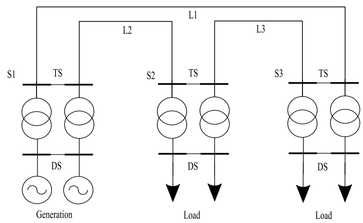

Fig. 3. Principle schematic of a transmission system used in a case study

Three cases are analysed within the case study. These are Case A - power system lines and transformers could overload after the failures in substations; Case B - similar to Case A, but with 3 times higher ($CoLC$); and Case C - similar to Case A, but with 3 times lower ($CoLC$). The $MTTR$ values for power transformers are assumed to be 24 hours and 8 hours for other equipment. The disconnection period of substation connections by disconnectors after a failure is 2 hours. The equipment included in the group C is circuit breakers. Three time periods (T, $T+1$ and $T+2$) are used for simulating the cost of asset management methods ($CoMM$). In the initial time period T, the threshold z is set to 1. It is increased to 1.25 in $T+1$ and to 1.5 in $T+2$.

IV. Results

The results are presented in Fig. 4... Fig. 8. Time period T includes x-axis values 1...10, $T+1$ values 11...20, and $T+2$ values 21...30. In each time period, the threshold value z, which is multiplied by the mean of the total CoF_i, is increased for simulating the increased failure probability. In addition, in each time period, inspection of equipment condition is assumed to take place. This increases also the $CoTBM$. In time period $T+2$, the replacement of measurement solutions increases the $CoCBM$.

In Case A, depicted in Fig. 4, the $CoCBM$ is higher than the $CoTBM$. Therefore, including all of the equipment in the group C at the initial time period T in CBM increases the total $CoMM$. On the other hand, the prioritization of equipment based on higher CoF_i allows to keep the $CoRBM$ lower than the $CoTBM$. From the 15 equipment in the group C, in T is prioritized 2, in $T+1$ 6 and in $T+2$ 3.

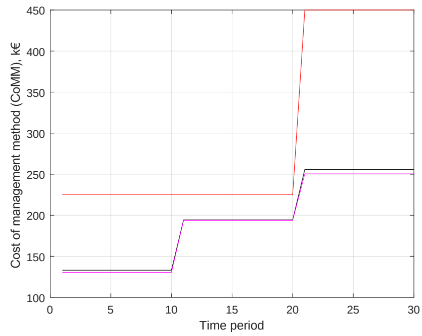

Fig. 4. Cumulative cost of management method ($CoMM$ in Case A: black - TBM; red - CBM; magenta - RBM

In Fig. 5 is depicted the (CoF based on Case A. Its values are shown in the case of using TBM and RBM. The difference between the $CoTBM$ and $CoCBM$ is also given. It can be seen, that the CoF in the case of RBM does not have steep increase compared to TBM. In addition, the methodology allows to maintain the total CoF in the case of RBM around similar levels by iteratively prioritizing the equipment with higher CoF. This means including them in CBM. This aspect also causes the increase in the difference between the CoF in the case of TBM and RBM.

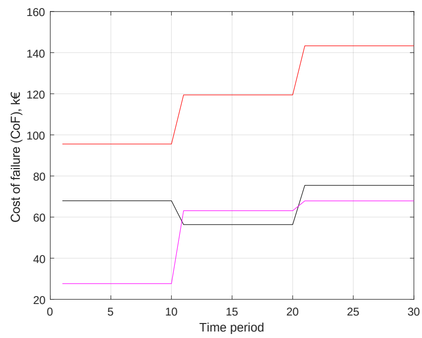

Fig. 5. Cost of failure (CoF in Case A: black - RBM; red - TBM; magenta - difference between TBM and RBM

It can be seen in Fig. 5 that the $CoTBM$ in $T+2$ exceeds the $CoCBM$ in $T+1$. Thus, without replacing the measurement solutions in $T+2$, the $CoTBM$ becomes lower than the $CoCBM$. This means that at the end of $T+1$ all of equipment can be included in CBM. Therefore, in the longer time period, initially including all of the equipment in group C in CBM can be justified. Also, this potentially allows to avoid all failures. There is a difference between the number of prioritized equipment based on the methodology and their total value in CBM after $T+1$. This is caused by the usage of mean CoF with increased z.

In Case B, the ($CoLC$) is 3 times higher than in Case A. The results of Case B are given in Fig. 6. It can be seen, that the $CoCBM$ is noticeable lower than the $CoTBM$. Therefore, it is cost-efficient to include all of the equipment in group C to CBM in the initial time period T.

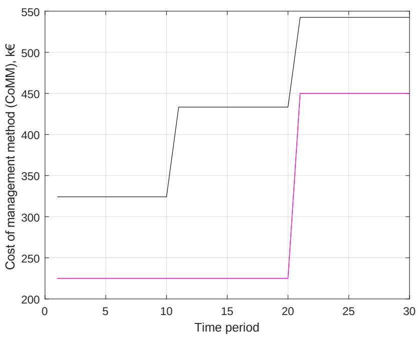

Fig. 6. Cumulative cost of management method ($CoMM$ in Case B: black - TBM; red - CBM; magenta - RBM

In Case C, the ($CoLC$) is 3 times lower than in Case A. The results of Case C are given in Fig. 7 and Fig. 8. The similar pattern as with Case A can be observed. Nevertheless, there are some differences. Firstly, the overall $CoTBM$ is lower than the $CoCBM$, when compared to Case A. Secondly, the calculated $CoRBM$ is above the $CoTBM$ in the initial time period T. Therefore, it is not cost-efficient to prioritize any of equipment by adding measurement solutions to them (including in CBM). In the following time periods, the prioritization is used, though. Thirdly, the $CoTBM$ stays below the $CoCBM$ in the time period $T+2$. Thus, the preventive inclusion of all the equipment in group C to CBM could not be cost-efficient within that time-frame.

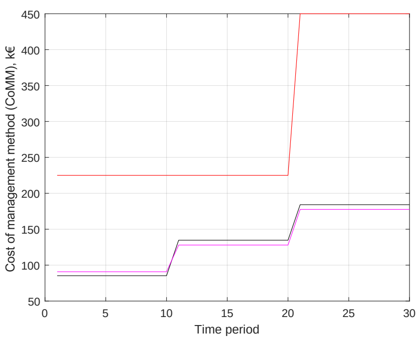

Fig. 7. Cumulative cost of management method ($CoMM$ in Case C: black - TBM; red - CBM; magenta - RBM

The results in Fig. 8 are also similar to Case A. It can be noticed in the initial time period T, that the total CoF in the case of TBM is the same as in the case of RBM. Thus, none of the equipment was prioritized in that time-frame, and therefore the overall CoF did not change.

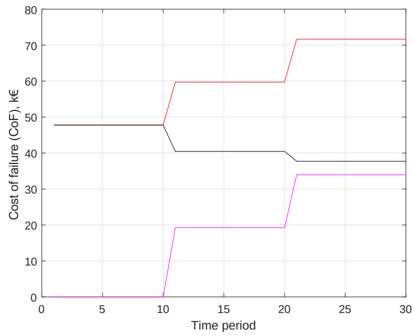

Fig. 8. Cost of failure (CoF in Case C: black - RBM; red - TBM; magenta - difference between TBM and RBM

V. Conclusion

In this paper, the methodology for evaluating the cost of asset management methods over a longer time period is proposed. It allows to increase the cost-efficiency of asset management and assists in the transition to the risk-based approach. Based on that, it is possible to analyse the impact of the equipment prioritization in the risk-based method. The methodology is also suitable in the case of not knowing the accurate failure probability values. The result indicated that the methodology keeps the cost of a risk-based approach lower than a time-based one, reducing overall failure cost. It is also observed that including all of the equipment initially in the condition-based method could be more cost-efficient than using the time-based method over a longer period of time. The methodology can be used as a preliminary tool for assessing the cost related factors of asset management.

References

[1] S. Fattaheian-Dehkordi, M. Fotuhi-Firuzabad, and R. Ghorani, "Transmission system critical component identification considering full substations configuration and protection systems," *IEEE Transactions on Power Systems*, vol. 33, no. 5, pp. 5365–5373, Sep. 2018.

[2] H. Yang, K. Zhang, and A. Tang, "Risk assessment of main electrical connection in substation with regional grid safety constraints," *IEEE Access*, vol. 10, pp. 27 750–27 758, 2022.

[3] H. N. Bhandari, V. Vittal, G. T. Heydt, F. L. Quintanilla, and W. B. Knuth, "Ranking of bulk transmission assets for maintenance decisions," in *2019 North American Power Symposium (NAPS)*, Oct 2019, pp. 1–6.

[4] D. Huang and B. Bagen, "System reliability risk model and its application to station breaker replacement," in *2020 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*, Aug 2020, pp. 1–6.

[5] A. P. Shishavan and A. Razi-Kazemi, "A practical knowledge-based ranking approach to identify critical circuit breakers in large power systems," *Knowledge-Based Systems*, vol. 227, p. 107237, sep 2021.

[6] R. D. Medina, D. A. Zaldivar, A. A. Romero, J. Zuñiga, and E. E. Mombello, "A fuzzy inference-based approach for estimating power transformers risk index," *Electric Power Systems Research*, vol. 209, p. 108004, aug 2022.

[7] S. Laohanan and D. Banjerdpongchai, "Dynamic programming approach to optimal maintenance scheduling of substation equipment considering life cycle cost and reliability," in *2018 15th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, July 2018, pp. 388–391.

[8] S. R. Khuntia, J. L. Rueda, S. Bouwman, and M. A. M. M. van der Meijden, "A literature survey on asset management in electrical power [transmission and distribution] system," *International Transactions on Electrical Energy Systems*, vol. 26, no. 10, pp. 2123–2133, feb 2016.

[9] D. Clements and P. Mancarella, "Systemic modelling and integrated assessment of asset management strategies and staff constraints on distribution network reliability," *Electric Power Systems Research*, vol. 155, pp. 164–171, feb 2018.

[10] H. A. R. Ardabili, M.-R. Haghifam, and S. M. Abedi, "A stochastic markov model for maintenance scheduling in the presence of online monitoring system," *IEEE Transactions on Power Delivery*, vol. 37, no. 4, pp. 2831–2842, aug 2022.

[11] E. Shayesteh and P. Hilber, "Reliability-centered asset management using component reliability importance," in *2016 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*. IEEE, oct 2016.

[12] A. Alizadeh, A. Fereidunian, M. Moghimi, and H. Lesani, "Reliability-centered maintenance scheduling considering failure rates uncertainty: A two-stage robust model," *IEEE Transactions on Power Delivery*, vol. 37, no. 3, pp. 1941–1951, jun 2022.

[13] Y. Fan and D. Zhang, "Reliability evaluation of power systems incorporating maintenance policy with partial information," in *2016 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS)*, Oct 2016, pp. 1–5.

[14] H. Mirsaeedi, A. Fereidunian, S. M. Mohammadi-Hosseininejad, and H. Lesani, "Electricity distribution system maintenance budgeting: A reliability-centered approach," *IEEE Transactions on Power Delivery*, vol. 33, no. 4, pp. 1599–1610, aug 2018.

Curriculum Vitae

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2. Education

2020–...	Tallinn University of Technology, School of Engineering, Electrical Power Engineering and Mechatronics, PhD studies
2018–2020	Tallinn University of Technology, School of Engineering, Electrical Power Engineering and Mechatronics, MSc *cum laude*
2015–2018	Tallinn University of Technology, School of Engineering, Electrical Power Engineering and Mechatronics, BSc

3. Honours and awards

- 2024, Best paper and presentation award in RTUCON 2024
- 2024, Participation in a competition "Science in 3 minutes" finals held by Estonian Science Academy
- 2020, 3rd best master thesis in the national thesis competition

4. Defended theses

- 2020, Development of Generators Reactive Power Control System for Electrical Power Plant and Testing with Realtime Simulator, MSc, supervisor Prof. Jako Kilter, Tallinn University of Technology, Electrical Power Engineering and Mechatronics
- 2018, Technical Condition and Aging Relation Analysis of Estonian High Voltage Overhead Lines, supervisor Prof. Jako Kilter and Henri Manninen, Tallinn University of Technology, Electrical Power Engineering and Mechatronics

5. Scientific work

Papers

1. G. Andreesen, M. Leinakse, J. Kilter, and M. Landsberg, “Maximum risk calculation process for individual substation equipment in primary side,” in *ISGT Europe 2024*. IEEE, oct 2024, pp. 1–5
2. G. Andreesen, M. Leinakse, J. Kilter and M. Landsberg , “Determining cost-efficient sequence of condition inspection based on estimated condition data,” in *ISGT Europe 2024*. IEEE, oct 2024, pp. 1–5
3. G. Andreesen, M. Leinakse, J. Kilter, and M. Landsberg, “Cost-efficient improvement of power system’s reliability within limited funds,” in *RTUCON 2024*. IEEE, oct 2024, pp. 1–6
4. G. Andreesen, M. Leinakse, J. Kilter and M. Landsberg, “Methodology for forecasting the cost of substation asset management in upcoming future,” in *PECON 2024*. IEEE, nov 2024, pp. 1–5

5. Asefi, S., Andreesen, G., Kilter, J., Landsberg, M., „Capacitor Coupled Voltage Transformer Inaccuracy Effect on Circuit Breaker Operation“, 2023, 23rd International Scientific Conference on Electric Power Engineering (EPE).

6. Andreesen, G., Leinakse, M., Kilter, J., Landsberg, M., „Ratio of Load Curtailment Based Detection of the Maximum Risk of Substation Devices“, 2023, IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe 2023).

7. Asefi, S., Andreesen, G., Leinakse, M., Kilter, J., Kalmet, T., Manninen, H., Landsberg, M, „Measurement and Operation Based Condition Monitoring Methodology for High Voltage Circuit Breakers“, 2022, IEEE PES Innovative Smart Grid Technologies Conference Europe.

8. Leinakse, M., Andreesen, G., Tani, P., Kilter, J., „Estimation of Exponential and ZIP Load Model of Aggregated Load with Distributed Generation“, 2021, IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON).

9. Trummal, T., Andreesen, G., Kilter, J. „Optimal Reactive Power Control in a Multi-Machine Thermal Power Plant“, Proceedings of the 2020 21st International Scientific Conference on Electric Power Engineering (EPE), Prague, Czech Republic, October 19 - 21, 2020.

Conference presentations

1. Guido Andreesen, Madis Leinakse, Jako Kilter and Mart Landsberg, "Maximum Risk Calculation Process for Individual Substation Equipment in Primary Side", in *ISGT Europe 2024*, October 2024, Dubrovnik, Croatia

2. Guido Andreesen, Madis Leinakse, Jako Kilter and Mart Landsberg, "Determining Cost-Efficient Sequence of Condition Inspection Based on Estimated Condition Data", in *ISGT Europe 2024*, October 2024, Dubrovnik, Croatia

3. Guido Andreesen, Madis Leinakse, Jako Kilter and Mart Landsberg, "Cost-Efficient Improvement of Power System’s Reliability within Limited Funds", in *RTUCON 2024*, October 2024, Riga, Latvia

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2. Haridus

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2018–2020	Tallinna Tehnikaülikool, Inseneriteaduskond, Elektroenergeetika ja Mehhatroonika, MSc *cum laude*
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3. Autasud

- 2024, Parim teadusartikkel ja ettekanne teaduskonverentsil RTUCON 2024
- 2024, Eesti Teaduste Akadeemia teaduse populariseerimise konkursi "Teadus kolme minutiga" finaalikoht
- 2020, Riikliku lõputööde konkursi parima magistritöö 3. koht

4. Kaitstud lõputööd

- 2020, Elektrijaama generaatorite reaktiivvõimsuste juhtimissüsteemi arendamine ja selle katsetamine reaalajasimulaatoriga, MSc, juhendaja Prof. Jako Kilter, Tallinna Tallinna Tehnikaülikool, Elektroenergeetika ja Mehhatroonika
- 2018, Eesti põhivõrgu õhuliinide tehnilise seisukorra ja vanuse analüüs, juhendajad Prof. Jako Kilter ja Henri Manninen, Tallinna Tehnikaülikool, Elektroenergeetika ja Mehhatroonika

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