RELIABILITY MODELLING IN TRANSMISSION NETWORKS

AN EXPLORATORY STUDY FOR FURTHER EHV UNDERGROUND CABLING IN THE NETHERLANDS

by

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Abbreviations

[redacted]	[redacted]
CAIDI	*Customer Average Interruption Duration Index*
CB	*Circuit Breaker*
CML	*Customer Minutes Lost*
[redacted]	[redacted]
[redacted]	[redacted]
EENS	*Expected Energy Not Supplied*
EHV	*Extra High Voltage*
EMF	*Electromagnietic Field*
[redacted]	[redacted]
FACTS	*Flexible Alternating Current Transmission Systems*
[redacted]	[redacted]
HV	*High Voltage*
HVDC	*High Voltage Direct Current*
KCPL	*Kansas City Power & Light*
[redacted]	[redacted]
KPIs	*Key Performance Indicators*
[redacted]	[redacted]
LOEE	*Loss of Energy Expectation*
LOLE	*Loss Of Load Expectation*
LOLP	*Loss Of Load Probability*
MISO	*Midwest Independent System Operator*
MTBF	*Mean Time Between Failures*
MTTF	*Mean Time To Failure*
MTTR	*Mean Time To Repair*
OHL	*Overhead Lines*
PSTs	*Phase Shifting Transformers*
RES	*Renewable Energy Sources*
[redacted]	[redacted]
SAIDI	*System Average Interruption Duration Index*
SAIFI	*System Average Interruption Frequency Index*
[redacted]	[redacted]
TSO	*Transmission System Operator*
UGC	*Underground Cables*
[redacted]	[redacted]

Summary

The large scale deployment of intermittent renewable energy sources (RES, in order to meet decarbonisation policy targets), the market-based cross-border flows, the intensive use of power electronic and/or FACTS devices, the high penetration of electric vehicles and the desire for demand side response and energy storage create new operational challenges for the transmission networks. In order to find a balance between adapting to a new more demanding reality and maintaining security of supply on top priority, long-term network developments are required and should be implemented in the most effective, economic and environment-friendly way. However, the installation of new overhead lines (OHL) faces many challenges due to societal, environmental reasons and governmental policies. One alternative that gains widespread public support is the installation of Extra High Voltage AC XLPE underground cables (UGC). It is accepted by the public, the environmental impact can be reduced and the transmission losses are lower. On the other hand, the lack of experience with EHV cables and the different electrical behaviour of cables compared to overhead lines arise new problems and challenges. A significant area of concern is the reliability of underground cables and how it impacts the overall reliability level. Although the cable failure frequency is very close to that of the overhead line, the additional components of UGC (joints and terminations) reduce the reliability of the whole system. In addition, if an underground cable fails, the required repair time is much longer (e.g. one month) than in the case of a line (a few hours).

The main goal of this thesis is to develop a reliability assessment approach in order to examine how the installation of EHV underground cables in transmission networks impacts the overall reliability level. The approach is used for the case study of the EHV Dutch transmission grid. First, an extensive literature review on basic reliability concepts and on main differences between OHL and UGC is conducted. In order to enrich the insight gained from this literature review, unstructured interviews took place with experts from the Dutch transmission system operator. By using the findings from both sources, a qualitative generic approach is proposed. This approach can be used as a framework for the decision making process that a planner should follow when he/she examines the possibility of installing EHV UGC in a transmission network from a reliability point of view. Different steps are included, from what input data are necessary until how to process and evaluate the results (reliability indicators) from the reliability assessment. In case that the new reliability level (after the installation of UGC) is unacceptable according to the standards that the TSO sets, actions for improvement are necessary. These actions indicate which key influencing factor(s) has to change in order to improve the reliability level. The key influencing factors regarding the installation of UGC are identified through an extensive literature review and interviews, and are the following ones: connection where UGC are installed, configuration of UGC, number of cable sections, cable length, repair time and failure frequency of UGC, topology of underground cables and the use of series compensation. After changing at least one of these factors, the planner has to re-examine the situation by checking if the new reliability level is now acceptable.

The proposed qualitative generic approach is applied for the case study of the EHV Dutch transmission grid. The purpose is to examine how further 380kV cabling in the Dutch transmission network impacts the overall reliability level. After modelling contingency analysis, DC load-flow and corrective measures and after selecting the reliability indicators to be calculated, the reliability assessment is performed for different simulation sets. It should be mentioned that two categories of reliability indicators are calculated: key performance indicators (KPIs) directly linked to loss of load and KPIs not directly linked to loss of load. The simulation sets are defined mainly based on variations of the key influencing factors regarding the installation of UGC. [redacted]

The results of this study highlight that the installation of underground cables in heavily loaded connections (above 50% loading) is very critical from a reliability point of view, while the conditions are more favorable in

weakly loaded connections (below 30% loading). By keeping the cable length constant, if the loading of the connection increases, the final reliability level drops significantly compared to the case with the initial loading. This decrease in the reliability level can be much more considerable than the increase of the loading, speaking in percentages. This conclusion becomes even more important by considering that a current weakly loaded connection might become more loaded in the future. [redacted]

Furthermore, if the installation of UGC in a specific connection leads to an unacceptable reliability level, at least one of the key influencing factors should change in order to improve it. By ranking their variations from the smallest to the largest improvement that they could bring, they are: reduction of the initial number of *cable sections* by half, installation of half *cable length* than initially planned, reduction of the *failure frequency* of UGC according to TSO's low estimation (if TSO's high estimation was initially adopted), change in the *configuration* of UGC by installing one cable per circuit phase (instead of two), reduction of the *repair time* of UGC by a factor of two and finally installation of UGC in a weakly loaded *connection*. As noticed, in almost all the influencing factors the same relative reduction is applied (by a factor of two), because only if these parameters change by the same relative amount, the comparison between them is feasible. In addition, it is assumed that when one factor changes, the rest remain constant.

Moreover, the results of this study reveal that both categories of KPIs (directly and not directly linked to loss of load) are necessary in order to determine the reliability level of the transmission network after the installation of EHV UGC. The reason for that is because the installation of UGC in specific connections does not influence the reliability indicators related to load curtailment, but this does not mean that the level of reliability remains the same. It is shown in the results that in these cases, the reliability indicators which are not directly related to loss of load, demonstrate significant change, leading to a lower reliability level. Therefore, it can be concluded that indicators that are not directly linked to load curtailment should be used as well.

Finally, the findings of this thesis show that the moment that UGC are installed (in any connection), at least one reliability indicator changes, leading to a lower reliability level. However, this amount of decrease in reliability differs significantly depending on the selected connection where UGC are installed. In the results, extreme cases are presented, where either the reliability drops dramatically as the cable length increases (more than 100 times) or it decreases very slightly, far less than 10%. This means that every project regarding the installation of UGC should be studied separately and extensively.

[redacted]

1

Introduction

1.1. Problem orientation

Growing populations, increasing living standards, industrializing countries, expanding economies and the continuous electrification of societies are the key drivers which lead to a huge demand for electrical energy. It is expected that the global electricity demand will increase by about 85% from 2010 to 2040 [1]. Unfortunately, as it is known, electricity is not always produced and used at the same time and place. There could be very long distances between different generating stations and load centres. For this reason, electricity transmission and distribution networks are necessary. Although both transmission and distribution facilities are the arteries through which electrical power is delivered to the final consumers, this thesis focuses on transmission networks.

1.1.1. Electricity transmission networks: objectives and challenges

The main function of transmission networks is to balance electricity production and demand at every moment and to ensure a reliable and uninterrupted supply of electricity to all users. According to world-wide recognized quality standards, their operation should be safe, reliable, sustainable and economical efficient. Uncertainties such as variability of load and unexpected equipment failures should be handled in the most efficient way.

However, these are not the only uncertainties that the transmission system operators face. The large scale deployment of intermittent renewable energy sources (RES, in order to meet decarbonisation policy targets), the market-based cross-border flows, the intensive use of power electronic and/or FACTS devices, the high penetration of electric vehicles and the desire for demand side response and energy storage create new operational challenges that the transmission system operators have to take into account as well [2].

1.1.2. Reinforcement of transmission networks: why UGC and not OHL?

In order to find a balance between adapting to a new more demanding reality and maintaining security of supply on top priority, long-term network developments are required (e.g. extensions of the grid or upgrades of the transmission capacity of existing connections). The flexibility of transmission networks should be enhanced and the network developments should be implemented in the most effective, economic and environment-friendly way.

The use of overhead lines (OHL) dominates the current transmission networks and the system operators count many years of experience and expertise in running OHL [3]. This important advantage in combination with the low relative capital cost and their proven safe and reliable operation explains why the use of OHL is so popular [4]. However, the installation of new overhead lines faces many challenges due to societal, environmental reasons and governmental policies. Especially in densely populated areas, there is a strong public opposition against overhead lines due to noise pollution (caused by the corona effect), radio interference (electromagnetic fields), precaution recommendations on low magnetic fields (micro Tesla) in built environment, distortion of the visual landscape and impact on natural reserves [5].

One solution that gains widespread public support is the installation of Extra High Voltage AC XLPE underground cables (UGC). The installation of underground cable links in the transmission networks seems to be a worth-to-study alternative for the reinforcement of the grid. It is accepted by the public, the environmental impact can be reduced and the transmission losses are lower [6-8]. Several transmission system operators examine this option and some EHV underground cable links have already been installed or planned as future projects around the world.

1.1.3. Statistics of AC UGC in transmission networks

In order to give some quantitative data for the amount of underground cable length that has been installed in different countries, a few statistics are presented. These statistics, which can be found in the Cigré technical brochure 379 [9], were gathered through a questionnaire sent to Study Committee members. They refer to projects planned for implementation by December 2006. Although the statistics were divided into five voltages ranges (50-109 kV, 110-219 kV, 220-314 kV, 315-500 kV and 501-764 kV), the focus should be on the two ranges 220-314 kV and 315-500 kV, which are normally classified as EHV. It should be mentioned that the division of these voltage ranges was made in order to group together similar design and operational principles.

Figure 1.1 shows what percentage of total AC circuit length is underground for each of the five voltage levels. As can be seen, the majority of circuits are above ground and this amount increases as the voltage level rises.

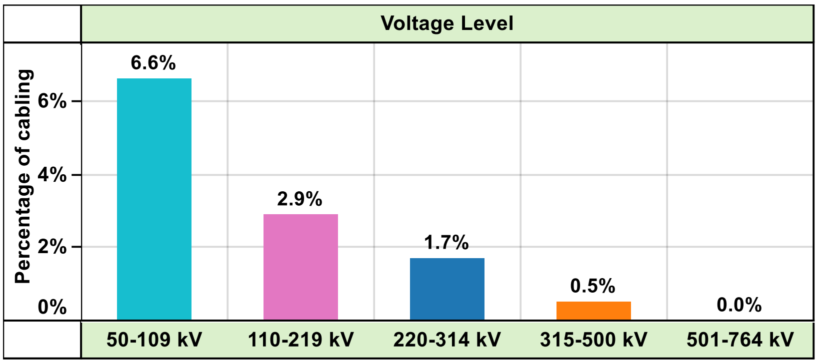
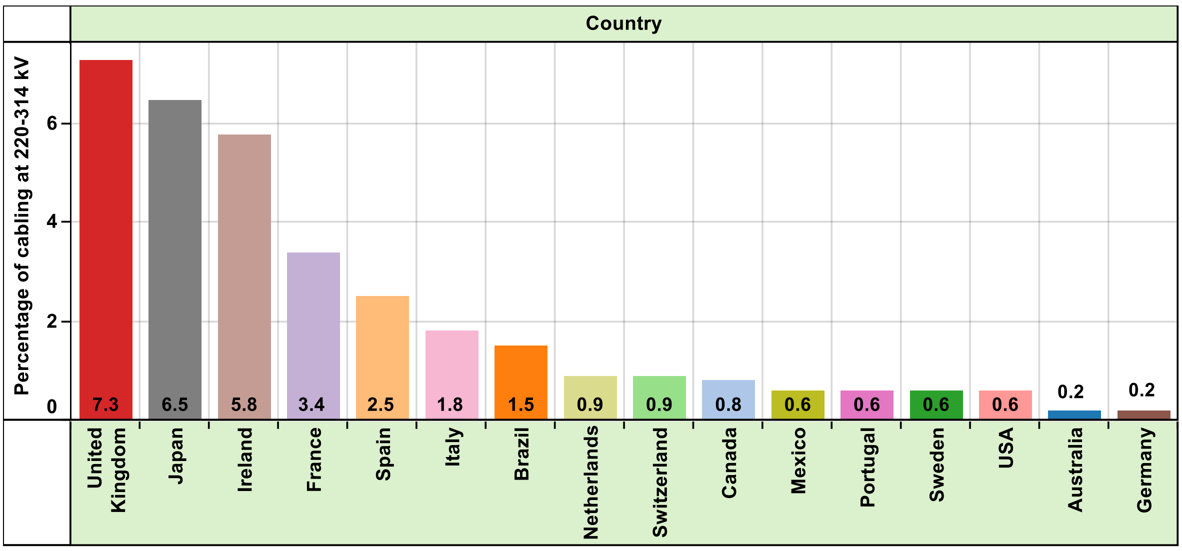


Figure 1.1 - Percentage of the total ac underground circuit length for each of the five voltage levels [9]

Figure 1.2 illustrates what percentage of total AC circuit length is underground for different countries at the



voltage range 220 – 314 kV.

Figure 1.2 - Percentage of the total ac circuit length underground at 220 – 314 kV [9]

The same data for the 315 kV to 500 kV range is shown in Figure 1.3.

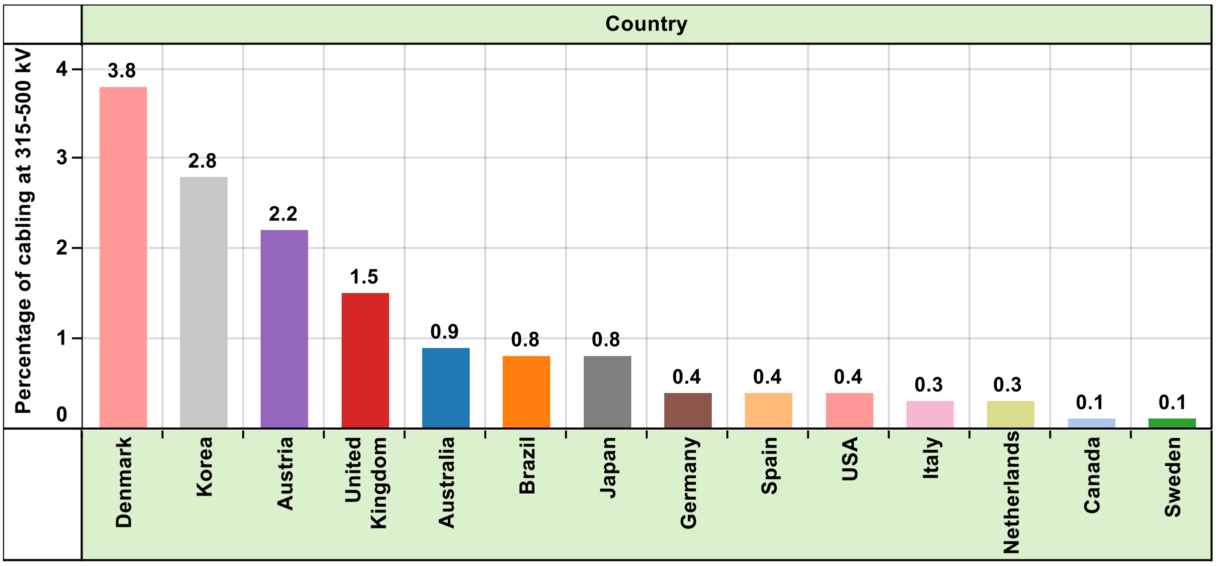


Figure 1.3 - Percentage of the total ac circuit length underground at 315 – 500 kV [9]

Although it is obvious from the small percentages that there is a clear preference for overhead lines rather than underground cables, today there is a rising trend for discussing the possibilities to install underground cable links, driven by societal aspects and governmental policies.

1.1.4. Bottlenecks in the installation of UGC

Although this development is quite encouraging from a societal perspective, new problems and challenges might arise, both from technical and economic aspects.

First of all, one needs to be aware of the lack of experience with EHV cables as the highly integrated European 380 kV transmission grid has been constructed mainly above ground [10]. As there are not many installed underground cables on land, the available statistics and data regarding failure rates and behaviour of cables (in particular in meshed grids) are limited. Although TSOs around Europe consider to include 380 kV cables in their grids, this lack of knowledge and data, has led them to be cautious regarding the extent of EHV cables.

Another issue in this new development is the different electrical behaviour of cables compared to overhead lines. The fact that cables present much higher capacity and lower inductance than lines, can cause serious voltage problems in the grid [11]. Issues related to this aspect, such as transient behaviour, harmonics and voltage stability should be assessed every time that underground cable links are to be installed [3, 12]. Another significant area of concern is the reliability of underground cables and how it can influence the reliability of the whole transmission network.

It can be easily concluded that a thorough investigation in several areas is needed if a transmission system operator examines the possibility of installing EHV underground cables in its network.

1.2. THE CASE OF THE DUTCH TRANSMISSION NETWORK

The Dutch transmission network is demonstrated in Figure 1.4 and consists of the following voltage levels: 110, 150kV (High Voltage) and 220, 380 kV (Extra High Voltage). Currently the Dutch transmission system operator, TenneT, manages over 21000km of transmission links both above and below ground and 36 million end users. It is a solid and reliable transmission grid with a relatively low number of customers' interruptions. This can be verified by observing the high figures of the availability of the network, which reaches 99.99% [13]. Apart from the top priority of TenneT to provide uninterrupted transmission of electricity, it aims to increase the social welfare as well. That is why interconnections have been constructed between the Netherlands and the neighbouring countries. In this way, cross-border electricity transmission is easier and consumers benefit from lower costs. More specifically, the Dutch transmission grid has three connections with Germany, two with Belgium, one high voltage DC (HVDC) with Norway (NorNed) and one with Great Britain (BridNed).

Although the Dutch transmission network is very robust, it faces similar challenges with the ones described in section 1.1.1. More specifically, the power demand in the Netherlands increases by approximately 2% every year, the power generation becomes more and more decentralized due to the construction of new wind parks and new production units of large scale are expected to be installed near coastal regions [14]. Although the Extra High Voltage Dutch transmission network has been developed mainly based on the use of overhead lines (like most of the European transmission grids), the construction of new OHL for the reinforcement of the network becomes more and more difficult due to Dutch regulations stemming from societal and environmental reasons. Therefore, the Dutch transmission system operator, TenneT, has started to examine the possibility of installing 380kV AC XLPE underground cables for grid reinforcements as an alternative to new OHL, since there is widespread public and political support for such a development.

So far, 380kV UGC have been already installed in the Dutch transmission network, while another 380kV cable project is coming into operation in the near future. More specifically, the Randstad 380 kV South Ring came into operation in 2013 and the Randstad 380 kV North Ring is expected to come into operation in around 2017 (both projects consist of two cable circuits). After the operation of both projects, around 20 kilometres will be underground in an entire route of approximately 80km across the Randstad region [15]. The south ring starts from substation Wateringen to substation Bleiswijk with length equal to 22 km including 10.8 km underground cable per circuit and the north ring is from substation Bleiswijk to Beverwijk with 57.3 km length consisting of 9 km underground cable per circuit.

[redacted]

.

Figure 1.4 - The Dutch transmission network [16]

1.3. PROBLEM STATEMENT

It does not come as a surprise that the operation of a transmission network can be characterized as successful if it can assure a high level of reliability (among other requirements). The availability of the grid should be maximized in order to provide continuously high quality electricity service to its consumers. As mentioned previously, the installation of UGC, which may be needed for reinforcements, might influence the reliability of the whole network. Since the reliability level is an important criterion for the safe operation of the grid and since the construction of underground links might constitute a good alternative for grid enhancement, it seems that the combination of these two issues is worthy research.

Although the cable failure frequency is very close to that of the overhead line, the additional components of UGC (joints and terminations) reduce the reliability of the whole system [17]. Therefore, the development of a grid with underground cables would entail higher failure probability than that of a grid with overhead lines.

The issue of repair time in case of failure has to be taken into consideration as well. If the underground cable fails, the required repair time is significant. Although there is no guaranteed repair time for such kind of cases, the experienced outage times for 380 kV XLPE cables in Europe vary between 2 weeks and 9 months [18]. This repair time is extremely long, especially if it is compared to the case of overhead lines, where no more than 48 hours are needed to repair a failed overhead line [15]. However, it is important to mention that repairing the cable itself requires only a small part of the total outage time. The remaining time is needed for other actions such as: locating the failure, getting permission, collecting evidence, cleaning the site, ordering new parts, finding available skilled personnel, etc. [19].

From the increased failure probabilities and longer repair times it is now understood better why the installation of UGC requires a separate thorough reliability study.

1.4. THESIS OBJECTIVES

Based on the research problem above, the main goal of this thesis is to develop a reliability assessment approach in order to examine how the installation of EHV underground cables in transmission networks impacts the overall reliability level. The approach is used for the case study of the EHV Dutch transmission grid. Reliability assessment of further 380kV cabling is performed and certain reliability indicators are calculated.

The main research question can be formulated as:

"How does the installation of more 380kV underground cables in the EHV Dutch transmission network impact the reliability level of the transmission grid?"

Based upon the main research question, several sub-questions arise:

- What are the steps of the decision making process that the planner has to follow when he/she examines the possibility of installing EHV UGC in the transmission network from a reliability point of view?
- Which performance indicators can be used to measure the reliability of transmission networks?
- What is the difference in reliability if an extension of the grid is implemented as OHL compared to UGC?
- Does the reliability level depend on the location of the 380kV UGC in the network topology?
- How is the reliability level influenced when the total cable length varies?
- How does the repair time of UGC influence the reliability?
- How does the reliability level change when the failure frequency of UGC varies?
- How can short-term operational measures be taken into account in the reliability assessment of further 380kV cabling?

The main research question in combination with the sub-questions is answered throughout the next chapters of this thesis. How these chapters are structured, is presented in section 1.5.

1.5. THESIS OUTLINE

This thesis is organized as follows. Chapter 2 provides the theoretical background for general reliability concepts and conducts a comparative analysis, based on literature review, between Extra High Voltage overhead lines and underground cables. Chapter 3 describes step by step the proposed qualitative generic approach that a planner can follow when he/she examines the possibility of installing EHV UGC in a transmission network from a reliability point of view. In Chapter 4, this generic approach is applied for the case study of the EHV Dutch transmission network. The input parameters, the methodology and the output data of the reliability assessment are elaborated. In the same chapter, it is explained how the different simulation sets are determined. In Chapter 5, the simulation results are presented, discussed and analysed. Chapter 6 draws conclusions and suggests recommendations for future research.

2

Power system reliability

2.1. What is power system reliability?

An electric power system consists mainly of three zones: power generation, transmission and distribution system [20]. The function of the electric power system is to produce and supply high quality and reliable electrical energy to all the consumers within acceptable standards and in the desired amounts. The power system reliability is a measure which quantifies the ability of the system to perform its function. Power system reliability can be sub-divided into adequacy and security [21].

Adequacy is a measure which describes the ability of the system to satisfy the electrical energy requirements of the customers by respecting component ratings and voltage limits when planned and unplanned outages of components occur. It refers to static conditions, since it is assumed that the system reaches a steady state after the outage of a component. All the dynamic studies are neglected. On the other hand, security is a measure which quantifies the ability of the system to withstand sudden disturbances, such as electric short circuits or equipment outages (also called resilience). It refers to the system dynamic response and it involves studies regarding cascading effect after disturbances and system transient responses [22]. Sometimes when the term reliability is used, it refers only to adequacy and not both to adequacy and security. This is the case for this study as well. It is a less accurate but very common perception of reliability.

Reliability assessment can be conducted for every zone of the electric power system (generation, transmission, distribution) separately, for the composite of both generation and transmission system (bulk system) or for the entire power system [22].

This study focuses on transmission networks because the numerous challenges that the electricity transmission networks face today create a need for special attention in the area of reliability. More specifically, the growing worldwide demand for electricity, the increasing uncertainty of production due to intermittent energy sources, the deregulation in the electricity sector, the liberalization of the electricity market, the desire for demand side management and the penetration of electrical vehicles are the key drivers that lead to a continuous need for analysing, developing and extending the electricity transmission networks. Under these circumstances a high level of reliability should be ensured.

2.2. Evaluation approaches of power system reliability

Since the reliability assessment of electric transmission networks is a challenging task, a lot of effort has been made to discover efficient approaches that need reasonable calculation time. A crucial subject, which has gained a lot of attention throughout the years, is the comparison between deterministic and probabilistic approaches.

The traditional way to design, plan and operate an electric transmission network is based on deterministic approaches. According to the deterministic framework, usually only the worst case scenario is considered, assuming that the solutions will be valid under any other conditions [23]. Another common strategy is to use deterministic criteria. The most used deterministic criterion is the so-called n-1 criterion [24]. According to this approach, if a single component of the network fails, the network should be able to remain stable and no violations should be observed. In other words, the grid should be able to withstand the loss of an individual component. In a similar way, the n-α criterion can be used as well, meaning that the network can withstand the failure of α components simultaneously [25]. However, most of the electric transmission networks have been designed and operated on basis of the n-1 criterion. The main advantages of both deterministic framework and deterministic criteria are simplicity, straightforward understanding, short calculation time and the need for a small amount of data. Despite the fact that they have ensured a satisfactory reliability level during the past decades, they carry an important drawback [22]. More specifically, the n-1 criterion is a conservative criterion and the probabilities of different faults are not taken into account, meaning that the stochastic nature of the real electric transmission networks is neglected [24]. Sometimes the n-1 criterion does not include all single contingencies referring to all component types, but only the ones that are critical for outages. These contingencies are chosen based on planners' and operators' experience and on experts' judgements [25].

The probabilistic framework can reflect the stochastic nature of the electricity transmission network behaviour [26]. This is the reason why this approach is used more frequently nowadays (e.g. Kansas City Power & Light (KCPL) and Midwest Independent System Operator (MISO)) [27, 28]. By using probabilistic techniques, a large number of operational situations are examined and uncertain events, which can influence the reliability of the network, are taken into consideration [29]. In the end, probability distribution functions and expected values of reliability indicators are calculated [22]. The results from probabilistic methods are free from the subjective planners' reasoning and give insight on the effects of outages in transmission networks, such as frequency and duration of not-supplied energy [30]. A case study of probabilistic reliability assessment is described in [30] and may attract the reader's interest, since it concerns a very large countrywide transmission network (800 overhead lines of total length above 40000km) and failures until third order referring to all different components of the grid are examined.

The numerous challenges of the current electricity transmission networks have increased uncertainty (e.g. the insertion of electric vehicles can change the load pattern in an unpredictable way) and have made necessary to reflect the stochastic nature of the network behaviour. This situation has given a lead to the probabilistic methods regarding the evaluation of reliability performance [24]. However, as already mentioned, most of the transmission networks have been planned based on deterministic approaches (either deterministic framework or deterministic criteria). Therefore, in order to bridge the gap between current deterministic practice and desired probabilistic approaches, it would be beneficial to combine these two approaches. This can be realized in the well-being analysis framework, which is a probabilistic framework with integrated deterministic criteria [31]. According to this method, the condition of the transmission network is classified into a number of operating states and the probability of each state is determined [25]. In this way, both deterministic perception (the operating states are defined according to a pre-defined deterministic criterion) and probabilistic concepts (probabilities are calculated) are taken into account [32]. Later in this chapter the operating states are presented analytically. An application of the well-being analysis for composite generation and transmission systems is illustrated in [32] and it appears to be very interesting, because it can capture load variations with time despite the use of non-sequential Monte Carlo simulation and the lack of chronological simulations.

2.3. PROBABILISTIC RELIABILITY ASSESSMENT OF POWER SYSTEMS

After describing the evaluation approaches of power system reliability and explaining the trend towards the probabilistic ones, it is important to focus on them by analyzing the steps of a probabilistic reliability assessment. In this section an overview of such an assessment is provided, while each step is elaborated separately in the next sections.

The first step is to perform a contingency analysis (section 2.3.2) by selecting one of the various state-of-the-art techniques and by deciding which components' failures are included (e.g. transformers, bus bars, circuit breakers, generators etc.). For each contingency a load-flow calculation (section 2.3.3) is realized for the static post-disturbance condition, in order to identify any constraints' violations (e.g. overloads) caused by contingencies. If violations are observed, it is necessary to restore the operation of the grid within constraints by applying remedial actions (section 2.3.3). Finally, by using the outcome of the application of remedial actions, several reliability indicators (section 2.3.4) can be calculated [21]. Before presenting each step with more details, it seems appropriate to provide some theoretical background on basic probabilistic concepts (section 2.3.1).

2.3.1. Basic probabilistic concepts

A power system component (e.g. transmission line/cable, transformer, generator etc.) can be represented by using the following simplified two-state Markov model (Figure 2.1) [20]. According to Figure 2.1, a component can be in one of the two states: either there is no failure and the component is available (above state S_0) or the component fails and is unavailable (below state S_1). Moreover, the failure rate (λ) and the repair rate (μ) are indicated in the arrows. The great advantage of the Markov process is the ability to describe the failure and the subsequent repair of a component in the same model [33].

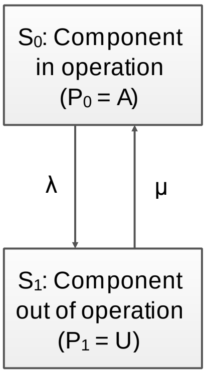


Figure 2.1 - Two-state Markov model [20]

Furthermore, the probability of the component being in state S_0, which is named as P_0 and is equal to the availability of the component, can be calculated. The same is valid for the probability of the component being in state S_1, which is named as P_1 and is equal to the unavailability of the component. More specifically, the unavailability U and availability A can be calculated by using the following equations based on the failure and repair rate [20, 34, 35]:

$$P_0 = U = \frac{\lambda}{\lambda + \mu} = \frac{MTTR}{MTTF + MTTR} = \frac{MTTR}{MTBF} = \frac{f * r}{8760} \qquad [2.1]$$

$$P_1 = A = 1 - U = 1 - \frac{f * r}{8760} \qquad [2.2]$$

Where:

$MTTR$: mean time to repair $= \frac{1}{\mu} = \frac{r}{8760}$ [y]

$MTTF$: mean time to failure $= \frac{1}{\lambda}$ [y]

$MTBF$: mean time between failures $= MTTF + MTTR = \frac{1}{f}$ [y]

f : failure frequency of the component [/y]

r : repair time of the component [h]

Given that a system with N independent components is considered and each component can be in one of the two states of Figure 2.1 (S_0 or S_1), there are 2^N states in which the overall system might be [36]. So, as the size of the system increases, the number of system states rises considerably. The probability P_i of the state S_i where M components have failed (M<=N) can be calculated by formula 2.3 [37]:

$$P_i = \prod_{j=1}^{M} U_j \times \prod_{j=M+1}^{N} A_j \qquad [2.3]$$

Where:
U_j : unavailability of component j
A_j : availability of component j
N : total number of components
M : number of failed components

The failure rate λ_i of the state S_i where M components have failed (M<=N) can be calculated by formula 2.4 [37]:

$$\lambda_i = \sum_{j=1}^{M} \mu_j + \sum_{j=M+1}^{N} \lambda_j \qquad [2.4]$$

Where:
μ_j : repair rate of component j
λ_j : failure rate of component j

The frequency F_i of the state S_i where M components have failed (M<=N) can be calculated by formula 2.5 [37]:

$$F_i = P_i \times \lambda_i \qquad [2.5]$$

Where:
P_i : probability of state S_i
λ_i : failure rate of state S_i

Although the Markov process is a simple and convenient modeling approach, it has a significant drawback. It cannot be applied for large systems because its simplicity disappears. The representation of all possible combinations of the states of the different components would lead to an extremely large and complicated model, which would be difficult to use [33]. Therefore, for large systems there are special techniques which allow the selection of specific system states, so the selection of specific contingencies. These techniques are presented in section 2.3.2.

2.3.2. Techniques for contingency analysis

As mentioned in section 2.3, during the reliability assessment, the transmission network is examined under different contingencies. Therefore, it is important to illustrate with what techniques the different contingencies' scenarios can be applied. There are two main categories: numerical and analytical techniques.

The most popular numerical technique is Monte Carlo simulation. It is a repetitive process which simulates the actual behaviour of an electrical power system. It relies on repeated random sampling and therefore it treats the problem as a series of experiments [22]. The results of Monte Carlo simulation in a reliability assessment are expected values of the reliability indicators. The desired statistical confidence in the results is directly related to the simulation time, meaning that high statistical confidence requires many system years to be simulated. On the other hand, Monte Carlo simulation is less sensitive to the size of the under examination system [38]. There are two main types of Monte Carlo simulation: sequential and non-sequential. In the first case a chronological order is followed and the simulation perceives all chronological aspects, while in the second case a non-chronological system state is obtained and the hours of the study time are chosen randomly. According to [39], the sequential Monte Carlo needs more computational time and effort in comparison to the non-sequential one. An application of the sequential Monte Carlo simulation is given in [40], with the purpose of evaluating the outage costs. In [41] a smart splitting technique, which can decrease the workload of Monte Carlo simulation for the determination of reliability indicators, is illustrated.

In analytical techniques, the expected values of reliability indicators are calculated by using mathematical models or analytical approaches. In [21] the following three analytical techniques are described: state space, minimal cut set approach and contingency (or state) enumeration. If the first one (state space) is applied in large systems, the computational effort can be extremely high and network reduction techniques are required. On the contrary, in the second technique (minimal cut set approach) the computational time can be reduced significantly by assessing the reliability of particular load points in the network and by considering only the contingencies concerning these points [21]. Although both are very useful, special attention will be given to the third technique (state enumeration), since it is the most common used technique for larger transmission networks.

During state enumeration a specific number of contingencies are selected and examined. Despite the fact that the analysis of all possible contingencies constitutes the safest choice, the extensive computational time makes this scenario unrealistic [21]. Therefore, it is important to include mainly the contingencies, which are critical for the reliability of the grid. Usually low-order contingencies are considered critical due to their high probability of occurrence, despite the fact that high-order contingencies with low probability of occurrence might have a larger impact on the operation of the grid [42]. A frequent choice is to investigate contingencies up to a particular order, for example until third order. This means that all combinations of up to three failed components are studied. Each combination is assessed exactly one time, while in Monte Carlo simulation some contingencies are simulated several times and some others might not occur at all. This happens because in the second case the selection of the contingencies is random, in spite of the fact that the probability of the contingencies is taken into account. In state enumeration, the reliability indicators are calculated by using mathematical equations and statistics. An application of state enumeration for the reliability assessment of the bulk power system of Eastern Croatia can be found in [43].

2.3.3. Load-flow study & Remedial actions

When at least one contingency occurs (during contingency analysis), a load-flow (or else power-flow) calculation is realized for the static post-disturbance condition in order to identify any constraints' violations (e.g. overloads in the network) [21]. An ac load-flow study gives information regarding the magnitude and phase angle of the voltage at each bus and the active and reactive power flowing in each line. The iterative processes for performing ac load-flow study, such as Gauss-Seidel and Newton-Raphson, but also fast approximate methods, like decoupled power-flow, are described in [44]. In the same book, it is also explained what simplifications need to be done for a dc load-flow study. By comparing an ac and a dc load-flow calculation, it is clear that the first one gives more information (e.g. any voltage or reactive power problems) while the second one has higher speed, since it is a linear non-iterative process [45]. In case of large networks, where complexity and calculation time increase significantly, the dc load-flow study can be an effective option. A smart strategy is first to run a dc load-flow calculation for a large number of contingencies, then to identify the most critical ones and finally to run an ac load-flow calculation only for these [21].

During the load-flow calculation an overload might be identified in the grid. The Transmission System Operator (TSO) is responsible to relieve the overload and restore the operation of the grid within constraints. This should be done within short time and with the least severe effects. Various remedial (or corrective) actions can be applied in order to alleviate the overload, protect equipment from serious damage and prevent cascading failures [46]. These corrective actions are short-term operational measures and their use depends on several factors such as: type and location of the contingency, topology of the network, severity of the situation, remedial action scheme of each TSO. However, all system operators follow the same principle: load curtailment should be avoided or (if this is not possible) at least minimized.

The most common used remedial actions are explained briefly below, but without prioritizing them.

Phase Shifting Transformers (PSTs): They can influence the power flows throughout the network significantly without changing grid injections (e.g. generation). More specifically, the active power flow in a connection can be influenced by changing either the impedance of this connection or the angle between the end voltages. The PSTs change the angle between the sending and receiving voltages and in this way the power flow can be controlled [47]. More information regarding the operation of PST can be found in [48].

Transmission switching: By switching bus-bars, transmission lines or shunt elements, an optimal network reconfiguration might be achieved and the normal operating state of the grid can be restored [49]. In [50] transmission switching is used as an efficient congestion management tool and the switching actions, which have to be applied in order to alleviate the congestion, are presented in order.

Generation re-dispatch: It refers to the rescheduling of the power plant's dispatch in order to relieve the overload. An interesting methodology for optimal generation re-dispatch is described in [51].

Cross-border re-dispatch: If the application of remedial actions at national level is not enough to solve the problem, the system operators might ask neighbouring TSOs, with which their grid is interconnected, to import or export (depending on the situation) more or less power. Since cross-border re-dispatch requires the participation of more than one TSO, the final action should ensure the safe operation of all the participating grids. Therefore, the availability of this remedial action is not always guaranteed. Even if the other TSOs can participate in re-dispatch, cross-border re-dispatch might not be possible due to unavailable cross-border transport capacity.

Load curtailment (or else load shedding): When all the options for remedial actions have been exhausted, then load curtailment can be applied. Load is curtailed in one or more regions of the grid in order to avoid total blackout of the system. It is the last resort. There are many load-shedding schemes but the objective of all is to minimize the curtailed load. In [52] three schemes are compared: basic optimization method, heuristic approach to local load shedding and local load shedding optimization method.

It should be noted that combinations of corrective actions are possible as well, depending on what is needed to overcome the problem.

2.3.4. Reliability indicators

As mentioned in section 2.3, the last step of the reliability assessment is the calculation of several reliability indicators (or else Key Performance Indicators KPIs) in order to acquire a quantitative measure of the expected supply reliability in the network. These indicators are calculated based on the consequences of the above described remedial actions. For example, customer interruption indicators have non-zero value if load curtailment is applied. It should be highlighted that depending on the application, different indicators are monitored [21]. According to [53], there are two main categories: the conventional and the well-being reliability indicators. Let us examine them separately.

2.3.4.1. Conventional reliability indicators

The conventional reliability indicators are usually based on customer interruptions and non-transmitted power. Although there are plenty, only the most common used ones are presented here by giving their definition and way of calculation.

(i) Customer Interruption Indicators

- **SAIDI**: System Average Interruption Duration Index

It measures the average outage duration of each customer during a given time period (usually on a yearly basis). First, each interruption is multiplied with its duration in order to calculate the Customer Minutes Lost (CML), then the CML of all interruptions are summed (total CML) and finally they are divided by the total number of customers. The exact equation is formula 2.6 [54]:

$$SAIDI = \frac{\sum(r_i \times N_i)}{N_t} \text{ (min)} \quad [2.6]$$

where,
r_i : restoration time of interruption i (min)
N_i : number of customers not served by interruption i
N_t : total number of customers

- **SAIFI**: System Average Interruption Frequency Index

It measures the average number of interruptions per customer during a given time period (usually on yearly basis). The number of customers not served is divided by the total number of customers. The exact equation is formula 2.7 [54]:

$$SAIFI = \frac{\sum N_i}{N_t} \text{ } (-) \quad [2.7]$$

where,
N_i : number of customers not served by interruption i
N_t : total number of customers

- **CAIDI:** Customer Average Interruption Duration Index

It represents the average restoration time during a given time period (usually on yearly basis). It is calculated in the same way with SAIDI, but now the denominator is the total number of customers not served and not the total number of customers. The exact equation is formula 2.8 [55]:

$$CAIDI = \frac{\sum(r_i \times N_i)}{N_i} = \frac{SAIDI}{SAIFI} \text{ (min)} \quad [2.8]$$

where,
r_i : restoration time of interruption i (min)
N_i : number of customers not served by interruption i

(ii) Load and Energy Based Indicators

- **EENS:** Expected Energy Not Supplied or **LOEE:** Loss of Energy Expectation or

It measures the total amount of energy that is expected not to be supplied during a given time period (usually on a yearly basis) due to supply interruptions. The probability of each outage is multiplied with the curtailed energy caused by this outage and the sum of all these products is calculated. The exact equation is formula 2.9 [56]:

$$EENS = \sum_{i=1}^{n} P_i \times E_i \text{ (MWh)} \quad [2.9]$$

where,
P_i : probability of outage i
E_i : curtailed energy due to outage i (MWh)

- **LOLP:** Loss Of Load Probability

It represents the probability that the demanded power cannot be supplied (partially or completely) during a given time period (usually on a yearly basis). Its weakness is that it does not give any information about the severity of the outage (amount of loss of load). The exact equation is formula 2.10 [57]:

$$LOLP = \sum_{i=1}^{n} \frac{P_i \times t_i}{100} \text{ (−)} \quad [2.10]$$

where,
P_i : probability of outage i
t_i : percentage of time that there is loss of load

- **LOLE:** Loss Of Load Expectation

It measures the expected amount of time that the demanded power cannot be supplied (partially or completely). It has the same weakness with LOLP. The exact equation is formula 2.11 [57]:

$$LOLE = \sum_{i=1}^{n} LOLP \times T \text{ (days or hours)} \quad [2.11]$$

where,
$LOLP$: loss of load probability
T : 365 days for annual load curve or 8760 hours for hourly load curve

2.3.4.2. Well-being reliability indicators

As mentioned in section 2.2, the deterministic considerations can be combined with probabilistic concepts in the well-being analysis. First, the operation of the transmission network is classified into several states depending on what extent the adequacy and security constraints are satisfied and then the probabilities of these states are calculated [58]. The main operating states are normal, alert and emergency and their probabilities constitute the well-being indicators [31]. Below, the operating states are described according to [58]:

Normal state: the system operates by respecting component ratings, voltage limits and in general all operating constraints. The n-1 deterministic criterion is valid, which means that there is sufficient margin to lose a single component without violation of constraints.

Alert state: the operating constraints are satisfied but the n-1 deterministic criterion is not valid any more. There is no margin to withstand a loss of a component. If a single contingency occurs, violation of constraints will be observed.

Emergency state: the system does not operate within constraints and violation of limits exists (e.g. overloaded connections). In this state, curtailment of load might occur.

After the occurrence of a contingency (at least one failed component), through the load-flow calculation and the application (if necessary) of remedial actions, it is possible to identify the operating state of the network (normal, alert or emergency). After identification, the probability of this state is calculated by using formula 2.3, so it depends on the unavailability and availability of the failed component(s). This is repeated for every contingency during contingency analysis. In the end, the total probability of each of the operating states is determined by adding all the separate probabilities relevant to the concerning state. For instance, the probability of alert state P_{alert_state} can be calculated by formula 2.12:

$$P_{alert\_state} = \sum_{i=1}^{n} P_i \qquad [2.12]$$

where,
P_i : probability of alert state i caused by a contingency (calculated by formula 2.3)
n : number of alert states that were identified during contingency analysis
Formula 2.12 can be used for the probabilities of the other operating states as well.

By calculating the well-being indicators, it can be estimated not only the probability of violated constraints but also the probability of being very close to such a situation [59]. In [60] multiple contingencies of an electric power system are assessed by using the concept of operating states and the Rough Set theory.

2.4. OVERHEAD LINES VS. UNDERGROUND CABLES

In section 2.3 the steps of a reliability assessment were described and it was explored how the key performance indicators of a transmission network can be calculated by determining the reliability level of the grid. Whether the transmission of electricity is realized by overhead lines (OHL) or underground cables (UGC) plays a significant role in the reliability level of the grid. Before analyzing the reasons behind this statement, basic information regarding the use of OHL and UGC is provided.

2.4.1. Benefits and Limitations of OHL

The use of overhead lines dominates the current transmission networks and the system operators count many years of experience and expertise in running OHL [3]. This important advantage in combination with the low relative capital cost and their proven safe and reliable operation explains why the use of OHL is so popular [4]. On the other hand, the overhead lines are exposed to external factors such as extreme weather conditions (excessive wind, lightning), falling trees, fires or car accidents, so they are subject to damage due to their nature [6]. However, this is not the main reason why today the construction of new overhead lines tends to be restricted. The installation of new overhead lines faces many challenges due to societal, environmental reasons and governmental policies [61]. Especially in densely populated areas, there is a strong public opposition against overhead lines due to risk for health generated by electric and magnetic fields (EMF), noise pollution (caused by the corona effect), distortion of the visual landscape, effects on property values, impact on natural reserves and archaeological sites and damage to wildlife [5]. This plurality of factors can explain the negative attitude of some citizens towards the reinforcement of the electricity grid infrastructure with OHL. This attitude often leads to protests which can extend the already long permit process of new OHL (3-15 years) [62]. This situation leads to political and environmental pressure from the public and government side towards the system operators to find an alternative solution, which can satisfy technical specifications, societal and environmental standards.

2.4.2. Benefits and Limitations of UGC

One solution that gains widespread public support is the installation of extra high voltage (EHV) AC XLPE underground cables. Although until recently, underground cables were mainly used in distribution networks, the state-of the art technology and their advanced design made it possible to use XLPE cables for EHV applications in transmission networks [3]. Nowadays more and more countries resort to this alternative and have already constructed or are planning to install that kind of links [12]. It should be mentioned that the installation of EHV UGC can be realized partially or completely in a connection. In the first case, underground cable(s) co-exist with overhead line(s) and they are connected in series [12], while in the second case the connection is fully cabled. The benefits of such a technological breakthrough are plenty, especially from an environmental and societal perspective.

More specifically, the impact from the electromagnetic fields can be minimized, the landscape impairments might be limited, areas with high environmental sensitivities can be crossed, the approval procedures can be faster and the public agreement for the extension of the electricity grid infrastructure increases [6, 7]. In addition, according to [8] the use of underground technology can reduce considerably the transmission losses and the need for maintenance. Moreover, UGC are less vulnerable to extreme weather conditions, since they are buried, out of sight [6].

However, there are also some areas where OHL score better than UGC. Although the difference in construction costs between the two alternatives is significantly reduced due to recent advancements in underground technology [6], the installation of underground cables still leads to substantially higher costs (3 to 20 times more) than the construction of new OHL [7]. Another issue that might hamper the further use of EHV XLPE cables is the limited knowledge and experience in this field. This can be noticed even with the limited available literature regarding the operation of UGC compared to OHL [10]. What is more, the electrical behaviour of an underground cable is very different than the one of an overhead line. The first presents higher shunt capacitance, much lower characteristic impedance and thus, it is almost always a source of reactive power [11]. Moreover, the difference between UGC and OHL in current ratings, thermal limits and in general in their operational characteristic explains why there is a necessity for thorough studies in several areas such as: steady state, switching transients and resonance conditions [3, 12]. Another significant area of concern is the reliability of underground cables and how it impacts the availability of the whole network.

2.4.3. Reliability perspective

The installation of underground cables in a connection in a transmission network might result to a different reliability level of the grid than the installation of overhead lines in the exact same connection [17]. This can be explained because a) the unavailability of a partially or fully cabled connection is different than the one of a line connection and b) the insertion of UGC with their low characteristic impedance may lead to a completely different load flow in a meshed grid than the insertion of OHL [3]. Both these reasons are analyzed in the next sections.

2.4.3.1. Unavailability of OHL & UGC

From formula [2.1] it is obvious that the unavailability of a component depends on its failure frequency and its repair time. If the component is the connection where UGC or OHL are installed and if we compare these two parameters (failure frequency and repair time) for the two alternatives (UGC and OHL), the difference in their unavailability is revealed.

(i) Failure frequency

Overhead lines experience failures more frequently than underground cables because they are susceptible to external factors [6]. However, since cables are always accompanied by the necessary accessories, joints and terminations, which are vulnerable to mechanical damage due to thermal-mechanical movement, UGC present as an overall higher failure frequency than OHL[17]. Furthermore, the actual configuration of UGC is very important from a reliability point of view, in the sense of how many individual cables per circuit phase are used. For instance, if not one but two separate cables per circuit phase are used for transmission capacity purposes, the failure frequency of the whole circuit increases [17]. What is more, the length of the connection in both cases (UGC or OHL) has an impact on the failure frequency and thus the unavailability of the connection. To wrap up, the total failure frequency of UGC depends on the failure frequency of each component (cable, joints and terminations), the cable length, the amount of joints and terminations and the selected configuration, while the total failure frequency of OHL depends only on the line length. In order to calculate the failure frequency of UGC, the same formula that Ir. Bart Tuinema used in his research [35], is applied in this study as well (formula 2.13). It is valid for a single cable circuit.

$$f_{c1} = l_c \cdot 2 \cdot f_{cable} + \left(N_{cp} - 1\right) \cdot 3 \cdot 2 \cdot f_{joint} + 2 \cdot 3 \cdot 2 \cdot f_{termination} [1/y] \qquad [2.13]$$

where,
f_{c1}: failure frequency of a single cable circuit [/y]
l_c: total cable length [km]
f_{cable}: failure frequency of an underground cable (one cable per phase) [/cctkm·y]
N_{cp}: number of cable parts where joints are needed [-]
f_{joint}: failure frequency of a single joint [/comp·y]
$f_{termination}$: failure frequency of a single termination [/comp·y]

As already mentioned, there is limited experience and knowledge in the field of EHV UGC and therefore there are not accurate values for the failure frequencies of UGC. However, in the research of Ir. Bart Tuinema [35], which is used as an input in this thesis, two useful sources for cable failure statistics are used: a report by Cigré and a study among European TSOs [19, 63]. According to the second source, high and low estimations of the average failure frequencies (TSO's high and TSO's low respectively) are proposed and they are demonstrated, together with the values of the Cigré report, in Table 2.1 below:

Table 2.1 - Failure frequencies of EHV UGC [35]

	Cigré	TSO's high	TSO's low
Component	Failure frequency	Failure frequency	Failure frequency
Cable	0.00133 [/cctkm*y]	0.00120 [/cctkm*y]	0.00079 [/cctkm*y]
Joint	0.00048 [/comp*y]	0.00035 [/comp*y]	0.00016 [/comp*y]
Termination	0.00050 [/comp*y]	0.00168 [/comp*y]	0.00092 [/comp*y]

By using formula 2.13, the above values and by knowing the configuration, the cable length and the amount of joints and terminations, the failure frequency of UGC can be calculated. Furthermore, in [35] the following failure frequency of OHL is used:

Table 2.2 - Failure frequencies of EHV OHL [35]

Component	Failure frequency
EHV OHL	0.00220 [/cctkm*y]

As can be seen in Table 2.1 and Table 2.2, the failure frequency of an individual cable (without accessories) is in all cases (Cigré, TSO's high and TSO's low) lower than the failure frequency of an overhead line. However, the existence of joints and terminations and the selection of configurations with two or more cables per circuit phase increase the failure frequency of UGC substantially (it might become more than three times larger than in the case of OHL) [35]. By observing formula 2.1, it is obvious that the increased failure frequency of UGC is converted into an increased unavailability of the connection where cables are installed, compared to the case of OHL.

(ii) Repair time

Apart from the failure frequency, the repair time of a component plays an important role in the determination of its unavailability as well (formula 2.1). Several studies in literature have reported the considerably longer repair time of UGC compared to OHL [4, 6, 62, 64]. According to [18], the minimum outage time that has been experienced for 380kV XLPE underground cables in Europe is 2 weeks, while the maximum one amounts to 9 months. It is clear that there is a big uncertainty in the estimation of repair time of UGC and no accurate values can be provided [19]. In [35] an extensive literature review on failure statistics is conducted and in the end the repair time of UGC is chosen equal to 730h, while the repair time of OHL equal to 8h. By observing formula 2.1, it is obvious that the increased repair time of UGC is converted into an increased unavailability of the connection where cables are installed, compared to the case of OHL.

It is interesting to note that the repair time of the cable itself constitutes only a small part of the total outage time, while there are other procedures which are very time consuming [18]. Finding the location of the failure, acquiring the necessary permissions, gathering evidence, cleaning the site, contacting supplier, getting spare or ordering new components, ensuring available skilled personnel and testing the component after repairing it are the most important ones [19]. Some of these processes are flexible and with careful planning they can be improved in order to lead to reduced repair times. For instance, by discovering smart and fast ways to locate the failure, by ensuring spare parts, by arranging suitable contracts with insurance companies or by acquiring the necessary permissions before the occurrence of the failure, can make the outage time considerably shorter [19].

2.4.3.2. Characteristic impedance of OHL & UGC

Apart from the unavailability of the connection where UGC or OHL are installed, the impedance of the connection can play a significant role in determining the reliability level of the grid as well. As previously mentioned, cables present higher shunt capacitance and much lower characteristic impedance than overhead lines [11]. This higher shunt capacitance reduces the ability of the cable to transmit active power and usually shunt reactors are used to compensate the excessive produced reactive power [65]. Furthermore, different characteristic impedance of a connection in a meshed transmission network means different load flow, because the power flows are determined by the impedances of the connections [3]. If UGC are installed in a connection, the impedance of this connection will be much lower than it would be if OHL would be installed. This means that the two alternatives (UGC and OHL) lead to different power flows. As a result, under contingency analysis different connections might be overloaded (or same connections but with different amount of overload), different frequency of remedial actions might be noticed, different values for the key performance indicators might be calculated and finally different reliability level of the grid might be reported. In order to know how the reliability level is influenced by the installation of UGC, it is necessary to conduct simulations and perform a load-flow study in the network. More information regarding load-flow studies were presented in section 2.3.3.

3

Methodology

3.1. Overview of the research framework

The main goal of this thesis is to examine how the installation of EHV underground cables in transmission networks impacts the overall reliability level. In order to achieve that and by looking from a high level (without many details), the following research framework is developed (Figure 3.1). In chapter 2 basic reliability concepts were introduced and a comparative study between OHL and UGC was conducted through an extensive literature review. In order to enrich the insight gained from this literature review, unstructured interviews took place with experts from different departments in TenneT (Risk & delivery Management, Grid Development and Strategy, System Operations Concepts, National Control Centre). By using the findings from both sources, a qualitative generic approach is developed in this chapter (section 3.2). This approach includes the steps of the decision making process that a planner has to follow when he/she examines the installation of EHV UGC from a reliability point of view. An overview of this approach and the analysis of each step are given in section 3.2.

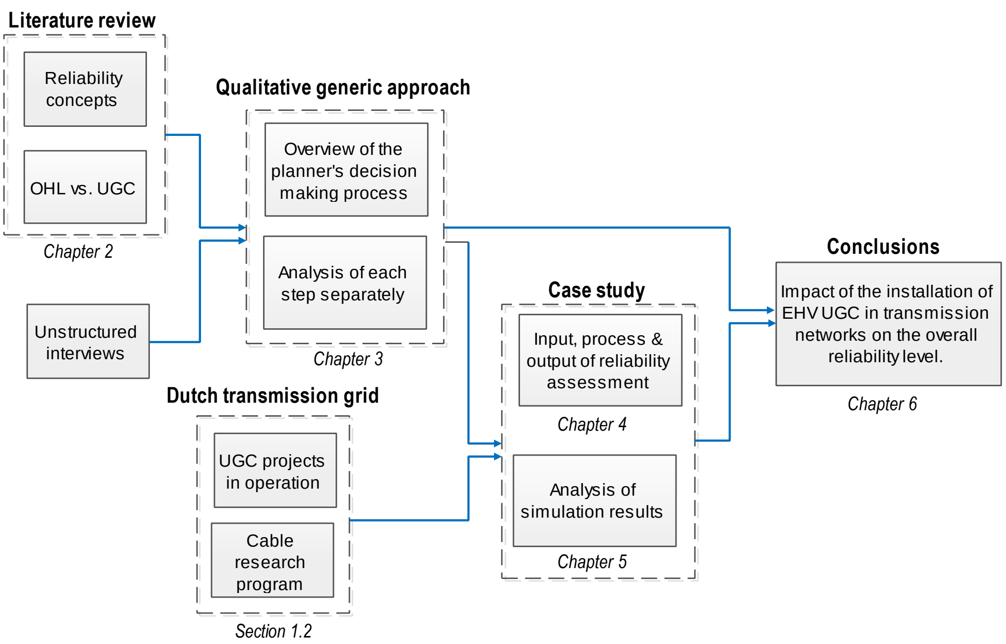


Figure 3.1 - Overview of the research framework

Then, this approach is implemented for the case study of the EHV Dutch transmission grid (chapter 4) by using the information regarding the cable projects which are already in operation in the Dutch transmission network, presented in section 1.2. Different simulation sets are performed and after analysing the results, conclusions are drawn regarding the impact of EHV UGC on the reliability of a transmission network.

Now that the research framework is clear, the reader may proceed to section 3.2 where the qualitative generic approach is described. As mentioned, this approach includes the steps of the decision making process that a planner has to follow when he/she examines the installation of EHV UGC from a reliability point of view. From what data are necessary until how to process and evaluate the results from the reliability assessment. The reliability assessment is only one step in the whole procedure.

3.2. QUALITATIVE GENERIC APPROACH

In order to give a clear description of the qualitative generic approach, it is divided into eight separate steps. First, by looking from a high level, an overview of the approach is provided through a flowchart (Figure 3.2). In this overview, all the steps are presented in order to illustrate how they are connected, but without details for each one. Later, for a closer look, each step is analysed separately by giving more information. It should be also mentioned that there are internal feedback loops that are not obvious in Figure 3.2, but will be presented in the analysis of each step. In Appendix A, the complete flowchart of the whole qualitative generic approach with the detailed steps is provided. For now, the flowchart of the overview is illustrated and its description starts in the next page.

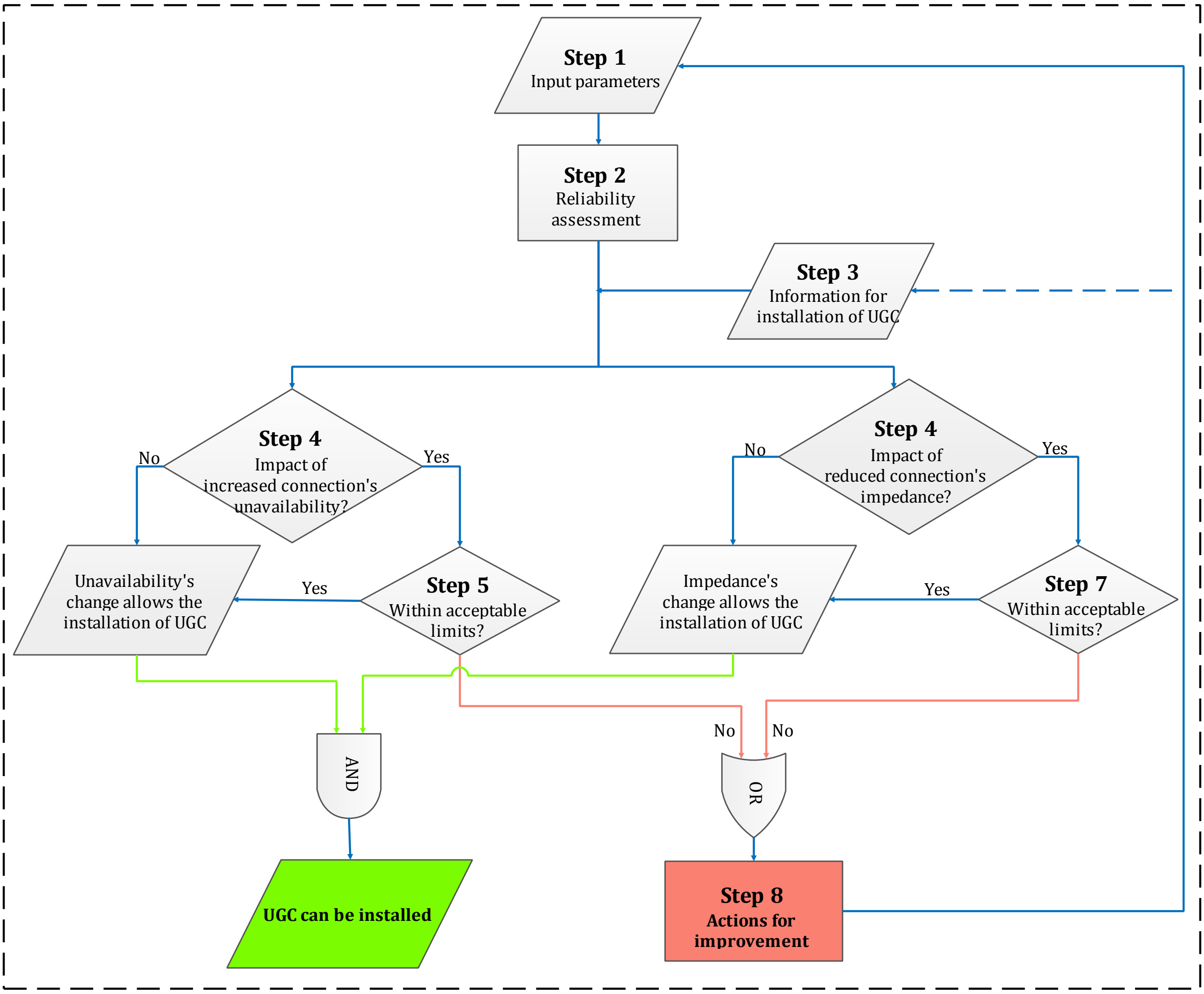


Figure 3.2 - Overview of the qualitative generic approach

Let us assume that a transmission system operator (TSO) desires to install EHV underground cables in the network, but wants first to examine how this installation will influence the overall reliability level. The planner (or the team of planners) who has been assigned this task, could follow the next steps.

In the first step (section 3.2.1) the input parameters of the analysis are recognized and all the information needed for each of these parameters is identified. However, it is important to clarify that these input parameters do not refer to the new UGC that the TSO wants to install in the network, and the network topology does not include them. More specifically, if the intention is to install UGC in a new connection of the network, then the current network topology changes and the new extended one is used as input. However, according to the proposed approach of this study, first it is assumed that this new connection is an overhead line. In a later step, it will become a partially or fully cabled connection. The reason for that is that a comparative study between the two alternatives (OHL and UGC) can always give some more insight. Similar idea applies if the intention is to install UGC in an existing connection of the network. In this case the current network topology is used as input without any change, meaning that first the selected existing connection remains an overhead line. Later it will become a partially or fully cabled connection.

With the network topology of step 1 (without new UGC) and all the input data that were introduced, the planner can proceed to the second step (section 3.2.2), which is the reliability assessment of the network. As explained in section 2.3, the reliability assessment consists of four major functions: contingency analysis, load-flow study, use of remedial actions if necessary and calculation of key performance indicators. In this step an algorithm needs to be developed and several calculations to be performed.

So far, no information regarding the installation of new UGC is introduced. This happens in the third step (section 3.2.3), where new input parameters are defined and new input data are introduced, all of them referring to the new underground cables that the TSO considers to install in the network. The reason why the information for the new UGC is gathered in this step and not in the first one is because they are not required for the second step (reliability assessment).

The fourth step (section 3.2.4) is based on the principle that the unavailability of a connection is higher when it is partially or fully cabled than when it is completely an overhead line (section 2.4.3.1). More specifically, this step examines how this increase in the connection's unavailability (due to the installation of UGC instead of OHL) impacts the overall reliability level, based on the results of the second step and the information of the third step. If there is no impact, the increased connection's unavailability does not hamper the installation of UGC, while if there is an impact the planner proceeds to the fifth step (section 3.2.4). There it is explored if the new reliability level is acceptable according to the standards that the TSO sets. If yes, then although the increased connection's unavailability changes the current reliability level, it allows the installation of UGC. However, if the new reliability level is not acceptable, there is a call for improvement actions (step 8).

By installing UGC instead of OHL, not only the connection's unavailability, but the impedance of the connection differs as well (section 2.4.3.2). The sixth step investigates how the lower characteristic impedance of UGC impacts the overall reliability level, based on the results of the second step and the information of the third step. If there is no impact, the reduced connection's impedance does not create obstacles for the installation of UGC, while if there is an impact the planner proceeds to the seventh step (section 3.2.5). There it is explored if the new reliability level is acceptable according to the standards that the planner sets. If yes, then although the reduced connection's impedance changes the current reliability level, it allows the installation of UGC. However, if the new reliability level is not acceptable, there is a call for improvement actions (step 8).

From Figure 3.2 it is obvious that only if both the increased connection's unavailability and the reduced connection's impedance allow the installation of UGC, the UGC can be installed (from a reliability point of view). On the other hand, if at least one of the two factors (increased unavailability or reduced impedance) leads to an unacceptable reliability level, then we move towards the eighth step (section 3.2.6) because actions for improvement are necessary. In this step possible actions to improve the new unacceptable reliability level are proposed and after adopting at least one of them, the planner should go back with a feedback loop to re-examine the situation. Although more information regarding these actions for improvement are given later, it should be clear that the planner might need to start again from step 1 or step 3, depending on the action. That is why in Figure 3.2 the feedback loop points to both steps.

3.2.1. Step 1: Input parameters

The first step identifies what input parameters are needed for the reliability assessment, which is realized in the second step. As demonstrated in Figure 3.3, questions are asked to the planner (green dashed box) and according to his/her answers the input data are determined (orange dashed box).

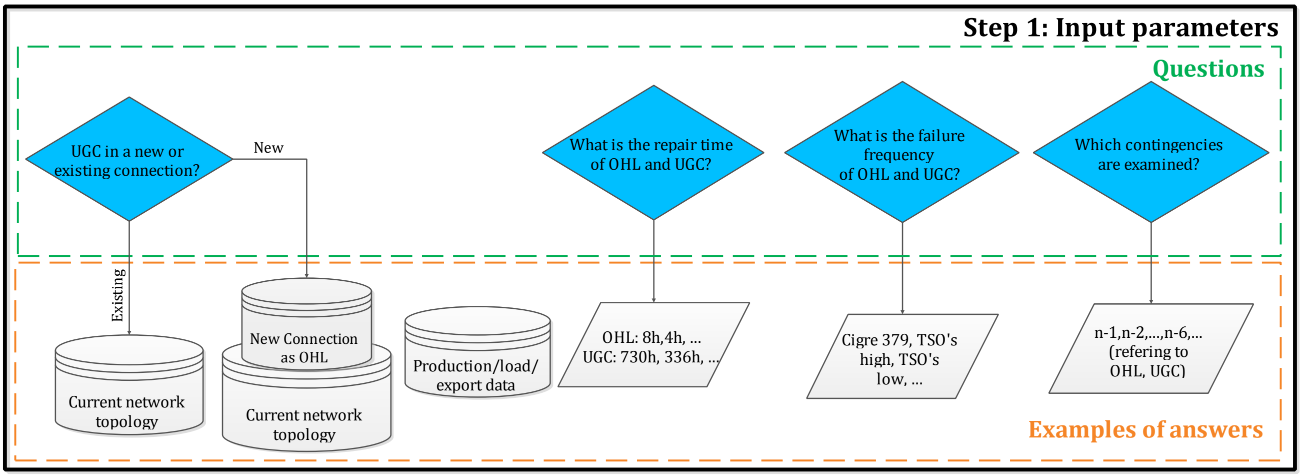


Figure 3.3 - Input parameters

The answer to the first question clarifies if the transmission system operator intends to install UGC in an existing or a new connection. If the first holds, the current network topology is used as input, while if the second is the case, an extended network topology is used by adding the new connection as an overhead line. As mentioned in section 3.2, the network topology of step 1 does not include the new UGC that the TSO might install. Then the hourly production/load/export data are provided. The next two questions ask information regarding the repair time and failure frequency of both OHL and UGC, since they are needed for the reliability assessment. Although the new UGC are not included in the network topology yet, there might be already cables in the existing grid. That is why the failure statistics of UGC are also needed. Finally, the planner decides what kinds of contingencies will be examined. Undoubtedly, contingencies related to EHV overhead lines and underground cables are included, but he/she can include contingencies of other components as well (e.g. generators, transformers etc.). Furthermore, the order of contingencies is determined. For instance, n-1 contingencies contain only single failures, while n-3 contingencies contain combinations of up to three failed components. More information on how to select the order of contingencies was given in section 2.3.2. Before proceeding to step 2, it is important to mention that the "current" network topology and the production/load/export data refer to the year of simulations. For instance, if the TSO plans to install UGC in 2030, the future network topology (including any network developments) and forecasted data for 2030 are used.

3.2.2. Step 2: Reliability assessment

After acquiring the necessary input data from step 1, the reliability assessment is performed. As already mentioned in section 2.3, the reliability analysis includes four main functions: contingency analysis, load-flow study, use of remedial actions (if necessary) and calculation of key performance indicators. However, as can be seen in Figure 3.4, in this qualitative generic approach a few additional intermediate processes are required.

First, contingency analysis is performed through state enumeration for the kinds of contingencies that the planner selected in step 1.The reason that state enumeration is chosen and not any other technique is because state enumeration examines all possible combinations of contingencies for every hour of the year and in this way it gives the possibility to investigate extreme cases (low probability but maybe severe consequences). More information for this technique can be found in section 2.3.2. After the occurrence of each contingency an ac or dc load-flow calculation is performed for the static post-disturbance condition and any constraints' violations are identified. It is up to the planner if an ac or dc load-flow is calculated. The section 2.3.3 provides some characteristics for both. If violations are observed, remedial actions are applied in order to restore the operation of the grid within constraints. Since the remedial action scheme can be different for each transmission system operator, the planner should determine first which remedial actions are applied.

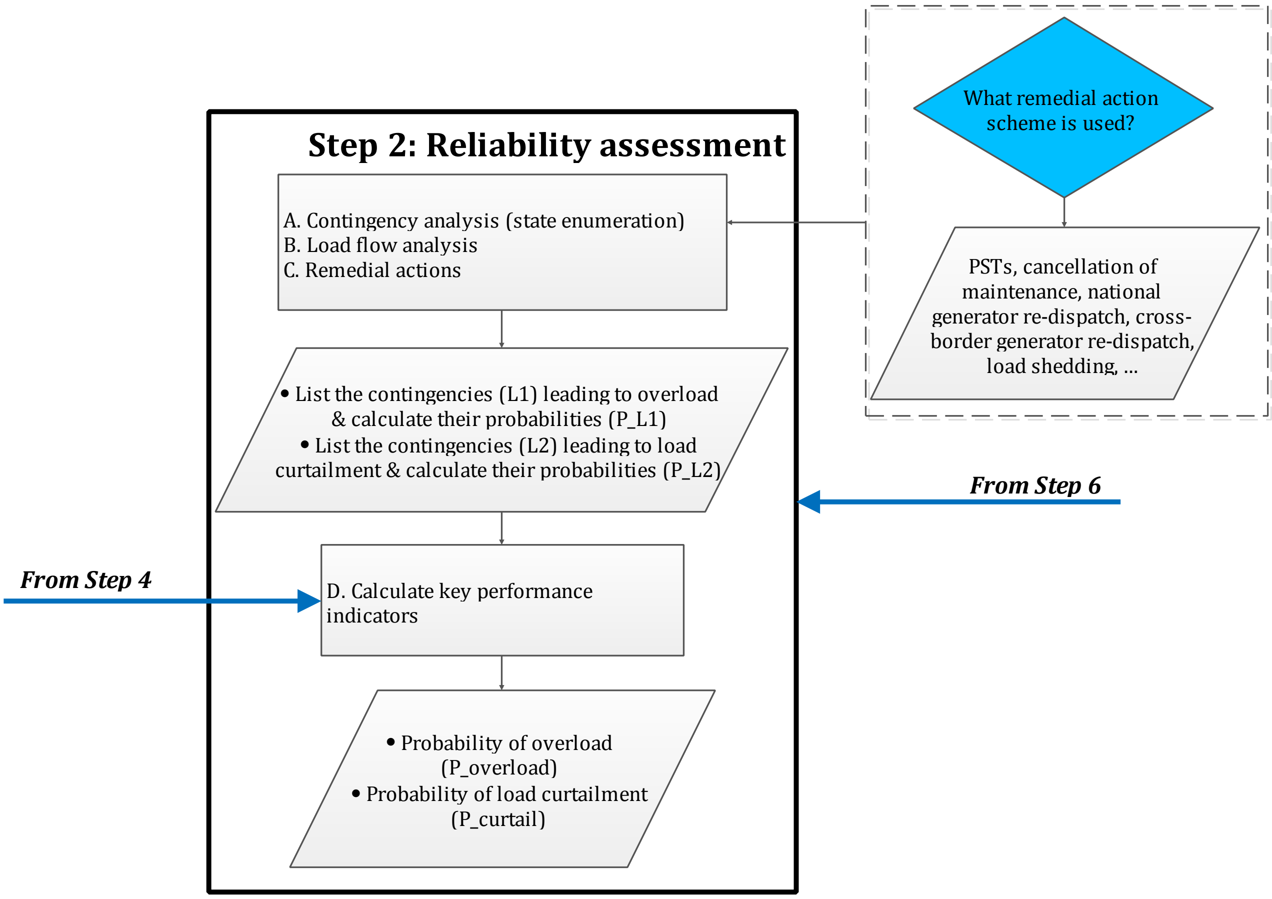


Figure 3.4 - Reliability assessment

After the use of corrective measures, several key performance indicators are calculated according to the interest of the planner. For simplicity reasons, here it is assumed that only two reliability indicators are measured: the probability to have an overload anywhere in the network and the probability of load curtailment. For the calculation of these indicators an intermediate process is required.

In order to calculate the probability of overload, the contingencies which lead to overload are listed (L1). This is possible because after the occurrence of each contingency, the load-flow calculation checks if this contingency leads to any constraints' violation, for instance an overload. So, we know which contingencies cause an overload and in the end we gather them. Then the probability of each of these contingencies is calculated (P_L1). If a contingency includes only one failed component, the probability of this contingency is the unavailability of the component and can be calculated by formula 2.1. If a contingency includes more than one failed components, the probability of this contingency can be calculated by formula 2.3. The sum of the probabilities of these contingencies (which lead to overload) equals to the probability of overload (P_overload).

In order to calculate the probability of load curtailment, the contingencies which lead to load curtailment are listed (L2). In a similar way as in the probability of overload, we know which contingencies lead to a violation that requires load curtailment and in the end we collect them. Then the probabilities of these contingencies are calculated (P_L2) and their sum is the probability of load curtailment (P_curtail). Finally it should be noticed that the two blue arrows in Figure 3.4 represent feedback loops, one from step 4 and the other from step 6. Later their existence will be explained.

3.2.3. Step 3: Information for the installation of new UGC

So far, no information regarding the installation of new underground cables is introduced and the reliability assessment of step 2 was conducted in a network topology without new cables. In this third step new input parameters are defined and new input data are introduced, all of them referring to the new underground cables that the TSO considers to install in the network. As illustrated in the following Figure 3.5, questions are asked to the planner (green dashed box) and according to his/her answers the input data are determined (orange dashed box).

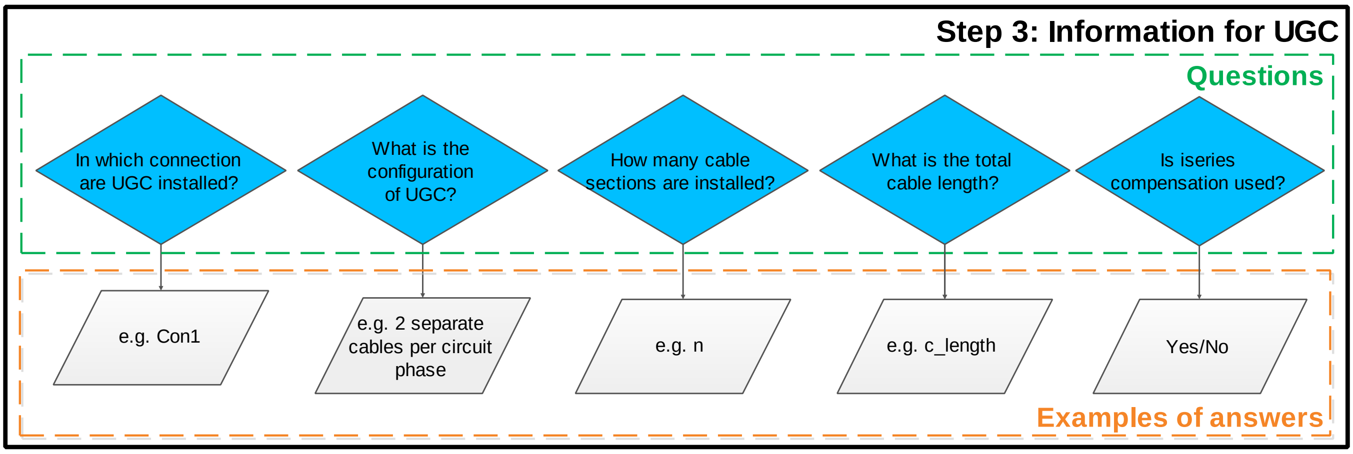


Figure 3.5 - Input parameters for the new UGC

The answer to the first question reveals the connection where the TSO plans to install new EHV underground cables. One could argue that this is already known from the first step (section 3.2.1) for the following reason. If the intention is to install cables in a new connection, the current network topology is extended, as described in step 1, by adding the new connection as an overhead line. So, the location of the connection is known. However, if the intention is to install new cables in an existing connection, the current network topology does not change and there is no need in step 1 to know the location of this existing connection. For this last case, the first question of Figure 3.5 is necessary. From now on the connection where it is planned to install UGC, will be referred as Con1. This Con1 (existing or new connection) during the reliability assessment (step 2) was an overhead line.

The next question is related to the configuration of UGC in the sense of how many individual cables per circuit phase are used. In general, EHV UGC can consist of one or more circuits and a separate cable is needed per circuit phase. However, in some cases it is necessary, from transmission capacity point of view, to install two or more separate cables per circuit phase [17]. Another important input parameter is the number of cable sections per connection and is valid only in the case of partially cabled connections. In a partially cabled connection there might be more than one cable section and more than one line section. The concepts regarding configuration of UGC and number of cable sections can be understood better through the example in Figure 3.6. In this single-phase scheme (Figure 3.6), a partially cabled connection of two circuits is illustrated. There are two cable and two line sections. In the cable sections there are two individual cables per circuit phase, while in the line sections there is only one individual cable per circuit phase.

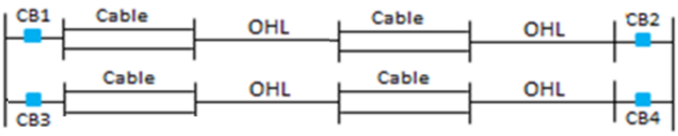


Figure 3.6 - Partially cabled connection with two cable sections

The next question concerns the length of the new underground cables, while the last question examines if series compensation is used along with the installation of UGC. As explained in section 2.4.3.2, when UGC are installed in a connection, the impedance of this connection is lower than when this connection is an overhead line. This impedance's change leads to different power flows in these two cases (UGC or OHL). However, if along with the installation of UGC compensation is used, in the form of series reactors, this phenomenon is restricted or even eliminated (partial or full compensation respectively). If full series compensation is used, the impedance of the connection is the same in case of OHL or UGC. If the TSO decides to use full series compensation, the planner does not have to perform steps 6 & 7, since these steps examine the impact of the reduced connection's impedance.

3.2.4. Steps 4 & 5: Acceptable impact of increased connection's unavailability?

In this section both steps 4 and 5 are elaborated, because they are strongly connected. Step 4 is based on the principle described in section 2.4.3.1: when a connection includes underground cables, it presents higher unavailability than when it is an overhead line. So far in this qualitative generic approach, Con1 (the connection where the TSO plans to install cables) is an overhead line. In step 4 Con1 becomes a cabled connection (according to input data of step 3), which means that its unavailability increases. To what extent this increase has an impact on the overall reliability level is investigated in this step. Given that there is an impact, in step 5 it is explored if this impact is acceptable. In Figure 3.7 below both steps are depicted in a flowchart, but first step 4 is analysed.

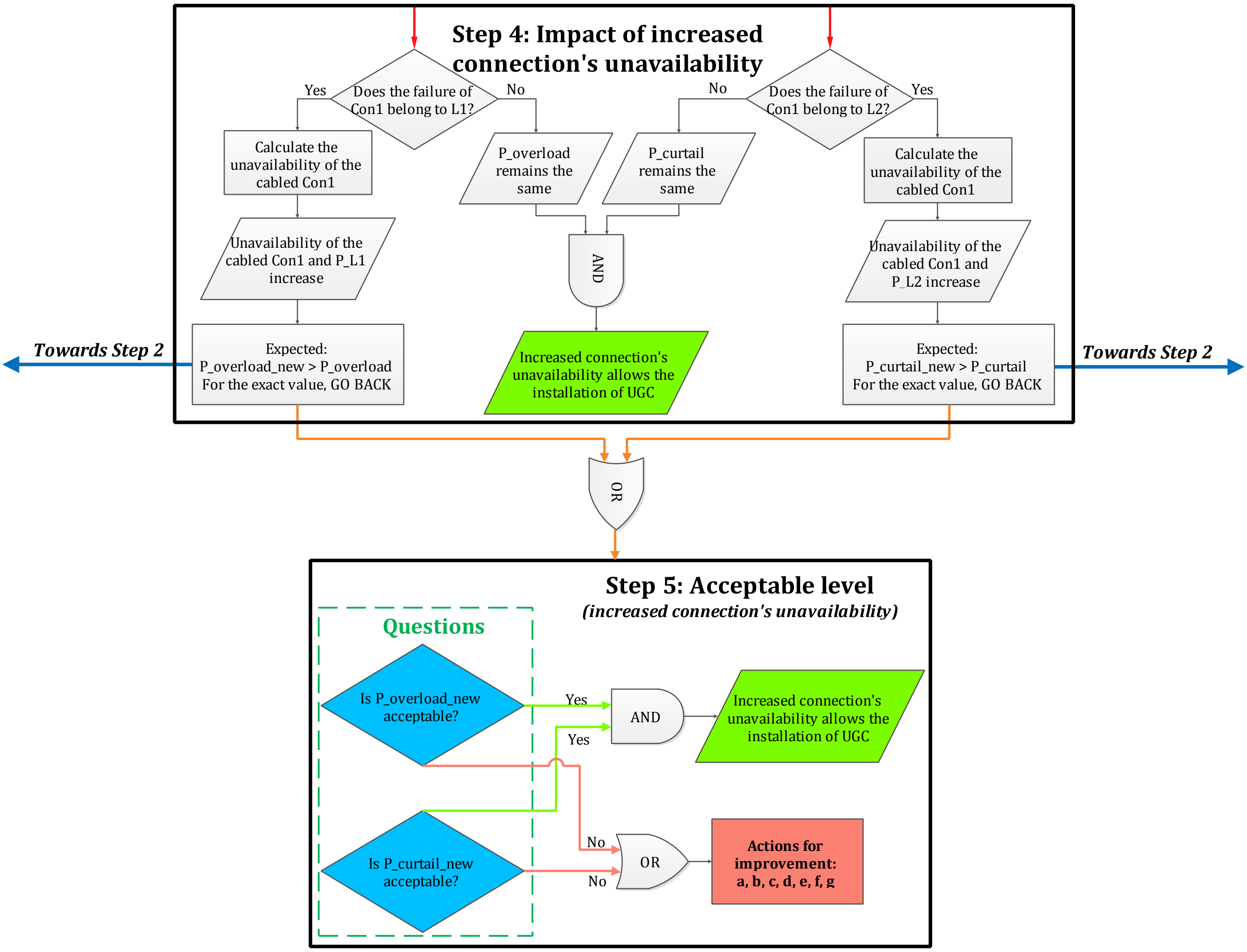


Figure 3.7 - (Un)acceptable impact of increased connection's unavailability

As can be seen in Figure 3.7, step 4 is divided from the start into two parts (left and right red arrows). Both parts follow the same logic but they concern different reliability indicators. The left part explores the impact of the increased connection's unavailability on the probability of overload, while the right part the impact on the probability of load curtailment. Let us focus first on the left part.

As explained in section 3.2, L1 is the list of contingencies whose occurrence leads to an overload anywhere in the network, P_L1 are their probabilities and P_overload, which is the sum of P_L1, is the probability of overload. The first question examines if the failure of Con1 belongs to contingencies L1. If it does not belong, the increased unavailability of Con1 (due to the installation of UGC) will not influence P_L1 (probabilities of L1) and will have no impact on P_overload. In this case whether Con1 is an overhead line or an underground cable does not play any role in the determination of the probability of overload. It remains the same. If the failure of Con1 belongs to contingencies L1, this means that the unavailability of Con1 influences P_L1 and P_overload. Therefore, it is necessary to calculate the new unavailability of Con1, when it is a cabled connection. As expected, its unavailability is higher than the previous one (Con1 as an overhead line) and this leads to a growth in P_L1. This means that the new probability of overload (P_overload_new) is higher than the old one (P_overload). In order to acquire the exact new value of the indicator (P_overload_new), the planner goes back with a feedback loop (blue arrow) to step 2 (Figure 3.4) and specifically to the process: "D. Calculation of key performance indicators". There is no need to perform again the whole reliability assessment (contingency analysis, load-flow study, remedial actions), because the list of contingencies leading to an overload (L1) does not change. Only the part, where the key performance indicators are calculated, is repeated by considering the new increased unavailability of the cabled Con1. After that the value of P_overload_new is known.

Similar procedure is followed for the probability of load curtailment (right part of step 4 in Figure 3.7). As explained in section 3.2, L2 is the list of contingencies whose occurrence leads to load curtailment, P_L2 are their probabilities and P_curtail, which is the sum of P_L2, is the probability of load curtailment. First it is examined if the failure of Con1 belongs to contingencies L2. If it does not belong, P_curtail remains the same despite the increased unavailability of Con1 (due to the installation of UGC). If the failure of Con1 belongs to contingencies L2, the new unavailability of the cabled Con1 is calculated and its increase leads to a growth in P_L2 and to an increased P_curtail (P_curtail_new). For the exact value, the planner goes back with a feedback loop (blue arrow) to step 2 (Figure 3.4) and specifically to the process: "D. Calculation of key performance indicators". Same as before, only the part with the calculation of reliability indicators is repeated by considering the new increased unavailability of the cabled Con1. After that the value of P_curtail_new is known.

As demonstrated in Figure 3.7, if the failure of Con1 belongs neither to L1 nor to L2, the probability of overload and the probability of load curtailment remain the same despite the installation of UGC in Con1. In this case the increased unavailability of Con1 does not hamper the installation of cables. However, if the failure of Con1 belongs to L1 or to L2, the installation of UGC in Con1 has an adverse impact on the probability of overload or load curtailment respectively and in this case the planner proceeds to step 5.

Since the values P_overload_new and P_curtail_new are known, the next step (step 5) is to investigate if these values are acceptable. This depends on the reliability standards that the TSO sets. That is why two questions are asked to the planner (green dashed box), one for each reliability indicator, regarding the acceptability levels. If both P_overload_new and P_curtail_new are acceptable, the increased unavailability of Con1 does not hamper the installation of cables. On the other hand, if at least one of the two is unacceptable, there are obstacles in the installation of UGC in Con1 and actions are needed to improve the situation. Finally, in the box "Actions for improvement" of Figure 3.7 there are some letters indicating which actions can be applied, but more information regarding this is provided in section 3.2.6.

3.2.5. Steps 6 & 7: Acceptable impact of reduced connection's impedance?

In this section both steps 6 and 7 are elaborated, because they are strongly connected. As already mentioned in section 3.2.3, these two steps are not performed, if full series compensation is used along with the installation of UGC. Step 6 is based on the principle described in section 2.4.3.2: the impedance of a connection is much lower when it is partially or fully cabled than when it is completely an overhead line and this reduced impedance influences the power flows. The reliability analysis was performed in step 2 with Con1 as an overhead line, but now in step 6 it is performed again by considering Con1 as a cabled connection (according to input data of step 3). It is necessary to conduct reliability assessment for a second time, because the reduced impedance influences the power flows and the overall reliability level might be different than the one of the first assessment (with Con1 OHL). If the overall reliability level remains the same, the reduced connection's impedance does not create obstacles for the installation of UGC, while if there is an impact the planner proceeds to step 7. There it is explored if the new reliability level is acceptable according to the standards that the TSO sets. In Figure 3.8 below both steps are depicted in a flowchart, but first step 6 is analysed.

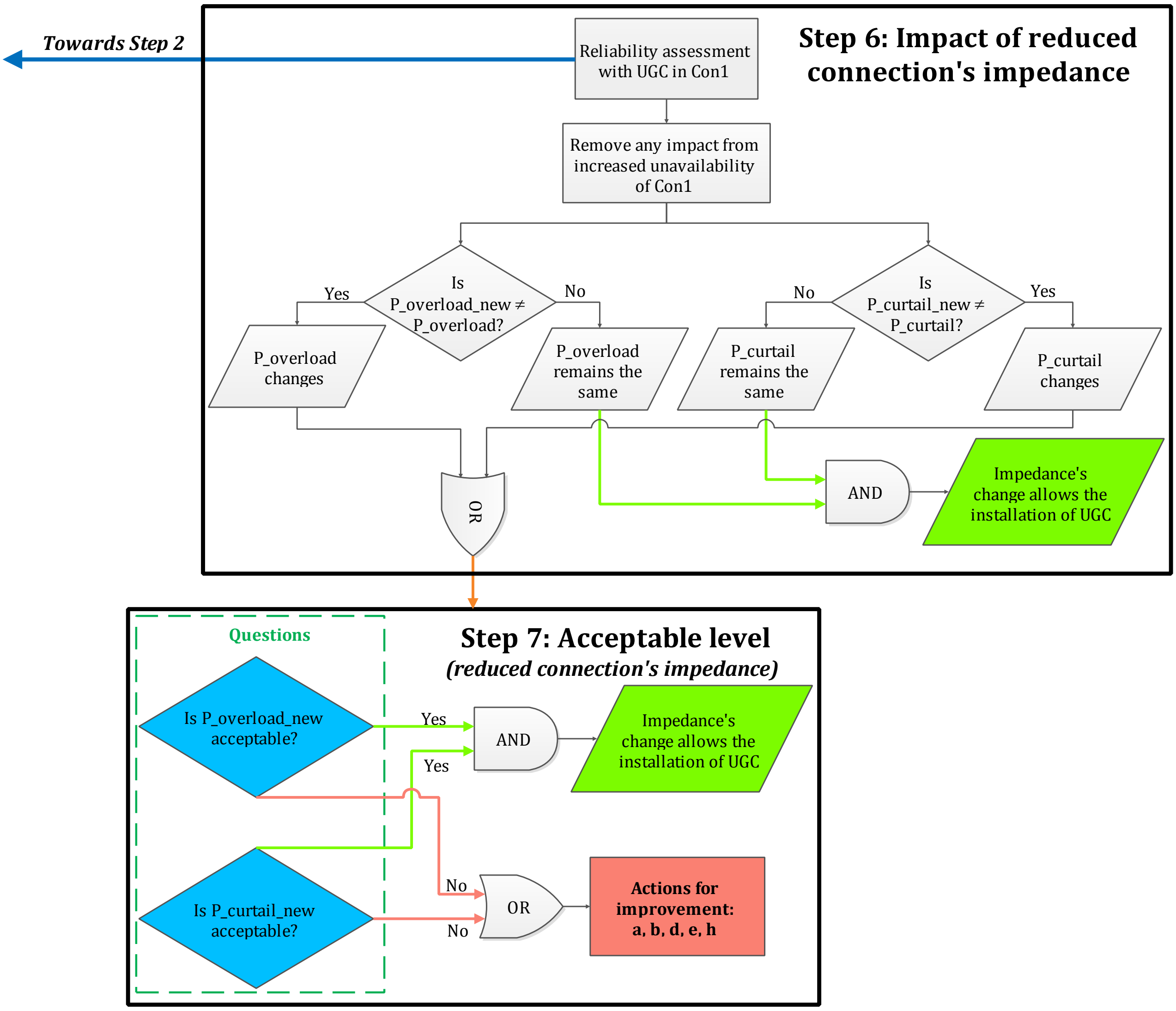


Figure 3.8 - (Un)acceptable impact of reduced connection's impedance

As illustrated in Figure 3.8, the first action of step 6 is to go back with a feedback loop (blue arrow) to step 2 (Figure 3.4) in order to perform again reliability assessment but now with cabled Con1. After the assessment, the new values of the reliability indicators (probability of overload and load curtailment) are known. However, these new values include the impact of both increased unavailability and reduced impedance of Con1. In order to study exclusively the impact of the reduced impedance, the impact of the increased unavailability, which is known from step 4, is removed.

Then in Figure 3.8 two parts (left and right) are identified, one for each reliability indicator. In the left part it is examined if the new probability of overload (P_new_overload), which includes the pure impact of the reduced impedance, is different than the old probability of overload (P_overload), which was acquired during the first reliability assessment (Con1 as OHL). In a similar way, in the right part the new probability of load curtailment (P_new_curtail), which includes the pure impact of the reduced impedance, is compared with the old probability of load curtailment (P_curtail). If the new values of both indicators are the same with the old ones, the reduced impedance of Con1 does not hinder the installation of UGC, while if at least one of them changes, the planner proceeds to step 7.

In step 7 it is investigated if the new values (P_new_overload and P_new_curtail) are acceptable. This depends on the reliability standards that the TSO sets. That is why two questions are asked to the planner (green dashed box), one for each reliability indicator, regarding the acceptability levels. If both P_overload_new and P_curtail_new are acceptable, the reduced impedance of Con1 allows the installation of cables. On the other hand, if at least one of the two is unacceptable, there are obstacles in the installation of UGC in Con1 and actions are needed to improve the situation. Finally, in the box "Actions for improvement" of Figure 3.8 there are some letters indicating which actions can be applied, but more information regarding this is provided in section 3.2.6.

3.2.6. Step 8: Actions for improvement

If the new value of at least one of the two reliability indicators is found to be unacceptable due to either the increased unavailability or the reduced impedance of Con1, underground cables cannot be installed. In order to invert the situation, the key influencing factors regarding the installation of UGC are identified in step 8. These influencing factors are actually the input parameters referring to cables, described in steps 1 (section 3.2.1) and 3 (section 3.2.3). As illustrated in Figure 3.9, questions are asked to the planner regarding the key influencing factors without suggesting any specific actions. Each question refers to a different factor. These questions act as guidelines to the planner by notifying him/her the variations of which factors might lead to an improved reliability level after the installation of UGC. Possible actions to improve the new unacceptable reliability level are proposed in chapter 6 after the analysis of simulation results. After adopting at least one of these actions, the planner goes back with a feedback loop to re-examine the situation. After Figure 3.9, it is explained why each of these factors is influencing for the installation of UGC.

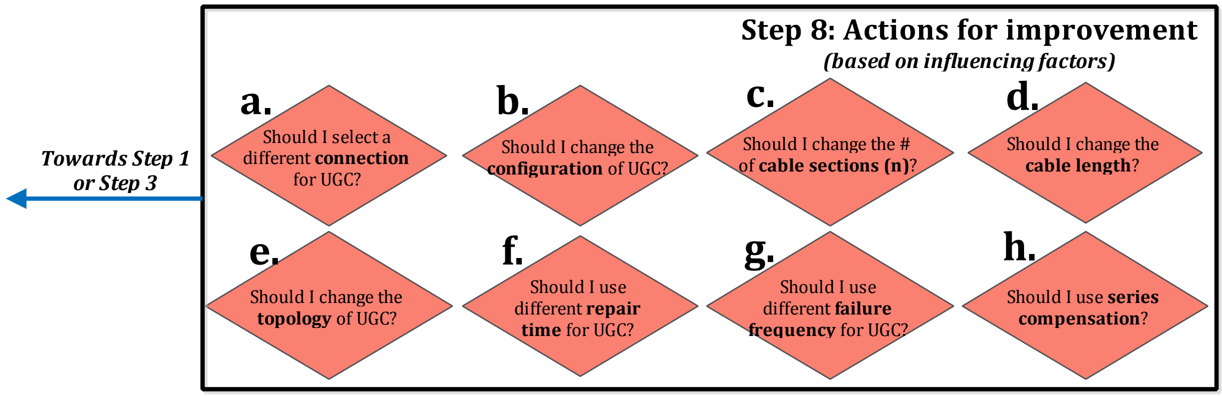


Figure 3.9 - Actions for improvement based on influencing factors in the form of questions to the planner

a. ***Connection*** *where UGC are installed*

If UGC are installed in Con2 instead of Con1, the reduced impedance of Con2 leads to different power flows under contingency analysis. In addition, depending on whether the failure of Con2 belongs to the contingencies leading to overload or not, it has a negative or zero respectively impact on the probability of overload. Same for the probability of load curtailment. In this sense, a selection of a different connection might alter the impact of both the increased unavailability and reduced impedance. In chapter 6 information is given regarding what a "good" choice of connection means.

b. ***Configuration*** *of UGC*

Change in the configuration of UGC means change in the number of separate cables per circuit phase. This information is important for the calculation of the unavailability of the connection (where UGC are installed) [35]. For instance, if not one but two separate cables per circuit phase are used (for transmission capacity purposes) the cable length, the number of joints and the number of terminations double. Therefore, the failure frequency and the unavailability of the connection increase by a factor 2 [35]. Moreover, the impedance of the connection decreases as the number of separate cables per circuit phase increases, since they are connected in parallel. Therefore, a selection of a different configuration might alter the impact of both the increased unavailability and reduced impedance.

c. ***Number of cable sections***

By keeping the total cable length constant, more cable sections in a connection mean a larger number of cable terminations. This leads to a higher failure frequency and thus a higher unavailability of the connection.

Although varying the number of cable sections might alter the impact of the increased unavailability, it cannot influence the impact of the reduced impedance.

d. ***Cable length***

For the analysis of this factor, it is assumed that there is only one cable section per connection. In this way, the number of cable terminations remains constant and the pure effect of the cable length can be identified. Given constant failure frequencies for the accessories of UGC (cable, joints and terminations), the failure frequency of UGC depends on the amount of cable length, the number of joints and the amount of cable terminations (section 2.4.3.1). Increasing cable length means increasing number of joints and both these factors lead to an increase in the failure frequency. Since there is only one cable section, there are always two cable terminations independently of the amount of cable length. Apart from the impact on the failure frequency, the total cable length is important for another reason as well. As already noticed (section 2.4.3.2), the smaller characteristic impedance of UGC (compared to OHL) can have an important effect on the distribution of power flows, since the connections with lower impedance tend to become more loaded than the ones with higher impedance. If the total cable length of a connection increases, then the effect of this change in the impedance might become more significant. Therefore, different cable length might alter the impact of both the increased unavailability and reduced impedance.

e. ***Topology*** *of UGC*

Different topologies of UGC mean that the same amount of cable length can be installed in one or in more than one connection. If the second holds, the cable length can be installed in series or parallel connections. Change in the topology of UGC might alter the impact of the increased unavailability but also the impact of the reduced impedance.

f. ***Repair time*** *of UGC*

Formula 2.1, which is used to calculate the unavailability of a component, includes the repair time of this component. Therefore, by varying the repair time of UGC, the connection's unavailability changes, while the connection's impedance remains the same.

g. ***Failure frequency*** *of UGC*

Formula 2.1, which is used to calculate the unavailability of a component, includes the failure frequency of this component. Therefore, by varying the failure frequency of UGC, the connection's unavailability changes, while the connection's impedance remains the same.

h. ***Series compensation***

As already described in section 2.4.3.2, when UGC are installed in a connection, the impedance of this connection is lower than when this connection is a line and this leads to different power flows. More specifically, the impedance is reduced leading to a higher loading of this connection. However, if along with the installation of UGC full compensation is used, in the form of series reactors, the impedance is the same if the connection is a line or a cable. However, the use of series compensation does not alter the impact of the increased unavailability.

4

Case study: EHV Dutch transmission network

This chapter is removed due to confidentiality reasons.

5

Results

This chapter is removed due to confidentiality reasons.

6

Conclusions & Recommendations

6.1. Concluding remarks on the proposed approach

The main goal of this thesis was to examine how the installation of EHV underground cables in transmission networks impacts the overall reliability level. First, an extensive literature review on basic reliability concepts and on main differences between OHL and UGC was conducted. Then, regarding the same topics, unstructured interviews took place with experts from the Dutch transmission system operator in order to enrich the insight gained from the literature review. By using the findings from both sources, a qualitative generic approach was proposed. This approach can be used as a framework for the decision making process that a planner should follow when he/she examines the possibility of installing EHV UGC in a transmission network from a reliability point of view. Different steps are included: from what input data are necessary until how to process and evaluate the results (reliability indicators) from the reliability assessment. In case that the new reliability level (after the installation of UGC) is unacceptable according to the standards that the TSO sets, actions for improvement are necessary. These actions indicate which key influencing factor(s) has to change in order to improve the reliability level. After adopting at least one of the actions, the planner has to re-examine the situation by checking if the new reliability level is now acceptable. The influencing factors regarding the installation of UGC are presented in Figure 6.1. Their identification was realized through literature review and interviews, while how the variations of these influencing factors impact the reliability indicators was explored through simulations. In section 6.2, where concluding remarks on the simulation results are discussed, it is shown how these key influencing factors should vary in order to enhance the reliability level. It is also elaborated which is the most determinant factor, meaning that it has the largest influence on the results.

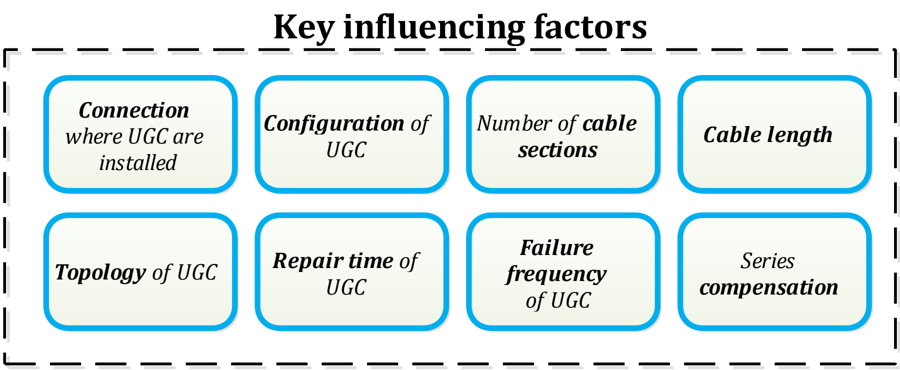


Figure 6.1 - Key influencing factors for the installation of UGC in transmission networks

6.2. CONCLUDING REMARKS ON THE SIMULATION RESULTS

The proposed qualitative generic approach was applied for the case study of the EHV Dutch transmission grid. The purpose was to examine how further 380kV cabling in the Dutch transmission network impacts the overall reliability level. After modelling contingency analysis, DC load-flow and corrective measures and after selecting the reliability indicators to be calculated, the reliability assessment was performed for different simulation sets. The simulation sets were defined mainly based on variations of the key influencing factors regarding the installation of UGC. More specifically, the reliability of the grid was studied when extensions of the 380kV network are realized as overhead lines or partially- (or fully-) cabled connections and when existing 380kV overhead lines are replaced by underground cables. Every simulation set is compared with the starting point, where the connections under examination are overhead lines. Through the interpretation of the simulation results several interesting conclusions are drawn:

- **The highest reliability level is achieved at the starting point, when all the connections under examination are overhead lines.** The moment that UGC are installed (in any connection), at least one reliability indicator changes, leading to a lower reliability level. By increasing the cable length, the reliability level drops more.

- However, this amount of decrease in reliability differs significantly from connection to connection and it might depend on several factors; loading of the connection, transmission length or if the grid is still n-1 redundant after the installation of UGC in the specific connection. In the results, extreme cases were presented, where either the reliability drops dramatically as the cable length increases or it decreases very slightly, far less than 10%. **This means that every project regarding the installation of UGC should be studied separately and extensively.**

- **The conditions for the installation of UGC might be more favorable in weakly loaded connections (below 30% loading).** It was shown that the KPI's, which are directly linked to loss of load, do not increase as the total cable length increases, while the rest KPI's show a small growth. However, if the partially-/fully-cabled connection leads to a grid which is not n-1 redundant any more, then this growth can be substantial.

- The installation of underground cables in a heavily loaded connection is very critical from a reliability point of view. By keeping the cable length constant, if the loading of the connection increases, the final reliability level drops significantly compared to the case with the initial loading. This decrease in the reliability level can be much more considerable than the increase of the loading, speaking in percentages. This conclusion becomes even more important if we realize that a current weakly loaded connection might become more loaded in the future. [redacted]

- The installation of UGC in specific connections might not influence the reliability indicators related to load curtailment, compared to the starting point. However, this does not mean that the level of reliability remains the same. It was shown in the results that in these cases, the reliability indicators which are not directly related to loss of load, might demonstrate significant change leading to a lower reliability level. **Therefore, it can be concluded that indicators that are not directly linked to load curtailment should be used as well.**

- If the installation of UGC in a specific connection influences both categories of reliability indicators (directly and not directly linked to loss of load), it seems that all of them show similar behaviour. They present an upward trend as the total cable length increases. Of course, the scale of the values is different but the pattern is similar. **This means that if one is interested in finding out the general behaviour and not the actual values, one reliability indicator from each category might be enough.**

- **The use of compensation (series reactors) along with the installation of UGC in order to maintain the impedance of the connection uninfluenced, changes the results favourably.** By removing the impact of the reduced impedance, the reliability level increases compared to the case without series compensation. Of course, it does not return to the initial value of the starting point, because there is still the impact of the increased unavailability of the connection. To what extent series compensation improves reliability differs from connection to connection. [redacted]

- By reducing the failure frequency of UGC, the unavailability of the connection (where UGC are installed) decreases and most reliability indicators are influenced favourably. For the indicators which do not show any improvement, it can be concluded that they depend exclusively on the impact of the changed impedance and not on the impact of the changed unavailability. **When the repair time of UGC is reduced by half, there is a significant increase in the reliability level which is more considerable than in the case of reduced failure frequency.** This gives an indication of which of these two uncertain parameters is most determinant.

- **By increasing the number of cable sections in a connection, the probability of overload shows a growing trend (linear behaviour), meaning that the reliability level deteriorates.** However, the amount of increase of the indicator is not significant. [redacted]

  - **Installing a specific amount of cable length in one weakly loaded connection leads to a slightly higher reliability level, rather than dividing the same amount of cable length in two weakly loaded connections.** The reason for that is because in the first case the number of terminations is half, while the number of joints and the cable length are the same in both cases. However, this is mainly applicable for lowly loaded connections. As already mentioned, if a specific amount of cable length is installed in a heavily loaded connection, the reliability deteriorates significantly. Therefore in this case it is better to divide this amount of cable length in two connections, in the heavily loaded one and in another weakly loaded. Although the number of terminations would be double, less cable length would be installed in the heavily loaded connection and this could lead to a better reliability level than the case with the whole cable length in the heavily loaded connection.

- **There is a strong dependence between the reliability indicators which are directly linked to load curtailment, and the availability of cross-border re-dispatch.** If this corrective action is not possible due to for instance unavailable cross-border transmission capacity, these indicators illustrate significant increase, which means more frequent load curtailment or larger amounts of curtailed load. The other indicators, which do not refer to loss of load, are not influenced.

- If the installation of UGC in a specific connection leads to an unacceptable reliability level, at least one of the **key influencing factors** (Figure 6.1) should change in order to improve it. **By ranking them from the smallest to the largest improvement that they could bring** , they are: reduction of the initial number of **cable sections** by half, installation of half **cable length** than initially planned, reduction of the **failure frequency** of UGC according to TSO's low estimation (if TSO's high estimation was initially adopted), change in the **configuration** of UGC by installing one cable per circuit phase (instead of two), reduction of the **repair time** of UGC by a factor of two and finally installation of UGC in a lowly loaded **connection**. As noticed, in almost all the influencing factors the same relative reduction is applied (by a factor of two), because only if these parameters change by the same relative amount, the comparison between them is feasible. In addition, it is assumed that when one factor changes, the rest remain constant.

- [redacted]

6.3. RECOMMENDATIONS FOR FURTHER RESEARCH

As already mentioned, the high complexity in determining the reliability of further cabling in the 380kV Dutch network has led us to make assumptions and to narrow down the boundaries of this research into a feasible computational level. Therefore, in order to gain more knowledge and to acquire a thorough idea of this topic, further research has to be undertaken. It would be interesting to explore the following issues:

- The algorithm of the reliability assessment that was developed in this thesis can be improved in a few ways. An attempt could be made to model more remedial actions such as phase shifting transformers or cancellation of maintenance in order to simulate reality even more effectively. The application of these two corrective actions might influence the final results significantly. In the same context, AC power flow instead of DC could be used, such that voltage behaviour can be included as well.

- This study focused on contingencies which refer to EHV overhead lines or underground cables. However, it would be interesting to include the contingencies of other components as well such as: generators, transformers, bus-bars etc. In this way, a more complete contingency analysis can be conducted. Especially the failures of generators might have a considerable effect on the frequency of load curtailment, since the availability of generators for re-dispatch would be reduced.

- [redacted]

- Finally it would be nice to study the different electrical behaviour of 380kV cables compared to overhead lines. Both lines and cables are characterized by the, so called, emergency power rated, which means that in case of emergency both of them can withstand an overload for a specific time. This time can differ considerably depending on the type of connection (lines or cables). In case of overhead lines it can last only a few minutes, while in case of cables it can last a few hours. If this information can be included while calculating the effects of different contingencies, the results could be even more realistic.

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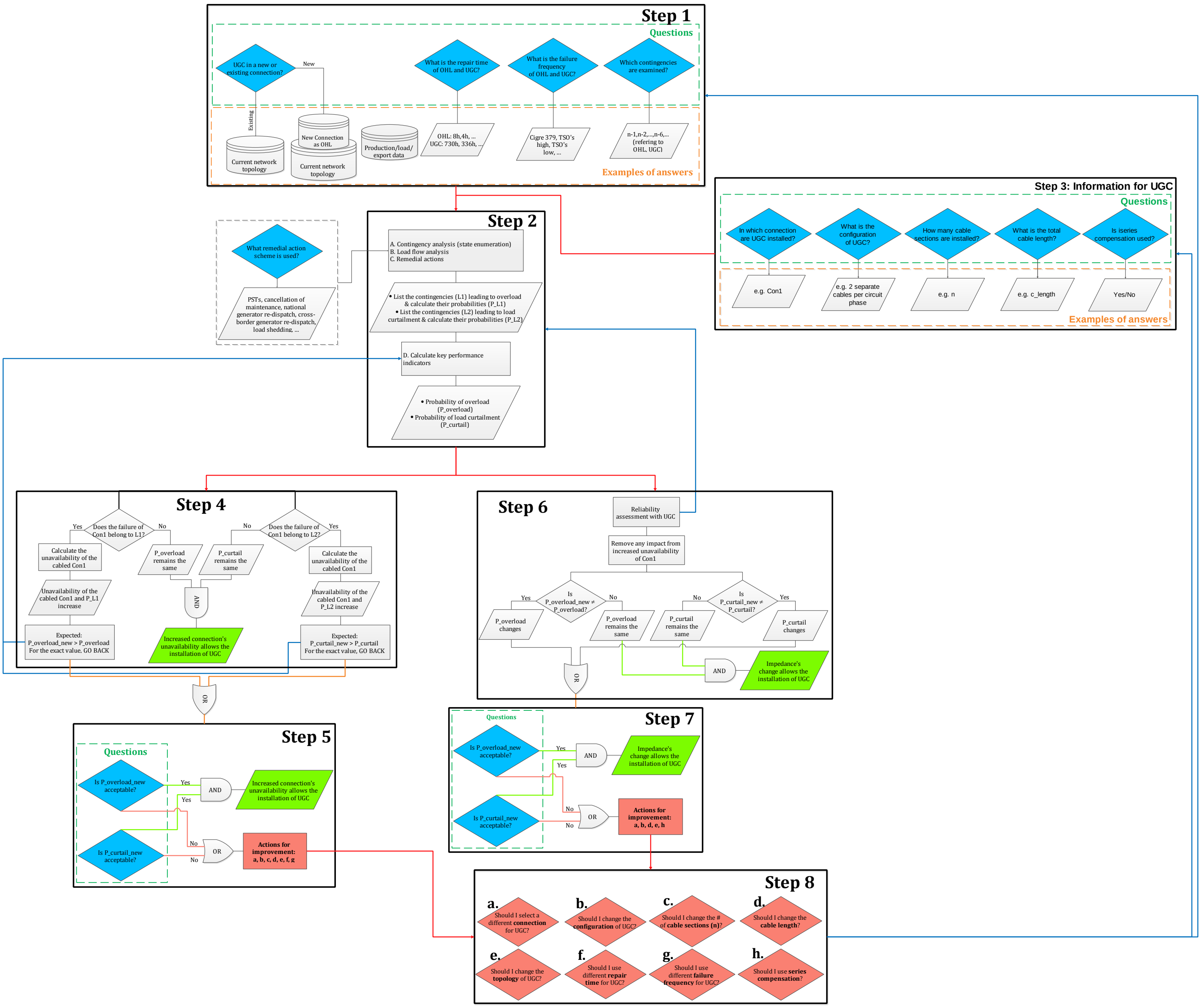
Appendix A

Qualitative Generic Approach



Flowchart of the qualitative generic approach

Appendix B

Additional Results

This chapter is removed due to confidentiality reasons.