Cost-Based Design of an Electric Reserve Grid Focusing on Reliability

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Cost-Based Design of an Electric Reserve Grid Focusing on Reliability

A thesis submitted to attain the degree of

DOCTOR OF SCIENCES of ETH ZURICH
(Dr. sc. ETH Zurich)

presented by

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Preface

This thesis documents my research activities at ewz (Elektrizitätswerk der Stadt Zürich) between 2010 and 2015.

I would like to express my gratitude to ewz for giving me the possibility to do a PhD. Special thanks go to Hansruedi Luternauer, Jürg Bader and Britta Heimbach who provided me with valuable research and practical inputs. I would also like to thank Benedikt Loepfe, Evdokia Kaffe, Andreas Hänger, Bruno Wartmann, Tom Lussenburg, Hans-Heinrich Schiesser, Peter Vogler and Florian Kienzle for their support and constructive discussions. Many thanks also to Dave Hearn for carefully and thoroughly proof reading and linguistically improving the dissertation.

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Abstract

The reserve grid investigated in this thesis is an electric power supply system on the medium voltage level which increases the reliability of power supply of connected customers. A power supply interruption of the primary grid can be compensated by switching to the reserve grid at the customer's site. The reserve grid can be used as the sole emergency power supply system or as an extension of other systems. Starting from a second primary substation, the system components of the reserve grid are installed independently from the primary grid, i.e. only the overlying 150 kV is in common. The reserve grid exceeds the power supply task of an electric utility and is hence considered as a grid service. Therefore, customers have to separately order a connection to the reserve grid and have to completely finance it themselves.

The planning of the reserve grid differs from the planning of the normal electric grid. Usually, the planning of the distribution grid involves reinforcement or extension. On the medium voltage level, an N-1 secure configuration is applied. By contrast, the reserve grid is a completely new grid which is operated independently from the primary reserve grid substation. As it is an emergency power supply, the prerequisites are also different. Specific customer requirements and alternative topologies are considered. As only the locations of the customers and the supplying primary substations are known, it is a Greenfield planning problem. There are no existing power lines and the grid structure can be chosen freely.

This thesis investigates how a reserve grid topology can be found which fulfills the customers’ requirements while having the lowest possible costs. Various optimization techniques are investigated and a new planning approach is developed. This \textit{a priori} method differs from the conventional N-1 standard by considering the specific required reliability of power supply of each customer. The reliability is calculated by the
symmetrical formulation of the reliability equation which can be applied to evaluate the reliability of each customer with just one equation. Furthermore, an investigation is conducted which has the objective to further increase reliability of power supply. It reveals the potential of a self-sufficient reserve grid which can operate in island mode. An example of such a scenario is a blackout of the transmission grid. The connection to a second primary substation as designed with the "normal" reserve grid does not cover this scenario. A comparison of PV and storage systems with emergency diesel generators is conducted.

The results show that significant cost savings are possible when the \textit{a priori} method is applied instead of the N-1 standard. The resulting topologies can be used as a base for discussion with reserve grid customers. A comparison reveals the advantages and disadvantages of both approaches. The investigation of the self-sufficient reserve grid shows that PV have a limited potential to supply the reserve grid with electric power and storages are required. Especially in the city center, where many buildings are under protection PV cannot be installed on a large scale. Furthermore, emergency diesel generators have the advantage to be available during the whole day. At this stage, emergency diesel generators and where suitable existing power plants are recommended for power supply. However, as the emergency diesel generators are solely used for emergency power supply, energy storages are more interesting from an economic point of view as they have also other potential applications. For the future, when a reliable operation can be guaranteed, also energy storages in combination with PV should be considered as a power source.
Kurzfassung


Die vorliegende Arbeit untersucht, wie eine Reservenetz-Topologie gefunden werden kann, welche die von den Kunden geforderte Zuverlässigkeit gewährleistet und dabei optimal bezüglich der Kosten ist. Dazu werden mehrere Optimierungsalgorithmen untersucht und daraus folgend eine neue Planungsmethode entwickelt. Diese a priori Methode unterscheidet sich vom üblichen N-1- Standard, indem sie die von den
einzelnen Kunden geforderte spezifische Zuverlässigkeit beachtet. Um
die für jeden einzelnen Kunden eigene Zuverlässigkeit berücksichtigen
to können, wird eine symmetrische Formulierung des Problems erstellt.
Diese erlaubt, die Zuverlässigkeit für die verschiedenen Kunden effizi
ten zu berechnen. Darüber hinaus wird eine weitere Untersuchung zur
Erhöhung der Versorgungssicherheit durchgeführt, welche das Potential
für ein autarkes Reservenetz in Zürich aufzeigt. Das autarke Reservenetz
cann im Unterschied zum ”normalen“ Reservenetz auch als Insel betrie
ben werden und einen Blackout des Übertragungsnetzes kompensieren.
Die Eignung von PV-Anlagen und Speichersystemen zur Netzstützung
wird mit derjenigen von Notstromdieselgeneratoren verglichen.

Die Resultate zeigen, dass mit der a priori Methode signifikante Kos
tenersparnisse gegenüber dem N-1-Standard möglich sind. Die sich aus
der Optimierung ergebenden Topologien können als Grundlage für Dis-
kussionen mit Kunden dienen. Ein Vergleich mit der konventionellen
N-1 Sicherheit zeigt, welches die Vorzüge der beiden Methoden sind.
Die Untersuchung zum autarken Reservenetz zeigt, dass PV-Anlagen in
Zürich ein beschränktes Potential zu Netzstützung haben. Insbesonde-
re in der Innenstadt, welche oft denkmalgeschützt ist und somit keine
großflächige Installation von PV-Anlagen zulässt. Notstromdieselgene-
ratoren haben zudem den Vorteil, den ganzen Tag verfügbar zu sein.
Zum jetzigen Zeitpunkt wird daher empfohlen, ein autarkes Reserven-
etz mit Notstromdieselgeneratoren und wenn möglich mit vorhandener
Produktion zu versorgen. Da Notstromdieselgeneratoren jedoch aus-
schließlich zur Notstromversorgung dienen, sind Energiespeicher aus
wirtschaftlicher Sicht interessant. Vielfältige Anwendungsmöglichkeiten
können genutzt werden. In Zukunft, wenn Energiespeicher ausgereift
sind und zuverlässig betrieben werden können, sollten sie in Kombina-
tion mit PV als alternative Stromquelle in Betracht gezogen werden.
# List of Acronyms

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<tr>
<td>ACS</td>
<td>ant colony search</td>
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<tr>
<td>BESS</td>
<td>battery energy storage system</td>
</tr>
<tr>
<td>BFS</td>
<td>backward/forward sweep</td>
</tr>
<tr>
<td>CHP</td>
<td>combined heat and power</td>
</tr>
<tr>
<td>DSO</td>
<td>distribution system operator</td>
</tr>
<tr>
<td>EDG</td>
<td>emergency diesel generator</td>
</tr>
<tr>
<td>EPS</td>
<td>emergency power supply</td>
</tr>
<tr>
<td>GE</td>
<td>greenhouse effect</td>
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<tr>
<td>LOLE</td>
<td>loss of load expectation</td>
</tr>
<tr>
<td>MILP</td>
<td>mixed-integer linear program</td>
</tr>
<tr>
<td>OPF</td>
<td>optimal power flow</td>
</tr>
<tr>
<td>PV</td>
<td>photovoltaics</td>
</tr>
<tr>
<td>TSP</td>
<td>traveling salesman problem</td>
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<td>UPS</td>
<td>uninterruptible power supply</td>
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Chapter 1

Introduction

In this chapter background information, assumptions used in the dissertation and an overview of the contributions are presented. Also the legal consideration of reliability in distribution grid planning in Switzerland is discussed. The reliability of power supply provided by the distribution system operator (DSO) is not legally specified with exact values. Increased reliability of supply can be achieved by emergency power supply (EPS). Conventional solutions and the reserve grid offered by ewz, the electric utility of the city of Zurich, are discussed. The assumptions used in the dissertation show the scope of this dissertation.

1.1 Distribution Grid Planning

Electric power for residential and industrial customers is usually provided by public utilities which operate the electric grid. In Switzerland, DSOs have the legal obligation to connect end users to the electric grid [1]. This task has to be efficiently and reliably fulfilled in coordination with the regulator [2]. An exact definition of an efficient and reliable power supply does not exist and is conceded to the DSOs. In the city of Zurich, the city council has assigned this task to ewz. The challenge for an utility is to find the optimum tradeoff between high availability of electric power supply per customer and investment costs.
Both factors affect the attractiveness of the city: an unreliable or an expensive power supply might deter possible customers (both private and business) from choosing Zurich as a possible location. Other DSOs face similar challenges.

1.2 Emergency Power Supply

Despite the effort of the DSOs to provide a reliable power supply, certain groups of customers invest in additional installations to increase the reliability and availability of their individual power supply. Typical examples are among others hospitals, stadiums, banks and data centers [3]. A power outage could be fatal for the individual organizations due to high outage costs or even life threatening situations. Therefore, they are often equipped with uninterruptible power supply (UPS) and emergency generators [4] or a connection for mobile emergency generators [5]. The UPS provides energy to crucial components connected to the emergency power system until the emergency generator, typically a diesel generator, starts its power supply. An emergency diesel generator (EDG) allows the operation of the equipment connected to the emergency system for hours. An advantage of diesel generators is the continuously variable power production, which can be adjusted to the demand within a short time. It is a wide spread application and an established solution. On the other hand, a diesel generator has several drawbacks: it is a high maintenance component and hence implies high fixed costs. Additionally, it requires a large area which could be difficult to find in cities where space is either limited or expensive. Furthermore, EDGs have a failure to start or failure to run risk [6] and often customers neglect to test the emergency power system thoroughly on a regular base.

1.3 Outage Analysis

The investigation of the main cause for outages might lead to an alternative EPS. When the weak points are identified, the location for grid reinforcement can be found. For the distribution grid of Zurich, all causes and locations of the faults are listed in the annual report of
1.3. Outage Analysis

ewz [7]. Table 1.1 and table 1.2 show the values for 2013 and 2012 for the cause and the location, respectively.

Table 1.1: Cause of faults in the distribution grid ([7] modified)

<table>
<thead>
<tr>
<th>Cause</th>
<th>2013</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitting and connectors</td>
<td>24</td>
<td>21</td>
</tr>
<tr>
<td>Damage by third parties</td>
<td>52</td>
<td>44</td>
</tr>
<tr>
<td>Others</td>
<td>30</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 1.1 shows that most faults in the distribution grid are caused by damages by third parties. Often, it means that construction companies drill in a cable duct bank and thereby damage the cables. In order to reduce these faults, ewz tries to improve the communication with construction companies and to sensitize them to this problem. A different design of cables will not help to prevent unintended damages as the cables themselves work properly. It should be considered in the reliability assessment of the grid that parallel cables in the same duct bank can lead to common mode failures. This means parallel cables can fail almost simultaneously in case of the damage of the duct bank.

Table 1.2: Fault location in the distribution grid of Zurich ([7] modified)

<table>
<thead>
<tr>
<th>Location</th>
<th>2013</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-voltage grid 150 kV</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Medium voltage grid 11 kV and 22 kV</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>Low voltage grid 230/400V</td>
<td>89</td>
<td>82</td>
</tr>
</tbody>
</table>

Table 1.2 shows that in both years most faults occurred in the low voltage grid. By contrast, failures in substations and the medium voltage grid are rare. The impression is hence that faults in the low voltage grid should be reduced. A closer look to the impact of failures in the low voltage grid and the overlying grid leads to the contrary conclusion. On 24.10.2013, a low voltage power line was damaged during construction work. As a result, about 50 customers lost the power supply for one
hour. On 18.12.2013, a test of the $CO_2$ extinguishing system unintentionally tripped the protection of all three transformers in a primary substation (150/22kV)$^1$. As a consequence, almost 25,000 customer experienced an outage for 12 minutes. The two examples show that a fault in a substation can potentially lead to an interruption of supply for thousands of customers. Between 1987 and 2001, 71 failures in primary substations with an interruption of power supply of at least one second were counted [8]. Therefore, faults in primary substations have been identified to play a major role in the reliability of supply.

### 1.4 Reserve Grid

A failure in a substation can lead to an interruption of power supply in the underlying medium voltage grid. In this case, the ring-shaped configuration of the medium voltage grid cannot increase the reliability. By contrast, the connection to an additional substation has a considerable effect. This type of grid is called reserve grid. A possible topology is shown in fig. 1.1 where the failure a MV ring and the switching to the reserve grid is demonstrated.

As depicted, three customers are connected to a second substation by the reserve grid (indicated by the red lines). A failure of one substation and/or the failure of the medium voltage ring of the primary grid$^2$ can be compensated. Only simultaneous failures in both supplying substations or the simultaneous failure of the medium voltage grid of the primary and the reserve grid leads to an interruption of power supply.

The main process in case of a failure is the following: if a customer detects a voltage drop, the power supply is switched from the primary to the reserve grid. The reserve grid itself is always kept energized from one substation. This configuration allows an immediate switch to the reserve grid and in combination with an UPS an uninterrupted power supply. Furthermore, an undesired power flow between the two substations is prevented by an open switch at one substation.

The power lines used for the reserve grid are operated independently of the primary grid and are installed only for this purpose. Thereby,

---

$^1$See appendix A for the naming of the grid levels and its components.

$^2$With primary grid, the grid operated by ewz for all customers is meant. This expression helps to distinguish between the "normal" grid, which is the primary power supply, and the reserve grid.
the services of the primary grid and the reserve grid are clearly separated. Furthermore, these additional installations of the reserve grid cables and the connection to at least two different substations have an impact on the reliability of power supply. This grid service increases the availability of the power supply for reserve grid customers significantly and is compared to EDG also interesting from an economic point of view [3].

The system as described does not cover all possible outages. If all substations in the city of Zurich fail, which can occur due to an outage of the transmission grid, also the customers connected to the reserve grid will not be supplied with power anymore. This worst case scenario can be covered by an extension of the reserve grid with power production and possibly also storages. Thereby, it would be enabled to operate in island mode, i.e even when it is disconnected completely from the primary and the overlaying transmission grid. The sources in this case can be either EDGs or locally available power sources. The required EDGs would be installed by ewz, which would also be responsible to find a location for them. Furthermore, ewz would be responsible for the proper testing of the equipment. Possible local productions are among others solar, hydro power, combined heat and power (CHP) and waste-
to-energy. Obviously, the location of the renewable power production sources is given. A reserve grid, which harnesses the local production and storages, can operate self-sufficient and also endure an outage of the transmission grid.

1.5 Assumptions and Scope

In this thesis, the optimal topology of the reserve grid and search methods to find it are investigated. The optimal topology of the reserve grid depends on the situation given. Especially the economy of the reserve grid depends strongly on the customer density. Here, it is assumed that the reserve grid is installed in the city center where a large number of potential customers exist. Furthermore, the reserve grid is investigated based on the planning of medium voltage grids in Zurich. Different planning strategies and components might be used in other cities. Furthermore, the studies focus mainly on the medium voltage grid. The connection of low voltage customers to the reserve grid is possible but out of scope of this dissertation. The algorithms provided in this dissertation can be applied to any hierarchy level.

The algorithms, which find an optimal grid, are chosen to enable an analysis of the reserve grid concept. The efficiency of the optimization methods is not the focus in this thesis.

Only the main installation costs are evaluated. The exact pricing of a reserve grid connection, e.g. the revenue, is not discussed.

The optimal planning of the reserve grid includes a reliability assessment for each customer. The main components of the reserve grid comprise power lines and switchgear which are the same as those used in the primary grid. As the investigations focus on the planning of the reserve grid, a time independent reliability is assumed.

The discussion concerning the self-sufficient reserve grid covers aspects of reliability of supply and local production in Zurich. The operation of the self-sufficient grid and its protection are not investigated and out of scope. Furthermore, with Zurich, only the city of Zurich and not the canton is meant.
1.6 Main Contributions

The main contributions of this dissertation are:

- Comparison of reserve grid topologies and the corresponding impact on reliability and costs.

- Formulation and investigation of three methods to solve the stated planning problem. A time complexity analysis is conducted which allows an assessment of the planning problem. With restrictions, all three methods can be extended with a reliability analysis.

- A reliability assessment method is developed which allows the calculation of the individual reliability of each reserve grid customer. This method utilizes the symmetry of the problem and is based on the tie set method.

- A new grid planning method is developed. The priority of the planning is the required power supply reliability of the customers. This \textit{a priori} consideration of the reliability is compared the common \textit{a posteriori} consideration.

1.7 Structure of the Thesis

The dissertation is structured as follows:

\textbf{Chapter 2:} Primary and reserve grid planning is discussed to provide information of the planning strategy in Zurich. Power flow and short circuit analyses are conducted to investigate the physical limits of the reserve grid in Zurich. Possible reserve grid topologies are compared and evaluated. Furthermore, an environmental impact analysis is conducted.

\textbf{Chapter 3:} The optimization problem without reliability constraints is discussed and the resulting time complexity investigated using the \textit{big O} notation. Search methods are formulated which are able to solve the stated problem.
Chapter 4: The search methods are applied in case studies and discussed. The most appropriate search method is chosen for the final optimization problem.

Chapter 5: Various reliability assessment techniques are explained and discussed. Basic knowledge of reliability analysis is provided and three calculation methods are evaluated. The final optimization problem, which contains reliability constraints, is formulated considering hierarchical clustering.

Chapter 6: Case studies are conducted for the optimization problem discussed in the previous chapter. A comparison is conducted for an optimization using a priori defined reliability and N-1 security.

Chapter 7: Potential power production for a self-sufficient grid in Zurich is discussed and assessed. The additional requirements for the self-sufficient grid are investigated.

Chapter 8: The main findings are summarized and discussed. An outlook for possible future work is given.

1.8 List of Publications

Five papers have been published in the course of work on this dissertation:


- R. La Fauci, M. Mangani, B. Heimbach, J. Bader, H. Luternauer and L. Küng, "Investigating applications of energy storages for the integration of renewables in the distribution grid. View from
1.8. List of Publications


- B. Heimbach, R. La Fauci, E. Chimi, J. Bader and H. Luternauer, "Fitting of high voltage cables in existing duct banks under new regulations: theoretical modelling and pilot project”, 23th International Conference on Electricity Distribution (CIRED), 2015.

Chapter 2

Reserve Grid Planning

In this chapter, grid components, grid planning and customer information are discussed. In the medium voltage grid of ewz, operated with 22 kV, two different cable types are typically used and hence considered for the planning of the reserve grid. A basic power flow and short circuit analysis should reveal, which physical limits are of special interest. It is shown that for the distances used in an urban distribution grid, the voltage can be kept within acceptable limits and the short circuit current is always sufficient. Only the thermal limit of the conductors is a limit which can be reached. Customer information contains among others the location of the customers and how they can be connected with each other. A rough comparison of EDG and the reserve grid shows that the environmental impact is comparable for both systems except from the diesel use.

2.1 Medium Voltage Grid Planning

The planning of the medium voltage grid of Zurich is a task which comprises two main goals: the grid has to enable a reliable power supply and reasonable installation costs have to be maintained. These two targets cannot be simultaneously maximized as in general the costs increase with increased reliability. The additional costs when designing a more reliable grid derive from additional installations, e.g. redundant power lines. For a balance between the goals, the medium voltage distribution
grid of Zurich is typically ring-shaped with two or three feeders in closed loops. The redundant cable makes the power supply N-1 safe, i.e. the failure of one cable does not lead to an interruption of power supply. Radial feeders can also be found but less often. Fig. 2.1 shows the two most common topologies on medium voltage level of ewz. A discussion for the other system levels can be found in appendix A. New challenges are constantly appearing which complicate the planning. An example is shown in [9].

Figure 2.1: Typical medium voltage grid topologies of ewz are ring-shaped with two or three feeders. Radial feeders also exist but are found less often.

For a safe operation, three main parameters have to be kept within predefined limits: the voltage has to be maintained between an upper and lower limit, the current has to be kept below the maximal loading and the short circuit current has to be high enough to trigger the relays.

The acceptable voltage deviation is chosen according to the norm EN 50160 for medium voltage customers. The norm requires for slow changes in voltage less than +/-10% deviations from the supply voltage (22 kV in Zurich). In order to offer a tolerance band to customers, ewz plans for normal operation a deviation of only +/-6%. During maintenance, it is raised to +/-10% and the customers are informed beforehand. For the 22 kV medium voltage grid, deviations of +/-1.32 kV or +/-2.2 kV are resulting. Different voltage bands are set for the different daily load situations by adjustments of the taps of the 150/22 kV transformers located in the primary substations are also redundantly structured (N-1).

According to EN 50160, the voltage deviation is allowed to deviate +10% /-15% in two two cases. The first is, when the grid has no connection to the transmission grid and the second, when the customer are particularly remote. In both cases, the customer should be informed.
2.1. Medium Voltage Grid Planning

transformers (50 MVA). For low, medium or high load hours the voltage bands are set according to table 2.1.

Table 2.1: Voltage band for different transformer loadings (50 MVA, 150/22 kV)

<table>
<thead>
<tr>
<th>Transformer loading</th>
<th>Set point</th>
<th>Lower limit</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (0%-25%)</td>
<td>22.4 kV</td>
<td>22.2 kV</td>
<td>22.6 kV</td>
</tr>
<tr>
<td>Medium (25%-75%)</td>
<td>22.6 kV</td>
<td>22.4 kV</td>
<td>22.8 kV</td>
</tr>
<tr>
<td>High (75%-100%)</td>
<td>22.8 kV</td>
<td>22.6 kV</td>
<td>23 kV</td>
</tr>
</tbody>
</table>

The maximal current depends strongly on the cable type. In Zurich, typically 150 $mm^2$ or 240 $mm^2$ copper cables are installed in duct banks. In future, also aluminium cables might be an option since they have lower costs compared to the copper cables. However, the diameter is bigger and it has to be ensured that the cables fit in the already installed duct banks. Detailed cable information can be found in appendix B.

The last parameter is the short circuit current, which has to last for a predefined time, with an amplitude which triggers the relays installed in the primary substations, transformer substations and distribution boards. Table 2.2 shows the short circuit current and the switching time that relays are programmed with to protect substations, transformers and power lines and correspond to an overcurrent protection [10].

Table 2.2: Short circuit settings of medium voltage relays

<table>
<thead>
<tr>
<th>Location of relay</th>
<th>Short circuit current</th>
<th>Switching time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substations</td>
<td>1000 A</td>
<td>1.4 s</td>
</tr>
<tr>
<td>Transformers MV/LV</td>
<td>150 A</td>
<td>0.4 s</td>
</tr>
<tr>
<td>Transformers MV/LV</td>
<td>500 A</td>
<td>0.0 s</td>
</tr>
<tr>
<td>Power lines</td>
<td>900 A</td>
<td>0.6-1.2 s</td>
</tr>
</tbody>
</table>

The relays are triggered according to a time schedule which minimizes the number of grid components that are tripped. The relays with the longest distance to the substation are triggered first. As a result, the

---

3 See appendix A for an overview of the grid levels
relays located at the substation are only triggered if the fault location is in or near the substation itself. Therefore, the relays in substations are programmed with the longest time delay which is 1.4 seconds and the current is set with the highest values which is 1000 A.

2.2 Relevant Physical Limits of a Reserve Grid

For a stable operation, the three physical limits have also to be considered in the planning of the reserve grid. As the reserve grid is a part of the distribution grid, it makes sense that for a start the same parameter limits are applied as in the primary grid. The advantage of applying the same limits is mainly that the engineers are familiar with them. This also helps to reduce the probability of human error. Following, the three parameters are discussed in more detail. The calculations are conducted with PowerFactory, a software tool for power system analysis developed by DIgSILENT [11].

Figure 2.2: The subtransmission grid of Zurich (150 kV) [12].
2.2. Relevant Physical Limits of a Reserve Grid

2.2.1 Investigational Approach

The investigation is conducted with two scenarios: First, the maximal line length in general is investigated which still fulfills the limits. Second, the limits are discussed for the maximal possible line length which is imaginable in Zurich. Fig. 2.2 shows a map of Zurich containing all substations and the 150 kV grid. The longest distance from one suburb to another is about 12 km which has been chosen as the theoretical maximal line length in Zurich. This distance corresponds to a connection from substation Auwiesen to a customer close to substation Frohalp. As there are many other substations in between, the customers would most probably be connected to a substation closer to them. Therefore, it is a worst case scenario.

The load is placed at the end of the power line to obtain the maximal possible voltage drop as depicted in fig. 2.3. In a realistic scenario, several customers can be expected to be located along the power line. This means that the voltage drop would be less than in the calculated worst case scenario.

Figure 2.3: Grid model used for voltage drop and short circuit analysis.

The customer is located at the end of the power cable to obtain the maximal voltage drop.

2.2.2 Voltage and Current Limits

In this section the question is discussed, under which circumstances the voltage and current limits are violated. As the reserve grid is operated independently from the primary grid, its topology might differ.
For example, a longer feeder could possibly be installed to connect all customers with one power line. Furthermore, the tap changer of the 150/22 kV transformers might need different adjustments than the normal grid in order to fulfill the requirement of the reserve grid.

The maximal line length for 150 $mm^2$ and 240 $mm^2$ cables is investigated to obtain the values when the voltage or current limits are reached. As mentioned above, the current limit depends strongly on the cable type and is independent on the cable length. By contrast, the voltage drop strongly depends on the cable length. As the voltage drop is increasing with the cable length and the current limit is constant, the maximal power transmission decreases proportional to the voltage drop. For the 150 $mm^2$ cable, the maximal current is 264 A and for the 240 $mm^2$ cable it is 352 A. For simplicity however, the resulting maximal power demand of the load has been kept constant in this investigation. It is 9.9 MVA (150 $mm^2$) or 13.3 MVA (240 $mm^2$) with a power factor of 0.9 inductive. This means for 1 km line length the cable is about 96% loaded and for the 42 km about 110%. As a result, the voltage drop for long cables is too high, as in reality cables should not be overloaded. If the maximal current is not exceeded, the voltage drop would be 0.1 kV less for the 150 $mm^2$ and 0.34 kV for the 240 $mm^2$ which is considerable. The voltage at the busbar of the substation is set to 22.6 kV instead of 22 kV (nominal voltage) which is common practice for planning in Zurich. It ensures that in normal operation the voltage can be kept above the lower limit. Fig. 2.4 shows the voltage drop for both cable types with increasing line length and constant loading (constant power).

The maximal possible line length is comparable for both cable types. The 150 $mm^2$ and 240 $mm^2$ are depicted with the green and blue line, respectively. For the -6% limit (black dotted line), the maximal distance is roughly 27 km and for the -10% limit at least 37 km (red dotted line). As mentioned above, the length can be even more as the calculation provides conservative results for longer line lengths. It can be concluded that voltage limit is fulfilled for the maximal single feeder line length of 12 km. On the other hand, a ring shaped grid topology results in the double line length and is close to the maximal line length according to the ewz norm. This means for the longest possible ring in Zurich the -6% voltage limit might be reached. The voltage limit according to EN 50160 (-10%) is fulfilled in any case.
2.2. Relevant Physical Limits of a Reserve Grid

Figure 2.4: Voltage drop estimation for a 150 mm$^2$ and for a 240 mm$^2$ cable with constant load (power demand). For the maximal assumed feeder length in Zurich of 12 km, the -6% and -10% voltage limit are fulfilled. For a N-1 secure configuration, the double feeder length can result (24 km) and the corresponding voltage is close to the -6% voltage limit. The voltage limit according to EN 50160 is fulfilled in any case.

2.2.3 Short Circuit Current

In this section the maximal line length is calculated for which the short circuit current still triggers the relays. As discussed in 2.1, the crucial value is 1,000 A which triggers the relays located in the substation. The other values are described in table 2.2. The 2-phase short circuit current has been evaluated since it is lower than the 3-phase short circuit current. The calculation method was chosen according to the standard procedure at ewz which is VDE 01201 [11]. Single phase short circuit currents have a lower amplitude than 2-and 3-phase short circuit currents. They are detected with separate measurements which do not require a high short circuit current. Therefore, they are not of interest and investigated. The results for both cable types are depicted in fig. 2.5.

As in the previous figure, the 150 mm$^2$ and the 240 mm$^2$ cables are
Figure 2.5: 2-phase short circuit analysis of a medium voltage grid. In Zurich, for a N-1 secure grid with a line length of 24 km, the required short circuit current amplitudes are reached.

depicted with the green and blue line, respectively. The minimal short circuit is indicated with the red dotted line. It can be observed that long distances are possible for both cable types. A critical length is roughly reached after 65 km. The line length which realistically occur in Zurich are far less. Even the longest possible ring-shaped cable with a distance of 24 km is enough protected.

2.2.4 Discussion

The investigation of the three limits has shown the maximal distances where requirements are still fulfilled. The -6% limit of the voltage is reached after a distance of 27 km and the less critical -10 % limit is reached at 37 km. Furthermore, the short circuit current still triggers the relays for a distance of 65 km. Both limits are not likely to be reached in a city with the dimensions of Zurich. It can be concluded that they do not set the limits of the reserve grid and hence are not critical for the planning. On the other hand, the maximal current with a power of roughly 10 MVA can also be reached in a realistic scenario. In order to prevent a cable overloading, the customer load must be considered with the maximal current being the crucial parameter.
2.3 Comparison of Typical Grid Topologies

As the reserve grid is an EPS, the redundancy can be designed differently compared to the redundancy of the primary grid. E.g., the design can be radial, N-1 secure or any other possible configuration. In this section, the most common topologies and their impact on the individual reliability of power supply and investment cost are investigated. It is a logical start for identifying the optimal reserve grid topology. As the customer is in the center of the attention, the requirements for both aspects have to be discussed with customers to ensure their needs are met.

2.3.1 Reserve Grid Topologies

The most common grid topologies on medium voltage level are radial, ring-shaped or a mixture of both. Fig. 2.6 shows an example for a ring-shaped reserve grid with connection to two substations. This version is denoted as medium voltage reserve grid A (MVRG A).

![Figure 2.6: MVRG A: Ring-shaped reserve grid.](image)

The customers are connected to a second substation with two power lines which have different routes. The main advantage of this configu-
RATION is the robustness of the grid concerning planned disconnections. These occur e.g. during street works when power lines are not permitted to be energized. Furthermore, a higher reliability of supply is expected compared to a radial configuration.

Two examples of radial connections are depicted in fig. 2.7 (MVRG B and C). The difference between MVRG B and C is how the customers are connected to the reserve grid. In MVRG B, a switchgear for two switches is installed whereas MVRG C requires only one switch. The latter is connected to the main cable with a sleeve connector. The advantage of MVRG B compared to MVRG C is that a disconnection of a part of the reserve grid power lines affects the customer less. An illustrative example is when the power line between two customers has to be disconnected. In MVRG B, only a part of the grid is affected whereas in MVRG C the whole reserve grid has to be disconnected due to lacking switch options. A disconnection can occur either planned or unplanned e.g. due to an earth fault. In MVRG B, an interruption of supply depends strongly on the location of the disconnected power lines. Certain customers might not be affected by a disconnected power line. On the other hand, all customers are affected with MVRG C as a specific disconnection is not possible. The main advantage of MVRG C is that costs are lower compared to MVRG B.

![Diagram of MVRG B and C](image)

Figure 2.7: MVRG B: radial topology with switchgear field. MVRG C: radial topology with sleeve connectors.
2.3.2 Reliability Assessment Method

The reliability indices are calculated with a deterministic model based on outage data of ewz\(^4\) [13]. This block diagram technique allows an intuitive evaluation of grid components or whole grids consisting of several components. Fig. 2.8 shows an example of this method. A primary substation with two double busbars and two transformers in parallel is modeled. This substation configuration represents the most common in Zurich. From the customer’s point of view it represents a part of the primary grid. The double busbars are divided in two single busbars arranged in parallel with the help of the triangular shaped symbol. Analogously, the transformers are modeled in parallel. A serial connection is achieved simply with the connection of two blocks. The order of the blocks in series does not effect the reliability result as the values of the block are multiplied with each other and hence commutative. However, an arrangement which is close to the physical installations increases the readability of the diagrams which is recommendable.

The results are depicted in the red box. \(H\), \(T\) and \(P\) denote the number of outages per year, outage duration in hours and the outage probability in hours per year, respectively. The latter is the multiplication of \(H\) and \(T\) \((P = H \cdot T)\). The calculation considers planned and unplanned disconnections of the individual modeled components.

A second, more complex example is depicted in fig. 2.9 \(^5\). The medium voltage grid is supplied by substation 1 which has an H-configuration, i.e. only a single busbar on the primary side. It is the second primary substation configuration in Zurich but less common and also less reliable.

The model covers the failure of a busbar of the primary side which requires conditional reliability\(^6\). If a failure of a busbar of substation 1 occurs, the isolator switch opens thereby alters the topology. In this situation, the transformer and the primary power supply is in series instead in parallel which means that the H-topology is not in use anymore. The component which causes the change in topology (here the busbar of the primary side) is placed on the bottom left to the white

\(^4\)An overview of the data used can be found in appendix B
\(^5\)The parallel connector (triangular shaped) is depicted with a red and blue color. The red color indicates that a calculation has not been conducted yet whereas the blue color indicates a completed calculation.
\(^6\)Basic reliability calculation is discussed in appendix E
bullet point. The topology for the case that the busbar is operating is connected to the green bullet point on the bottom. The topology in case of a failure of the busbar is connected to the red bullet point. The configuration of the secondary side is not affected and remains parallel and the values are required in both cases. The component denoted by ”FlowSplit” generates two identical signals of the input signal.

One aspect which can affect the reliability of the reserve grid is under frequency load shedding. At 49 Hertz, 5% of the load of a utility should be shed. It is desirable that the reserve grid is excluded from all partial load shedding procedures. The reserve grid should be only disconnected in case of a complete load shedding.

2.3.3 Case Studies

In this section, a reliability assessment of MVRG A, B and C is conducted. The model comprises the primary and reserve substation, the primary and reserve medium voltage grid and the customer’s busbar. For all three topologies, the model of the primary and reserve substation are identical. By contrast, the reserve grid security is different
2.3. Comparison of Typical Grid Topologies

Figure 2.9: Conditional reliability model for a primary substation with a H-shape. The single busbar on the primary side contains a switch which is usually closed. The resulting reliability model is depicted on the left hand side. If the switch is opened, the reliability model on the right hand side results. The probability that the switch is closed is considered in the reliability component depicted on the bottom. The total conditional reliability is the output of the reliability component on the bottom.

for all three topologies. The primary substation model with the H-configuration has been chosen in these case studies. It is less reliable and hence more critical. As discussed above, the impact of a busbar failure on the primary side is modeled with a conditional reliability.

The reliability model of the medium voltage grid varies slightly for MVRG A, B and C. In MVRG A, both the primary and secondary are ring-shaped. This is modeled as two cables in parallel. MVRG B and C have a radial reserve grid and hence require similar blocks. The primary grid is ring-shaped and identical to MVRG A. The difference here is the lower failure probability of MVRG B compared to C. As
Chapter 2. Reserve Grid Planning

mentioned above, when a failure in the reserve grid occurs, only part of the reserve grid is disconnected. By contrast, the complete reserve grid is offline in MVRG C. This is considered a different length between the substations. The complete model of MVRG A is depicted in fig. 2.10 and the models B and C can be found in Appendix C.

Figure 2.10: The reliability model of MVRG A consists of a primary substation with H-shape and a N-1 secure medium voltage grid. In parallel, the reserve grid with a primary substation consisting of two single busbars and a single transformer is connected with a N-1 secure medium voltage grid.

The results of all three reserve grid versions and the primary grid are depicted in table 2.3. In case of an outage, the customer is connected to the reserve grid by an automatic switch (switching time 10 s) without UPS. Therefore, outage rates are in all cases almost the same (every 5 year an event). By contrast, the outage times differ significantly for customers without a connection to the reserve grid and customers with a connection: the outage time decreases from 82 min, in the case of a connection solely to the primary grid, to approximately 1.6 min, 2 min and 2.4 min for MVRG A, B and C connection, respectively. The economic version MVRG C has a 50% higher outage probability as MVRG A but the 0.5 min/a is still a small value.

The reliability for an outage duration of 17 minutes per year \(\text{min}_{\text{year}} = 365 \cdot 24 \cdot 60\) corresponds to
2.3. Comparison of Typical Grid Topologies

\[ r_{primary\text{grid}} = 1 - \frac{P_{primary\text{grid}}}{min_{year}} = 1 - \frac{17}{525600} = 0.999677 \]  \hspace{1cm} (2.1)

0.3372 minutes per year \( min_{year} = 365 \cdot 24 \cdot 60 \) correspond to

\[ r_{MVRGA} = 1 - \frac{P_{MVRGA}}{min_{year}} = 1 - \frac{0.3372}{525600} = 0.9999994 \]  \hspace{1cm} (2.2)

Table 2.3: Reliability indices for MV customer

<table>
<thead>
<tr>
<th>Index</th>
<th>Prim. Grid</th>
<th>MVRG A</th>
<th>MVRG B</th>
<th>MVRG C</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV H (#/a)</td>
<td>0.2159</td>
<td>0.2113</td>
<td>0.2113</td>
<td>0.2114</td>
</tr>
<tr>
<td>MV T (min/a)</td>
<td>82.3200</td>
<td>1.5960</td>
<td>1.9800</td>
<td>2.4120</td>
</tr>
<tr>
<td>MV P (min/a)</td>
<td>17.7729</td>
<td>0.3372</td>
<td>0.4184</td>
<td>0.5099</td>
</tr>
</tbody>
</table>

2.3.4 Cost Analysis

For a basic cost analysis, the installation costs for the three reserve grid versions (MVRG A, B and C) are estimated. Other factors as e.g. revenues required for a price are not considered. Furthermore, it is assumed that the whole cable capacity is sold which is the ideal case. The estimation comprises the required equipment for three different locations and a different number of customers. The locations are the city center, the districts and the outskirts. The distance between primary substations is lowest in city center and highest in the outskirts. As a result, the line length of the reserve grid is different for each location and hence has an impact on the costs (variable costs). The number of customers denoted by \(|C|\) is also a variable cost as each customer requires a switch gear field.

The equipment costs comprise the required cables, switches, customer connection, automatic communication, space in primary substations and share of primary transformer. The first three listed costs depend on the number of installations. As an example: a higher number of installed switches results in higher costs. The other costs are fixed and
equal for all reserve grid versions. Table 2.4 lists the cost range of the components.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Price range</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV cable [kCHF/m]</td>
<td>0.2 - 1</td>
</tr>
<tr>
<td>MV circuit breaker [kCHF/unit]</td>
<td>80-150</td>
</tr>
<tr>
<td>MV switch gear field [kCHF/unit]</td>
<td>1-2.5</td>
</tr>
<tr>
<td>MV plug connection [kCHF/unit]</td>
<td>1.5-2.5</td>
</tr>
<tr>
<td>Automatic communication [kCHF]</td>
<td>20-30</td>
</tr>
<tr>
<td>Space in primary substations [kCHF]</td>
<td>50-100</td>
</tr>
<tr>
<td>Share primary transformer [kCHF]</td>
<td>30-50</td>
</tr>
</tbody>
</table>

In order to calculate the total costs, the quantities of the equipment have to be determined. As mentioned above, the quantities depend on the grid version, the location and the number of customers. The grid version influences the cable length and number of customer’s connection. In order to determine the cable length, a Manhattan metric is chosen, i.e. a rectangular connection of the customers. The Manhattan metric allows a general discussion of the resulting costs and does not reflect the exact situation in Zurich. For MVRG A and B, two MV connections per customer are required and for MVRG C only one. The location determines the distance between primary substations. For MVRG A, two main power lines are modeled which split the area of interest in three parts and for the other two topologies only one. The required cable length is hence for MVRG A twice the distance between two substations and the customer. For MVRG B it is only once the distance between two substations because of the radial configuration and the connection to the customers is longer. The difference of MVRG C compared to MVRG B is that the connection to the customer is shorter because they are connected with only one power line. For the city center, districts and outskirts the average length is 2 km, 3 km and 4 km, respectively. The chosen width is 0.75 km, 1 km and 1.5 km, respectively. It is assumed that construction costs are identical in all three areas. The last factor is the number of customers, i.e. the number of MV connections. As an example, for MVRG A and 5 customers, a total of 10 connections and 5 switch gears are required. For 20 customers, a total of 40 connections
and 20 switch gears have to be installed. Therefore, a high number of
customers results in higher total costs.

The total costs are normalized with the costs of an EDG which allows
an intuitive comparison of the various versions. The costs of an EDG
with fix installation is about kCHF 420 [5]. The MV reserve grid for
the three versions is regarded, assuming that the total required reserve
power in a potential supply area is 20 MVA. The reserve power is equally
distributed per customer and varies from 1- 4 MVA. The reserve power
density is set to 13, 7 and 3 [MVA/km²] respectively.

Table 2.5 shows the resulting cost ranges per kVA in relation to the
average costs of a self-contained power supply by an EDG [5]. It can be
observed that the reserve power density and the number of connections
have a strong impact on costs. More connections lead to a greater cable
length, which can be identified as the major cost factor. MVRG A
with the best reliability is in most cases the most expensive version to
construct a reserve power of 20 MVA. MVRG C is the most cost efficient
version. When 20 customers are connected to the reserve grid, MVRG
A results in lower costs than MVRG B. The reason is that the radial
configuration with the simple Manhattan metric results in longer line
lengths due to the required customer connections.

<table>
<thead>
<tr>
<th>Area supplied</th>
<th>MVRG A</th>
<th>MVRG B</th>
<th>MVRG C</th>
</tr>
</thead>
<tbody>
<tr>
<td>City center</td>
<td>75 - 110 %</td>
<td>50 - 120 %</td>
<td>45 - 90 %</td>
</tr>
<tr>
<td>Districts</td>
<td>95 - 135 %</td>
<td>65 - 145 %</td>
<td>55 - 110 %</td>
</tr>
<tr>
<td>Outskirts</td>
<td>125 - 170 %</td>
<td>85 - 195 %</td>
<td>70 - 135 %</td>
</tr>
</tbody>
</table>

2.3.5 Conclusions

The investigations show that a reserve grid decreases the outage proba-
bility considerably because of the reduced outage duration. The highest
reliability is obtained applying a ring-shaped topology (MVRG A) and
lowest for MVRG C. In general, a reserve grid is competitive for high re-
serve power density and high reserve power requirements per customer.
The reason is that the cable length is a major cost factor which is higher
for lower reserve power density. The best case scenario is a customer cluster in commercial areas or industrial estates with short distance for power supply. The assumption that all reserve power is sold is a best scenario. When a certain amount of capacity is still available, the costs have to be covered by ewz.

### 2.4 Customer Information

The specific requirements of reserve grid customers have a great impact on the reserve grid design. Relevant parameters are the required reliability, the customer’s location and the electric load. Certain customers have clear regulations regarding the reliability of supply. Others install a tailored EPS solution according to suggestions by reliability engineers. The geographic location is given by the customer’s geographic coordinates. This value is given and cannot be altered. The electric load is defined by the customer’s purchase order. In this thesis, it is estimated with measurement data.

#### 2.4.1 Reliability Requirement

As mentioned above, reserve grid customers can either have a clear perception regarding reliability requirement or have the general desire for an increased reliability of supply.

An example for the first group are stadiums which organize football games for the International Federation of Association Football (FIFA). The technical requirements of the power supply and the installed components in a football stadium are clearly described in [4]. The downtime during a football game is expected to be zero which corresponds to a reliability of 0.99999. It is discussed that one or more EDG are required depending on the reliability of supply provided by distribution grid. A collaboration with the supplying electric utility is hence required.

The second example is that customers also require an increased reliability of supply, however they do not possess clear rules. In this case, a comparison with EDG can be helpful. The experience of ewz concerning EDG shows that roughly every third till eighth start of EDG fails ($q_{EDG} = \{0.125, 0.333\}$). A high reliability for a successful start can be achieved by regular and thorough test. This also includes testing if the
power supply of the primary grid is interrupted by the local DSO. With these procedures, faults can be detected. Often, a flaw in the software causes a failure of the EDG operation. The resulting reliability of EDG is:

\[ r_{EDG} = 1 - q_{EDG} = 0.875 \] (2.3)

The resulting reliability of power supply depends on the reliability of the primary grid and the EDG. The first value has been calculated in section 2.3.3 and is \( r_{primarygrid} = 0.999677 \). An EDG in parallel to the primary grid results in the following reliability:

\[
\begin{align*}
  r_{tot} &= 1 - (1 - r_{primarygrid}) \cdot (1 - r_{EDG}) = \\
  &= 1 - (1 - 0.999677) \cdot (1 - 0.875) = 0.999996 \\
\end{align*}
\] (2.4)

Therefore, a reliability of 99.999 % is exceeded. The minimal required reliability for EPS to obtain a 99.999 % reliability is

\[
\begin{align*}
  r_{EPS} &= (1 - \frac{(1 - r_{customer})}{(1 - r_{primarygrid})}) = (1 - \frac{(1 - 0.99999)}{(1 - 0.999677)}) = 0.6908 \\
\end{align*}
\] (2.5)

This means for a EDG only every fourth start is allowed to fail \( r_{EPS} > 0.6908 \).

### 2.4.2 Customer Locations

In section 2.3.5, the most profitable area for a reserve grid is located in the city center. Therefore, the city center is chosen as the area of interest in the case studies. In general, medium voltage customers are potential reserve grid customers and their locations are identified. The customers’ locations are specified with the Swiss coordinate system LV95 [14]. It is a two-dimensional Cartesian system where both coordinates are given in meter. Fig. 2.11 on the next page shows the map with potential customers of the city center.
The locations slightly deviate from the actual location for reasons of data protection. The figure also indicates the supplying primary substation with individual colors. Customer A is supplied by substation "Letten" (not depicted, black circle). Substation Sempersteig is providing customers C, D and H with electric power (red circles). The last two groups B, E, F, G, I and T are supplied by substations Zeughaus (green circles) and J, K, L, M, N, O, P, Q, R, S, U and V and by Katz (blue circles).

Various possibilities exist to place the reserve grid and to connect customers to an additional substation. One example is that reserve grid customers with a connection to substations Zeughaus and Katz are supplied by substation Sempersteig.
2.4.3 Customer Load

The load of the various customers is an additional parameter required for the reserve grid planning. Every customer orders a specific electric power and the reserve grid must be adequately designed. Therefore, no simultaneity factor is considered in planning. As power factor, the standard ewz value is used which is 0.9 inductive.

The measurement of the fifteen minutes average values of all customers in 2012 are used to estimate the peak demand. Fig. 2.12 depicts the load of customers J, K, L, M, N, O, P, Q, R, S, U, and V as an example. They are supplied in the primary grid with substation Katz and could be connected to substation Sempersteig for the reserve grid. The maximal demand is indicated by the red, dotted line.

Several observations are possible: the drop of demand during night time and weekends is clearly visible. Furthermore, the minimal and maximal load are mostly between 2 and 7 MW. However, the peak demand in summertime is the highest and approximately 8.5 MW.

The sum of all the loads of all customers is depicted in fig. 2.13. The maximal demand of the sum of all customers and the sum of the individual demand of the customers are indicated by the red and green
line, respectively. It can be observed the latter is about 7 MW higher compared to the first. In a symmetrical case, one half of the customers can be assigned to one substation and the other half to a second.

\[ l_{mn}^p = \sqrt{(x_m - x_n)^2 + (y_m - y_n)^2} \]  

(2.6)

---

Figure 2.13: Consumption of MV customers in city center

2.4.4 Connection between Two Nodes

The question, how the nodes (customers or substations) are connected to each other can be answered by two approaches. The first is a greenfield approach and the shortest distance between two nodes is calculated. This is an adequate approach for the transmission grid where direct connections are possible. The second approach uses the Manhattan metric, also known as the taxicab metric, which assumes that the cables have to follow streets and only vertical and horizontal directions are allowed. In cities as e.g. New York, this approach is more accurate than the first.

The first approach is calculated using the rule of Pythagoras:
The second approach is calculated using the taxicab geometry in the plane:

\[ l_{mn} = |x_m - x_n| + |y_m - y_n| \]  

(2.7)

In Zurich, the cables are located in cable ducts which are mostly underneath a street. As shown in fig. 2.11, the streets are built in a metric which is between the two discussed above. An example of the actual situation is shown in fig. 2.14. An additional aspect of the real situation in Zurich is that the orientation of the coordinate system can have a large impact on the resulting line length. In the optimal orientation, the resulting total line length is minimal and a rotation of the coordinate system results in longer line lengths. As the streets in Zurich have differing alignment, the influence of the orientation is assumed to be minimal and chosen north-south oriented.

Figure 2.14: MV grid in city center of Zurich

2.5 Environmental Impact of EPS

In 2008, Zurich has decided to reduce the power consumption and CO\(_2\) emissions. The Municipal Code states that the average power consumption is targeted to be 2000 W per capita and CO\(_2\) emission of 1 ton per year per capita [15]. Especially ewz, which is a municipal company of Zurich, has to contribute to achieve these goals. The EPS systems investigated in this thesis have an impact on the environment as any other power system. Therefore, the impacts on the environment of EDGs are compared with the installation of a reserve grid. The comparison is
conducted with a rough estimation which allows general conclusions. More detailed analyses are necessary for an exact assessment.

The environmental impact is evaluated with two different methods: the first is the ecological scarcity method [16] and the second the calculation of carbon dioxide equivalent. The ecological scarcity method uses eco-factors as key metric. They are measurements of the environmental impact of pollutant emission or activities of resource extraction. The final value is given in eco-points (EP=UBP) [16]. The second method comprises the calculation of the carbon dioxide equivalent which describes the greenhouse effect (GE) of the materials. A life cycle analysis is conducted for the main materials used and calculated to determine the annual impact in \([UBP/a]\) and \([kgCO_2eq/a]\). The system boundaries are discussed for both the reserve grid and the EDG. They are based on a reserve grid between substations Katz and Sempersteig (see fig. 2.11). The maximal consumption is roughly 10 MVA and the distances between two substation in the city about 1200 meter. Table 2.6 lists the impact factors of the main materials used in the systems according to [16], [17], [18] and [19]. Copper has a relatively high number of UBP compared to the other listed materials and the \(CO_2\) equivalent due to the high \(SO_2\) emission when copper in South America is recovered [20].

<table>
<thead>
<tr>
<th>Material</th>
<th>Eco-factor ([UBP])</th>
<th>GE ([kgCO_2eq])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper ([kg_{Mat}])</td>
<td>49,476.414</td>
<td>1.8388</td>
</tr>
<tr>
<td>Chromium steel ([kg_{Mat}])</td>
<td>11,026.767</td>
<td>4.4798</td>
</tr>
<tr>
<td>Steel, low-alloyed ([kg_{Mat}])</td>
<td>3,749.0512</td>
<td>1.7479</td>
</tr>
<tr>
<td>Conventional diesel fuel ([L])</td>
<td>786</td>
<td>2.65</td>
</tr>
</tbody>
</table>

### 2.5.1 Environmental Impact of Reserve grid

The reserve grid consists from a material point of view mainly of the underground cable and the medium voltage switch gear. Therefore, other equipment is not considered in this study. The total cable length depends strongly on the redundancy of the grid. The cable length of the radial reserve grid is assumed to be the distance between two substations, i.e. 1200 meter. For a N-1 secure reserve grid, the double
length is assumed, i.e. 2400 meter. The main material used for cable is copper. The second component is the medium voltage switch gear. It is assumed that a total of ten switch gear systems are used, i.e. eight customers are connected to the reserve grid. The remaining two switch gears are located in the substations. For cables, a life cycle of 45 years is assumed [20] and 35 years for the switch gears [21].

In 2012, ewz ordered a study concerning the ecological impact of low voltage cable [20]. A comparison of copper and aluminium cables was conducted based on the ecoinvent database v2.2 [17]. For a 3x150/150 copper cable, a total of 5.6 kg copper per meter was calculated. By comparison, a 3x150/35 medium voltage copper cable has according to ewz-internal studies a weight of 4.9 kg copper per meter. For a radial and a N-1 secure reserve grid, a total amount of 6720 kg and 13440 kg copper, respectively, are required for medium voltage cables. The resulting UBP per year for a life cycle of 45 years and eco-factor according to table 2.6 are 6.52 [MUBP/a] \(^7\) and 13.03 [MUBP/a]. The CO\(_2\) equivalent values are 242 [kgCO\(_{2eq}\)] and 484 [kgCO\(_{2eq}\)].

The annual ecological impact of three medium voltage switch gear have been investigated in [21]. The investigated suppliers are ABB (UniSec), M&Z (SYStem6) and Siemens (8DJH). The UBP per year for these three switch gear fields and a life cycle of 35 years are: 0.377 [MUBP/a], 0.288 [MUBP/a] and 0.26 [MUBP/a]. And the CO\(_2\) equivalent are: 394 [kgCO\(_{2eq}\)], 294 [kgCO\(_{2eq}\)] and 223 [kgCO\(_{2eq}\)]. The Siemens system is in favor regarding annual UBP and is also the most installed system in Zurich. Therefore, it has been chosen as a reference. As mentioned above, ten switch gear systems with a total of twenty switches are assumed which results in a total of 5.2 [MUBP/a] and 4,450 [kgCO\(_{2eq}\)].

For a radial and a N-1 secure reserve, the total UBP are 11.74 [MUBP/a] and 18.26 [MUBP/a], respectively. The cable is the dominant component for the N-1 secure reserve grid. For the radial grid, the amount is comparable for the switch gear and the cable. By contrast, the impact evaluated in CO\(_2\) equivalent is dominated by the switch gears. The total is 4,693 [kgCO\(_{2eq}\)] and 4,935 [kgCO\(_{2eq}\)]. The values for the radial and the N-1 reserve grid are comparable because the CO\(_2\) equivalent of the switch gears are high. The highest share originates from the production and the transport of the switch gear [21]. The results are summarized in table 2.7.

\(^7\)1,000,000 UBP is denoted as MUBP to increase the readability.
Table 2.7: Annual environmental impact of reserve grid

<table>
<thead>
<tr>
<th>Material</th>
<th>Radial Reserve Grid</th>
<th>N-1 Secure Reserve Grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP $^{[\text{MUBP/}a]}$</td>
<td>11.74</td>
<td>18.26</td>
</tr>
<tr>
<td>GE $^{[\text{kgCO}_2\text{eq/}a]}$</td>
<td>4,693</td>
<td>4,935</td>
</tr>
</tbody>
</table>

2.5.2 Environmental Impact of EDG

The environmental impact of a 10 MW EDG is estimated with two different aspects: the first comprises the impact of the main construction materials and the second the fuel consumption. A list of the main materials can be found in [17]. The fuel consumption is estimated for monthly test which last for one hour. This is common practice for EDGs operated by ewz. In [22], a minimal test duration of 10 minutes is recommended.

The main materials required are according to [17] copper, chromium steel and steel (low-alloyed). The amount is 18 t, 9 t and 180 t, respectively. This yields a total weight of 207 t. By comparison, most heavy KU-diesel generator set (range 3.5 - 15 MW) offered by Mitsubishi Heavy Industries weigh about 60 t [23]. As these are significantly lighter, a second set of a materials list is calculated. The same proportions as in the first example were used. The result is 5.2 t copper, 2.6 t chromium steel and 52 t steel (low-allowed). The total weight is as desired 60 t. The resulting annual environmental impacts for a life cycle of 45 years using values of table 2.6 for the 207 t diesel generator set are: 19.8 [MUBP/a] copper, 2.21 [MUBP/a] chromium steel and 15 [MUBP/a] steel (low-alloyed). The total is hence 37 [MUBP/a]. The corresponding annual $CO_2$ equivalent is 735 [$kgCO_2eq/\text{a}$], 896 [$kgCO_2eq/\text{a}$] and 6,990 [$kgCO_2eq/\text{a}$]. The sum of all $CO_2$ equivalent values is 8,620 [$kgCO_2eq/\text{a}$].

The second aspect is the fuel consumption. It is estimated with the following values: an efficiency of 50 %, lower heating value of 42.612 MJ/kg and a density of 0.82 [$kg/L$] [24]. The monthly test duration is assumed to be 1 hour at maximal power, i.e. annual duration of 12 hours. The resulting annual energy consumption for a 10,000 kW diesel generator set with an efficiency of 50 % and a 12 hours operation time is 240,000 kWh. The consumption can be converted to liters by using the lower heating value and the density. A total of 24,500 l of
diesel is consumed in this scenario. The ecological impact according to the ecological scarcity method and the greenhouse emission (table 2.6) is 17.6 [MUBP/a] and 65,729 [kgCO2eq]. As the installed power is the same for the 207 t and the 60 t unit, the consumption is for both identical. The result are summarized in table 2.8.

Table 2.8: Annual environmental impact of EDG

<table>
<thead>
<tr>
<th>Material</th>
<th>207 t unit</th>
<th>60 t unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP installation</td>
<td>MUBP/a</td>
<td>37</td>
</tr>
<tr>
<td>GE installation</td>
<td>kgCO2eq/a</td>
<td>8,622</td>
</tr>
<tr>
<td>EP monthly test</td>
<td>MUBP/a</td>
<td>17.6</td>
</tr>
<tr>
<td>GE monthly test</td>
<td>kgCO2eq/a</td>
<td>65,730</td>
</tr>
<tr>
<td>EP total</td>
<td>MUBP/a</td>
<td>54.6</td>
</tr>
<tr>
<td>GE total</td>
<td>kgCO2eq/a</td>
<td>74.353</td>
</tr>
</tbody>
</table>

The main finding of table 2.8 is that the environmental impact of monthly tests is significant. The total annual eco-points are about 50% higher for the 207 t unit and doubled for the 60 t unit compared to the installations. The greenhouse effect is clearly dominated by the monthly test. Including monthly test, the total amount is increased about ten-fold for the 207 t unit and by thirty for the 60 t unit compared to the installations.

### 2.5.3 Comparison of Environmental Impact of EPS

The environmental analyses conducted in this chapter is a rough estimation. Only materials considered as significant by the author are evaluated and two different methods are applied. A more detailed analysis and additional methods can be used for a more founded assessment. Furthermore, a sensitivity analysis could reveal the impact of the variables used. However, certain conclusions can already be drawn. The results concerning the installation of tables 2.7 and 2.8 are listed in table 2.9.

Table 2.9 indicates that installation of the reserve grid and the EDG have comparable impact on the environment. Dependent on the mater-
Table 2.9: Annual environmental impact of EPS

<table>
<thead>
<tr>
<th>EPS type</th>
<th>EP $\frac{MUBP}{a}$</th>
<th>GE $\frac{kgCO2eq}{a}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reserve grid installation (rad)</td>
<td>11.74</td>
<td>4,693</td>
</tr>
<tr>
<td>Reserve grid installation (N-1)</td>
<td>18.26</td>
<td>4,935</td>
</tr>
<tr>
<td>207 t EDG installation</td>
<td>37</td>
<td>8,622</td>
</tr>
<tr>
<td>60 t EDG installation</td>
<td>10.7</td>
<td>2,499</td>
</tr>
</tbody>
</table>

The situation is different if also the monthly test of a EDG is considered. Both the eco-points and the greenhouse effect are significantly higher in this case. If the tests are operated at less than the rated power and for a shorter time period, the environmental impact can be reduced. However, the reliability of the EDG is likely to be affected and possible faults might not be detected.
In this chapter, the planning problem of finding a reserve grid topology with minimal costs is investigated. Constraints are that the physical limits are maintained and all customer supplied with power. Reliability constraints are not considered yet. The optimization problem is discussed and its complexity investigated. Search methods are formulated which are able to find the optimal reserve grid topology.

3.1 Optimization Problem

Typical problems of system engineers are the planning of the electric grid or optimal operation of a grid, e.g. economic dispatch of power generation in order to minimize costs. Often, these problems are solved using power flow or optimal power flows (OPFs). The boundary conditions comprise the power flow equations and depending on the algorithm, the maximal current in power line and voltage limits. All calculations concerning optimal operation have in common that the grid topology is known. Therefore, finding the optimal reserve grid topology differs from common power flow calculations as the topology is an output instead of an input variable. The solution has to be found among all possible reserve grid topologies in order to find the optimal solution considering the objective function. Figure 3.1 shows the problem for a four node system with possible connections.
The objective of the search is to find the grid topology with lowest costs which fulfills the constraints. In section 2.3.4, the cable costs per meter are identified as the dominant cost factor. Therefore, the line length has to be minimized. The physical constraints discussed in section 2.2 are the voltage and current limits and the minimal short circuit current. It has been shown that both the voltage limit and the short circuit current would be fulfilled in any case. In order to calculate the branch currents, the voltage is required and hence also calculated. By contrast, the short circuit current is not determined and assumed that it is in any case high enough.

The cost of the cables consist of the cable length and the price in CHF/m. In section 2.4.4, the direct connection (2.6) and the Manhattan/taxicab metric (2.7) are discussed to calculate the line length $l_{m,n}$ between nodes $m$ and $n$. The line length of a grid topology is denoted by $L_i$. The set which contains the total line lengths of all grid topologies is denoted by $\mathcal{L} = L_1, L_2, \ldots, L_p$ where $L_p$ indicates the total line length of the last investigated grid topology. The costs per meter are denoted by $\pi$. A price range is shown in table 2.4. For an installation of cables without duct banks, CHF 200 per meter is chosen. The
optimization problem is hence:

Minimize:

\[ f(L) = L \cdot \pi, L \in \mathcal{L} \]  \hspace{1cm} (3.1)

The voltage and current limits are defined according to ewz norm and the specification of the cable producer, respectively. The first is discussed in section 2.2.2 and is +/-6 %. Data for the second can be found in appendix B. Both limits are inequality constraints as the values have be kept within an upper and/or lower limit.

\[ V \leq V \leq \nabla \]
\[ |I| \leq I \]  \hspace{1cm} (3.2)

The load and distributed production at each node is based on measurements. The optimal reserve grid topology has to be chosen from all possible connections. It has also to be ensured that the boundary conditions are considered and none are violated.

### 3.2 Big O Notation of Various Search Methods

Finding the optimal topology of a grid is a discrete optimization problem and hence a challenge to solve. Furthermore, the number of possible grid topologies is increasing rapidly with additional nodes. The increase can be described with the big O notation. This notation contains the term which is most responsible for the growth speed of the function [25]. With the big O notation, the growth of functions can be quickly assessed. The condition is that the numbers are high and the term with the highest order becomes dominant. Two common examples are \( O(N) \), which represents a linear function, and \( O(N^2) \), which shows a quadratic behaviour. As a result, \( O(N^2 + N) \) is not a proper expression as only the dominating term is considered, therefore, the big O notation is in this case \( O(N^2) \). Typical functions are the following:

Following, an upper limit of the growth for a grid with limited number of nodes is calculated. In graph theory, the term vertex is used to
Table 3.1: Growth rate of common functions, [25] modified

<table>
<thead>
<tr>
<th>Function</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mathcal{O}(c))</td>
<td>Constant</td>
</tr>
<tr>
<td>(\mathcal{O}(\log N))</td>
<td>Logarithmic</td>
</tr>
<tr>
<td>(\mathcal{O}(N))</td>
<td>Linear</td>
</tr>
<tr>
<td>(\mathcal{O}(N\log N))</td>
<td>(N \log N)</td>
</tr>
<tr>
<td>(\mathcal{O}(N^2))</td>
<td>Quadratic</td>
</tr>
<tr>
<td>(\mathcal{O}(N^3))</td>
<td>Cubic</td>
</tr>
<tr>
<td>(\mathcal{O}(c^N))</td>
<td>Exponential</td>
</tr>
<tr>
<td>(\mathcal{O}(N!))</td>
<td>Factorial</td>
</tr>
</tbody>
</table>

describe the nodes. The number of vertices in a graph \(G\) is depicted with \(|V(G)|\). This value contains a power source and the customers of the distribution grid, \(|V(G)| = 1 + |V(C)|\), where \(C\) is the set of customers. The customers are loads and do not feed power into the grid. The upper limit for the number of possible topologies is obtained in two steps: first, the number of lines in a complete graph is calculated; second, the resulting number of possible topologies. For each topology, a power flow calculation is required to ensure that all physical constraints are fulfilled.

### 3.2.1 Number of Edges in a Complete Graph

The number of edges in a graph correspond to the number of power lines in an electric grid. With the notation of graph theory, the number of edges in a complete graph \(|E(G_c)|\) can be found with \(^1\):

\[
|E(G_c)| = \left( \frac{|V(G)|}{2} \right) = \frac{|V(G)|!}{2!(|V(G)| - 2)!} = \frac{|V(G)||(|V(G)| - 1)}{2} = \frac{(|V(G)|)^2}{2} - \frac{|V(G)|}{2}
\]

\(^1\)The subscript \(c\) indicates a complete graph. As the number of vertices is not influenced by the edges, e.g. radial and a complete graph, the number of vertices is denoted without subscript.
3.2. **Big O Notation of Various Search Methods**

As a result, the *big O* notation of $|E(G_c)|$ is:

$$
\mathcal{O}(|E(G_c)|) = \mathcal{O} \left( \frac{(|V(G)|)^2}{2} - \frac{|V(G)|}{2} \right) = \mathcal{O}((|V(G)|)^2) \quad (3.4)
$$

Therefore, the number of power lines in a fully meshed grid $|E(G_c)|$ is growing quadratically depending on the number of nodes (3.4). Fig 3.2 shows the number of edges in complete graphs between two and thirty vertices. The growth of the exact number of edges (3.3) is depicted with the blue line and the approximation with the *big O* notation (3.4) with the black line. Already for low number of vertices, the difference is small.

![Graph showing the growth rate of number of power lines in a complete graph](image)

Figure 3.2: Growth rate of number of power lines in a complete graph

### 3.2.2 Number of Grid Topologies

The second step comprises the possible topologies for the system. This step requires a combinatorial analysis: the lines of the optimal topology have to be chosen among all possible lines. In the general, the number of combinations of grid topologies can be found using binomial coefficients
$\binom{n}{k}$. The optimal result is between a grid consisting of single feeders or fully meshed grid. The minimal number of edges to connect a general graph $G$ with $|V(G)|$ vertices is $|V(G)| - 1$. Using the previous notation, the minimal number of power lines required is:

$$|E_{\text{min}}(G)| = |E(G_r)| = |V(G)| - 1 \quad (3.5)$$

The maximal number of power lines has been discussed in the previous section (3.3).

The number of radial grids $|G_r|$ by using binomial coefficients can be found by choosing the minimal number of required power lines ($|E(G_r)|$) out of all possible power lines ($|E(G_c)|$) spanning trees, i.e. a graph where all vertices are connected without building loops:

$$|G_r|_{\text{bin}} = \binom{|E(G_c)|}{|E(G_r)|} = \binom{|E(G_c)|}{|V(G)| - 1} \quad (3.6)$$

In order to use the big $O$ notation, the asymptotic expansion of binomial coefficients is conducted [26].

$$\binom{n}{k} = \frac{n^k}{k!} \left(1 + O\left(\frac{1}{n}\right)\right), \text{ for } k = O(1) \quad (3.7)$$

For applying this expansion to (3.6), $n$ is $|E(G_c)|$ and $k$ is $|E(G_r)|$:

$$O(|G_r|_{\text{bin}}) = O\left(\frac{|E(G_c)||E(G_r)|}{|E(G_r)|!} \left(1 + O\left(\frac{1}{|E(G_c)|}\right)\right)\right) = \quad$$

$$= O\left(\frac{|E(G_c)||E(G_r)|}{|E(G_r)|!}\right) \quad (3.8)$$

Therefore, the number of radial topologies by applying combinatorics is:

$$O(|G_r|_{\text{bin}}) = O\left(\frac{|E(G_c)||E(G_r)|}{|E(G_r)|!}\right) \quad (3.9)$$
3.2. Big O Notation of Various Search Methods

The drawback of this method is that for graphs with more than three nodes, also grid topologies are counted where not all nodes are connected. This is demonstrated with the following examples:

**Example with three nodes:**
In this example, (3.6) is applied to a three node system ($|V(G)| = 3$). The number of lines in a complete graph is according to (3.3):

$$|E(G_c)| = \binom{|V(G)|}{2} = \binom{3}{2} = 3$$ \hspace{1cm} (3.10)

The minimal number of power lines is (3.5):

$$|E(G_r)| = |V(G)| - 1 = 3 - 1 = 2$$ \hspace{1cm} (3.11)

As a result, the number of radial topologies according to (3.6) is:

$$|G_r|_{bin} = \binom{|E(G_c)|}{|E(G_r)|} = \binom{3}{2} = 3$$ \hspace{1cm} (3.12)

Fig. 3.3 shows all combinations:

![diagram](image)

**Figure 3.3: Three node radial systems**

The three topologies show similar structures: there are two nodes with a single connection and one node with two connections.

**Example with four nodes:**
The same steps are taken as in the previous example. The number of lines in a complete graph is in this case (3.3):

$$|E_{G_c}|_{bin} = \binom{|E(G_c)|}{|E(G_r)|} = \binom{4}{2} = 6$$ \hspace{1cm} (3.13)
Chapter 3. Optimization Methods

The minimal number of power lines is (3.5):

\[ |E(G_r)| = |V(G)| - 1 = 4 - 1 = 3 \]  
\[ (3.14) \]

As a result, the number of radial topologies according to (3.6) is:

\[ |G_r|_{bin} = \left( \frac{|E(G_c)|}{|E(G_r)|} \right) = \binom{6}{3} = 20 \]  
\[ (3.15) \]

Fig. 3.4 shows the 5 different combinations:

Figure 3.4: Four node systems with minimal number of edges

The topologies a, b and c can be rotated three times each by 90° which results in additional topologies. Topology d can be rotated only once by 90°. When mirrored, topology d provides another two topologies. The last topology listed can also be rotated three times which results in a total of 20 different topologies as calculated in (3.15). However, topology e does not provide a valid result as one customer is not supplied with power.

Another approach can be found in with enumerative combinatorics. Finding all radial topologies in a grid equals finding all spanning trees in a graph. The number of all radial topologies can be found by Cayley’s formula, where \(|V(G)|\) denotes the number of vertices in a graph:

\[ |G_r| = |V(G)|^{(|V(G)| - 2)} \]  
\[ (3.16) \]

When applied to a three node system, (3.16) yields three topologies (\(|V(G)| = 3\)) and to a four node system, it yields 16 (\(|V(G)| = 4\)). The result for the three node system can quickly be verified by fig. (3.3): Only three topologies are possible. For the four node system, topologies a-d shown in fig. (3.4) are the solution: for each topology
shown, a total of four variations are possible when rotated. As a result, 16 valid topologies exist. Topology e is a meshed grid and hence not a part of the solution.

Therefore, the growth of the number of radial topologies depends on the number of nodes:

\[
\mathcal{O}(|G_r|) = \mathcal{O}((|V(G)|)^{(|V(G)| - 2)}) \tag{3.17}
\]

For meshed grid, no simple formula could be found which determines the number of different topologies. Therefore, an upper limit of the growth is estimated with the help of binomial coefficients as used in (3.6). A sum is built where each summand determines the number of choices out of a defined number of power lines \(|E(G)| \in \{|E(G_c)|, |E(G_c)| - 1, \ldots, |E(G_r)|\}\). The first summand represents the number of topologies of a complete graph and the last the number of radial topologies. All these graphs are in the set \(\mathcal{G} = \{G_c, \ldots, G_r\}\)

\[
|\mathcal{G}| = \left( \frac{|E(G_c)|}{|E(G_c)|} \right) + \left( \frac{|E(G_c)|}{|E(G_c)| - 1} \right) + \cdots + \left( \frac{|E(G_c)|}{|E(G_r)|} \right) \\
\Rightarrow 1 + \left( \frac{|E(G_c)|}{|E(G_c)| - 1} \right) + \left( \frac{|G_c|}{|E(G_r)| - 2} \right) + \cdots + |(G_r)| \tag{3.18}
\]

The first summand represents the situation when all power lines are in use. Therefore, only one topology exists. The second summand calculates the number of possible topologies if all power lines are chosen except from one. Finally, the last depicted summand determines the number of topologies if the minimal number of power lines are used (3.16). The first and the last summand have in common that the minimal number of topologies is calculated. By contrast, all summands in between contain also topologies where certain customers are not supplied with power, i.e. these summands contain invalid topologies. As a result, the sum represents an upper limit. As this sum contains binomial coefficients, again (3.7) is applied:

\[
\mathcal{O}(|\mathcal{G}|) = \mathcal{O} \left( \frac{|E(G_c)|^{E(G_{max})}}{|E(G_{max})|!} \right) \tag{3.19}
\]
Fig. 3.5 depicts the number of topologies depending on the number of power lines used for a graph with 10 vertices. The number of edges for a complete graph is 45. It can be observed that the maximal number of topologies is between 21 and 24 used power lines ($|E(G_{max})|$).

![Graph showing number of topologies vs number of power lines](image)

Figure 3.5: Number of topologies for ten node grid

In fact, the actual number of suitable topologies with desired properties depends strongly on the search algorithm used. An algorithm which considers symmetrical topologies is in favor compared to a brute force method. Furthermore, the search algorithm can be accelerated by the introduction of more constraints which narrow down the search. Every topology requires a calculation of the power and later reliability which is increasing the computational time. Therefore, an efficient power flow is favorable.

### 3.3 Heuristic Approach

An efficient way to find a grid topology with desired properties is by applying a heuristics. Methods are available which are able to find radial or meshed topologies for the stated problem. For both cases, optimal solutions can be found under certain conditions. Especially for finding
Minimal line lengths in radial grids, various methods are available. The search for a meshed grid can be accelerated by reducing the problem. This can be achieved by making the assumptions which are discussed in the following.

### 3.3.1 Radial Grid

A common solution to build a minimal spanning tree is applying Prim’s algorithm. The result is a radial grid with minimal line length. By contrast, physical limits are not considered. The growth rate of Prim’s algorithm\(^2\) depends on the implementation of the priority queue. If it is implemented with binary heaps, the rate is [27]:

\[
O_{\text{bina,heap}}(|G_r|) = \mathcal{O}(|E(G_c)| \log |V(G)|) = \mathcal{O}(|V(G)|^2 \log |V(G)|) \quad (3.20)
\]

If Fibonacci heaps are applied, the rate is [27]:

\[
O_{\text{fib,heap}}(|G_r|) = (|E(G_c)| + |V(G)| \log |V(G)|) = \\
= (|V(G)|^2 + |V(G)| \log |V(G)|) \quad (3.21)
\]

Both growth rates are considerably slower than the growth according to the binomial coefficients (3.9) and to Cayley’s formula (3.17) as depicted in fig. 3.6.

### 3.3.2 Discussion

In this thesis, a thorough discussion of reserve grid topologies is conducted. As heuristics as discussed in [28–30] reduce the number of possible solutions, the relevance of these solutions might be diminished. For this reason, only optimization techniques are applied.

\(^2\)See appendix D for a summary of Prim’s algorithm.
Chapter 3. Optimization Methods

3.4 Search Methods

Several approaches can be applied to find the reserve grid topology with minimal installation costs. Three fundamentally different approaches have been implemented.

**Complete Search** is a brute force method which tests all possibilities. The optimal solution is found by comparing the results using the objective function.

**Software Toolkits** which can solve mixed-integer linear problems. An example is CPLEX®milp (cplexmilp) a feature of IBM®ILOG®CPLEX ® [31]. cplexmilp is able to evaluate the solution by providing solution status values and to determine whether the solution is optimal or not.

**Heuristic optimization** can find solutions for various types of optimization problems. In contrast to the two other methods mentioned above, obtained results cannot be proven to be the optimal solution. It is mainly used for computationally intensive calculations.

All three approaches are discussed in more detail in the following sections. The objective of them is to minimize the length of power lines.
Other costs discussed in section 2.3.4 are fixed because the number of customers is considered as given.

### 3.5 Complete Search

The complete search of all possible solutions of a mixed-integer problem can theoretically find the optimal solution by the calculation and comparison of all topologies. For this reason, the power flows of all possible topologies are calculated, tested on feasibility and the value of the objective function compared. A simple depiction of the process is shown in figure 3.7.

![Figure 3.7: Simple depiction of complete search algorithm. The power flow of all possible topologies is calculated and the resulting costs are compared.](image)

The formulation of the complete search algorithm is adjusted for the power flow algorithm used in this thesis. The backward/forward sweep (BFS) power flow algorithm has been chosen because it converges fast for radial grids and is expandable to calculated meshed grid [32,33]. An additional advantage is that the layer representation of the investigated topology can be applied. This representation allows an intuitive implementation of the incidence matrix. The search algorithm is building all possible incidence matrices and hence all grid topologies.

#### 3.5.1 Layer Representation of the Topology

For a intuitive implementation of the program, the layer representation of the power grid structure is applied. The predefined node numbering and definition of the layers results in a good readable incidence matrix.
In \( L \), each column contains all nodes connected to the node with this number, e.g. the first column contains all nodes connected directly to node 1. The value -1 indicates the node of the column itself whereas 1 indicates the nodes connected to this node. The first entry on the top left is always -1 and denotes node 1 in column one. The second and third entries in the first column denote the nodes 2 and 3. Both are are connected to node 1. In the following investigations, node 1 represents the primary substation.

The inverse of the incidence matrix denoted by \( \Gamma = L^{-1} \) also visualizes the grid topology. The topology is depicted in the rows. An example is row 5: there are 3 entries with the value -1. The columns of these entries indicate a connection. Node 5 is hence connected to node 3 which is connected to node 1.

Both the numbering of the nodes and power lines depend on the distance to the slack node. Figure 3.8 shows an example of a grid with five nodes (node 0 is only required for the BFS for the line 1 which is usually set to have no length.).

![Figure 3.8: Layer representation of a grid](image)

The incidence matrix and its inverse of the example grid are shown in fig. 3.9.

### 3.5.2 Algorithm Finding all Possible Connections

The objective of the algorithm is to compare all possible topologies and to identify the topology with minimal length while fulfilling all physical limits discussed in section 2.2. The layer representation described above is used to construct all possible radial grid topologies. The construction consists of two main steps: step 1 comprises building all topology types...
3.5. Complete Search

Step 1: Algorithm finding all possible topologies

The incidence matrix $L$ can be used to find all possible topologies. The algorithm is implemented with a recursive function. It starts with the topology where all customers are directly connected to the primary substation of the reserve grid. The algorithm ends with the topology with only one customer connected to the primary substation and all other customers indirectly connected. The following example shows the algorithm:

Example with a 5 node system

As stated above, the algorithm starts with the topology where all customers are connected to the slack node (node 1). According to the explanation in section 3.5.1 this means that for all nodes, i.e. row 2 to 5, the number 1 is located in the first column. The matrix and the topology are depicted in figure 3.10.

The algorithm continues until it ends with the topology where only one customer is connected to the slack node. As a result, all ones in the rows are in a different column. This is shown in fig. 3.11.
Chapter 3. Optimization Methods

Figure 3.10: Incidence matrix and layer representation if customers are connected to primary substation

```
L =
[1  2  3  4  5]
[1 -1]
[2  1 -1]
[3  1 -1]
[4  1 -1]
[5  1 -1]
```

Figure 3.11: Only one customer connected to slack node

```
L =
[1  2  3  4  5]
[1 -1]
[2  1 -1]
[3  1 -1]
[4  1 -1]
[5  1 -1]
```

**Step 2: Algorithm finding all possible situations within the same topology**

The numbering of the layer representation has the effect that different grid topologies lead to the same incidence matrix $L$. An example can be demonstrated with fig. 3.11. The order of the customers is not visible. It could be an arrangement of customer A, B, C and D or any other combination. A second algorithm is required which places all nodes at the possible positions of $L$. This is accomplished by applying all possible permutations of the customers. Recapitulated, the second step is necessary because several different node arrangements are formulated with the same incidence matrix $L$. 
3.5. Complete Search

3.5.3 Objective Function and Constraints

The objective of the complete search is as mentioned in section 3.1 to minimize the costs of the reserve grid. Every topology is tested with the following optimization problem:

Minimize:

\[ f(L) = L \cdot \pi, L \in \mathcal{L} \quad (3.22) \]

The voltage and current limit are examined applying a power flow algorithm with the **BFS** method. Physical specifications of the components are required to implement the algorithm. The cable data used in the thesis can be found in appendix B. In the **BFS**, the nodal voltages depend on the nodal voltages of the previous iterations \((k - 1)\) where \(k\) denotes an iteration. Therefore, it can be regarded as a Gauss-type numerical method. The exact algorithm is described in appendix G. The dependence of the current on the voltage is an equality constraint and shown in (3.23).

\[ I_s = g(V_{k-1}) \quad (3.23) \]

3.5.4 Overview of the Complete Search

The flow chart containing all steps of the complete search is depicted in figure 3.12. The complete search algorithm starts with the initialization of all required parameters, e.g. cable and customer information. It continues with the first incidence matrix and finds all possible customer combinations. Afterwards, the power flow algorithm is applied and the costs calculated. If all limits are kept and the objective is closer to the optimum than the current result, it is chosen as the new local optimum. These steps are repeated until all combinations are tested and hence the optimal result is found.
Chapter 3. Optimization Methods

3.6 Mixed-Integer Linear Programming

Another approach to solve the optimization problem is to formulate a mixed-integer linear program (MILP). It is a method which has been applied for decades to solve planning problems [34–37]. Similar to the complete search algorithm, an objective function and constraints have to be formulated. As mentioned above, cplexmilp which is a part of the toolbox function of CPLEX® is applied [31] to solve the problem. The
decision if power lines are used is formulated with an integer variable. It only takes the values one or zero. The power flow is formulated with a DC optimal power flow. It is a simple implementation and can be extended to an AC optimal power flow which is more precise compared to the DC OPF.

### 3.6.1 Optimal Topology

In order to find the optimal topology, the OPF required has to consider all possible topologies. This is achieved by the formulation of a fully meshed grid where each power line between two nodes has an assigned integer denoted by $s_{mn}$. The integer $s_{mn}$ can be considered as switch status indication: the value 0 indicates that the switch is closed and hence the value 1, when it is open:

$$s_{mn} = \begin{cases} 
0 & \text{if switch is closed}, \\
1 & \text{if switch is open} 
\end{cases}$$

(3.24)

The basic idea to obtain a minimal grid is that the power lines used are related to costs (see fig. 3.13).

![Figure 3.13: The use of switches incurs costs](image)

### 3.6.2 DC OPF

The DC OPF constraints comprise the power flow between two nodes (3.6.3), angle setting at slack node, Kirchhoff’s first law, power consumption and the capacity of the slack node and the power lines. The
first four are equality constraints (3.25) and the last two inequality constraints (3.26).

\[ P_{mn} + \frac{\theta_m - \theta_n}{\theta_1} = 0 \] power flow between two nodes
\[ P_m - \sum_{n \in N \setminus m} P_{mn} = 0 \] Kirchhoff’s first law
\[ (P^l_m - P^p_m) - \eta_m \cdot P^d_m = 0 \] power consumption

and

\[ P_S \leq \frac{P_S}{P_{mn}} \leq \frac{P_S}{P_{mn}} \] Slack power limits
\[ P_{mn} \leq P_{mn} \leq P_{mn} \] Power capacity (3.26)

3.6.3 Extension of the OPF Formulation

In the following, the DC OPF formulation is extended to find an optimal grid topology. All constraints are depicted as inequality constraints and only as “less than or equal to” following the syntax of cplexmilp.

Effect of a switch on the power flow constraints

The switches mentioned above are introduced in the power flow constraints which define the upper and lower line capacity:

\[ P_{mn} + s_{mn} \cdot P_{mn} \leq P_{mn} \]
\[ -P_{mn} - s_{mn} \cdot P_{mn} \leq P_{mn} \] (3.27)

Example with closed switch

When the switch is closed, i.e. \( s_{mn} = 0 \), equation 3.27 yields:

\[ P_{mn} + 0 \cdot P_{mn} \leq P_{mn} \]
\[ -P_{mn} - 0 \cdot P_{mn} \leq P_{mn} \] (3.28)
3.6. Mixed-Integer Linear Programming

which results in:

\[
P_{mn} \leq P_{mn} \\
-P_{mn} \leq P_{mn}
\]

(3.29)

Therefore, power flow occurs within the upper and lower limits.

**Example with open switch**

When the switch is open, i.e. \(s_{mn} = 1\), (3.27) yields:

\[
P_{mn} + 1 \cdot P_{mn} \leq P_{mn} \\
-P_{mn} - 1 \cdot P_{mn} \leq P_{mn}
\]

(3.30)

which results in:

\[
P_{mn} \leq 0 \\
-P_{mn} \leq 0
\]

(3.31)

The power flow must thus be zero, i.e. the desired effect of an open switch is achieved.

**Effect of a switch on the power flow equations**

In the power flow calculation (3.25) the switch indicator variable must also be considered. Otherwise infeasible or invalid solutions might occur. The DC power flow is usually formulated as:

\[
P_{mn} + \frac{\theta_m - \theta_n}{X_{mn}} \leq 0 \\
-P_{mn} + \frac{\theta_m - \theta_n}{X_{mn}} \leq 0
\]

(3.25)

It leads to infeasible problem statements as this simple example shows:

**Example with open switch**

When the switch is open \(s_{mn} = 1\) the power flow is \(P_{mn} = 0\):

\[
P_{mn} + \frac{\theta_m - \theta_n}{X_{mn}} \leq 0 \\
-P_{mn} + \frac{\theta_m - \theta_n}{X_{mn}} \leq 0
\]
\[
\frac{\theta_m - \theta_n}{X_{mn}} \leq 0 \\
- \left( \frac{\theta_m - \theta_n}{X_{mn}} \right) \leq 0 \tag{3.32}
\]

(3.32) results in the constraint:

\[
\theta_m \leq \theta_n \\
\theta_n \leq \theta_m \tag{3.33}
\]

which is \(\theta_m = \theta_n\). It states an invalid power flow constraint as the angle of two nodes is not required to be equal when there is no short-circuit and especially when two nodes are isolated from each other. Obviously, this is the case when a switch is open. Therefore, the formulation (3.25) leads to an infeasible problem.

**Introduction of a switch**

As a result of the discovered problem, a switch is required in the power flow equations as well. It has to ensure that the power flow equations are correctly formulated when a switch is closed or open. This is achieved by the introduction of the switch indication variable \(s_{mn}\) and a correction variable denoted by \(M_{mn}\).

\[
P_{mn} + \frac{\theta_m - \theta_n + s_{mn} \cdot M_{mn}}{X_{mn}} \leq 0 \\
- \left( P_{mn} + \frac{\theta_m - \theta_n - s_{mn} \cdot M_{mn}}{X_{mn}} \right) \leq 0 \tag{3.34}
\]

The switch indication variable in combination with the correction variable prevents the invalid constraint demonstrated in (3.33). This is shown in the following example:

**Example with closed switch**

When the switch is closed, i.e. \(s_{mn} = 0\), (3.34) corresponds to the ordinary DC OPF (3.25) and yields:

\[
P_{mn} + \frac{\theta_m - \theta_n + 0 \cdot M_{mn}}{X_{mn}} \leq 0 \\
- \left( P_{mn} + \frac{\theta_m - \theta_n - 0 \cdot M_{mn}}{X_{mn}} \right) \leq 0
\]
3.6. Mixed-Integer Linear Programming

It results in:

\[
P_{mn} + \frac{\theta_m - \theta_n}{X_{mn}} \leq 0 \\
-\left( P_{mn} + \frac{\theta_m - \theta_n}{X_{mn}} \right) \leq 0
\]

Therefore, the power flow equation equals the ordinary power flow (3.25). The condition of a closed switch is hence correct.

**Example with open switch**

When the switch is open, i.e. \( s_{mn} = 1 \), (3.34) yields:

\[
P_{mn} + \frac{\theta_m - \theta_n + 1 \cdot M_{mn}}{X_{mn}} \leq 0 \\
-\left( P_{mn} + \frac{\theta_m - \theta_n - 1 \cdot M_{mn}}{X_{mn}} \right) \leq 0 \quad (3.35)
\]

\[
P_{mn} + \frac{\theta_m - \theta_n + M_{mn}}{X_{mn}} \leq 0 \\
-\left( P_{mn} + \frac{\theta_m - \theta_n - M_{mn}}{X_{mn}} \right) \leq 0 \quad (3.36)
\]

As \( P_{mn} = 0 \)

\[
\frac{\theta_m - \theta_n + M_{mn}}{X_{mn}} \leq 0 \\
-\left( \frac{\theta_m - \theta_n - M_{mn}}{X_{mn}} \right) \leq 0 \quad (3.37)
\]

(3.32) results in the constraint:

\[
\theta_m - \theta_n \leq M_{mn} \\
-M_{mn} \leq \theta_m - \theta_n \quad (3.38)
\]

Therefore, the angles \( \theta_m \) and \( \theta_n \) do not equal as it was the case in (3.33). The resulting formula is \( \theta_m - \theta_n = M_{mn} \). Therefore, they are independent from each other. The switch is also open in the power flow formulation and the power flow is calculated correctly.
### 3.6.4 Objective Function

The objective of the MILP is to minimize the grid costs as in the previous two search methods. It is assumed as in section 3.5.3 that the costs denoted by $\pi$ are linearly dependent on the cable length. The minimization has the objective to reduce the fully meshed grid in order to obtain the grid with minimal line costs. Therefore, a constant term which represents the fully meshed grid is formulated and all unused power lines are subtracted.

$$f(s_{mn}) = \sum_{i=1}^{n} \sum_{n>m} \pi \cdot (l_{mn} - l_{mn} \cdot s_{mn})$$  \hspace{1cm} (3.39)

It is a convex function and can hence be solved by cplexmilp.

### 3.6.5 Optimization

The complete formulation of the MILP is:

Minimize:

$$f(s_{mn}) = \sum_{i=1}^{n} \sum_{n>m} \pi \cdot (l_{mn} - l_{mn} \cdot s_{mn})$$  \hspace{1cm} (3.39)

subject to

$$\begin{align*}
(P_{m}^l - P_{m}^p) &= \eta_{m} \cdot P_{m}^d & \forall m \in \mathcal{N} \\
P_{m} - \sum_{n \in \mathcal{N} \setminus m} P_{mn} &= 0 & P_{in} \\
\theta_1 &= 0
\end{align*}$$  \hspace{1cm} (3.40)

and

$$\begin{align*}
P_S \leq & \quad P_{mn} + \frac{\theta_{m} - \theta_{n} + s_{mn} \cdot M_{mn}}{X_{mn}} \leq P_{mn} \\
& - \left( P_{mn} + \frac{\theta_{m} - \theta_{n} - s_{mn} \cdot M_{mn}}{X_{mn}} \right) \leq 0 \leq P_S \\
& - P_{mn} - s_{mn} \cdot P_{mn} \leq -P_{mn} \leq P_{mn}
\end{align*}$$  \hspace{1cm} (3.41)
3.7 Heuristic Optimization

The third investigated search method is a heuristic optimization. This category of search algorithm is often chosen for computational intensive calculations and is typically nature inspired [38]. The main difference compared to the complete search and MILP is that it cannot be proven that the optimal solution is found. In [39], this fact is stated as an advantage as a set of solution can be found which all might be good. Fig. 3.14 shows the concept of a heuristic optimization.

![Concept of heuristic optimization](image)

Figure 3.14: Concept of heuristic optimization: from the solution found the optimal is chosen.

3.7.1 Comparison of Various Methods

Several heuristic optimization techniques have been investigated and two families of algorithms are primarily used today [40]: evolutionary computing and swarm intelligence. The first models biological evolution and four different categories have been developed since the 1950s: evolutionary programming, genetic algorithm, evolution strategies and genetic programming. In grid planning, examples can be found in [39, 41–45]. Swarm intelligence is by comparison a newer field which has started in the 1980s. The collective behavior of insects such as ants, bees and others were identified as a promising method to solve optimization problems. In [46–48], the ant colony search (ACS) has been chosen for the grid planning. In [49], the ACS is applied to solve the traveling salesman problem (TSP). Since the problem of finding an optimal grid with loops is similar to the TSP, the ACS has been chosen in this thesis as the third approach. As stated in the introduction, the objective of the thesis is to solve the optimization problem and not specifically to develop the most efficient algorithm. Therefore, solutions which require less computational time might exist.
3.7.2 Concept of ACS

The ACS mimics the method ants use to search for food [49]. It is impressive that such small insects which are almost blind are able to find a path with a high efficiency. The trick of the ants is to communicate with pheromone trails: ants are able to mark a trail with pheromone and to detect it later. The probability of an ant to chose a path depends on the laid pheromone trail. The higher the density is the more likely a path is chosen. The advantage of this method is that a short path is more visited which increases the pheromone density. When time passes, the pheromones evaporate which make longer paths even less attractive. However, the probability to chose a path never drops to zero. This leaves a way open to search for even more efficient paths. The ACS models agents with a similar behavior, e.g. the ability to mark and to detect a pheromone trail. A taboo list can be introduced to restrict the agents to find only feasible solutions.

3.7.3 Formulation for Optimal Grid Search

The ACS is conducted to find feasible grid topologies. The topology is constructed with several iterations: for each customer, the ants have to decide which connections to other nodes should exist. The algorithm starts with customer \( C_A \in \mathcal{C} \) where \( \mathcal{C} \) is the set of nodes containing all customers:

\[
\mathcal{C} = [C_A, C_B, \ldots, C_{|\mathcal{C}|}] \quad (3.42)
\]

Therefore, the ants require connection options for every customer. This list looks different for every customer. One reason is to prevent that a customer is connected to itself. By contrast, every customer has the option to connect to the substation. For a grid with \(|\mathcal{C}| + 1\) nodes, \(|\mathcal{C}|\) paths exist for each customer. All information is inherently stored in the the pheromone trail \( t \). It represents all possible connections an ant can have to connect customer \( C \in \mathcal{C} \) with another node and the current pheromone density \( \tau_i \in \{\tau_{\text{min}}, \tau_{\text{max}}\} \). The limits \( \tau_{\text{min}} \) and \( \tau_{\text{max}} \) prevent that \( \tau_i \) becomes lower or higher than a predefined value. This ensures that all nodes can be visited. An example of a pheromone trial for customer A is shown (3.43).

\[
t_A = [\tau_{\text{sub}}, \tau_B, \ldots, \tau_{|\mathcal{C}|}] \quad (3.43)
\]
Fig. 3.15 visualises the pheromone trail for customer A.

Figure 3.15: Choices of an ant from customer’s A point of view. The length between two dots determines the probability of choosing a node.

The ACS consists of a colony as the name says. This means the number of ants \(|A|\) is limited. Once every ant of the colony has looked for a path, an iteration of the search is finished. At this point, the pheromone trail is updated with the chosen paths and the pheromone tail of the previous iteration \(k\) partially evaporates. The chosen paths are contained in the vector \(\Delta t_{A,k}\) and the evaporation rate is denote by \(\rho \in \{0, 1\}\). An example how the update is conducted for all customers is shown with customer \(C_A\) (3.44).

\[
t_{k+1,A} = \rho \cdot t_{k,A} + \Delta t_{k,A} \tag{3.44}
\]

The vector \(\Delta t\) is built according to the chosen connection. The elements are length dependent in order to prioritize short distances. The distance from other nodes to customer A define the line length \(L_{An}\) which can be adjusted with the constant \(Q\). An example for customer A is shown in (3.45).

\[
\Delta t_{A,k} = \begin{cases} 
\frac{Q}{L_{An}} & \text{if a path to a node } n \text{ is used} \\
0 & \text{otherwise}
\end{cases} \tag{3.45}
\]

The ant can choose more than one connection, i.e. a meshed grid is allowed. Once the choices are completed for customer A, it is already
determined which nodes are connected to customer A and which are not. The taboo list (paths not chosen or path to itself) is accordingly updated and reduces the choice of a connection of the remaining customers. Similarly, the connections list contains the information, which connections must exist (chosen by ant). These mandatory connections still remain in the choices an ant has. Only this enables the situation that a customer has only a single connection to another node (customer or substation). Both lists must be considered during the ACS and help to reduce the run time of the algorithm. As a result, an iteration with $|C|$ repetitions must be conducted for one search: for each customer the connection to another node or other nodes must be found. The constraint is that the taboo and mandatory connection list are considered. Once a path has been chosen for each customer by an ant, the resulting topology is further processed. The following example shows one iteration of the ACS with choices which might occur.

**Example of ACS on a five node system**

In the example shown in fig. 3.16, the steps taken by one ant are described for a system with one substation and four customers. The algorithm starts with customer A and ends with customer D. The blue arrow depicts a path chosen. The black, red and green lines indicate a path which can be chosen, which is on the taboo list and which is mandatory, respectively. The length of a pheromone trail segment reflects the probability that the corresponding connection is chosen. In this example, the connection probability distributions ($\tau_A - \tau_D$) are for all customers equal. In reality, this is usually not the case and the probabilities vary for each customer. For example, the long segment indicating a high probability for a connection to customer D is not useful for the connection of customer D itself as this segment is on the taboo list (a connection to itself is prohibited as indicated with the red line in $\tau_D$).

For customer A, the ant has the possibility to connect to all nodes except from itself (see red line in $\tau_A$). In this example, the ant chooses a connection to the substation and customer B. As a result, the connection to customer A is mandatory which is indicated with the green line in $\tau_B$. Despite the fact that customer A and B must be connected, the ant can choose not to be connected to A. This will not change the mandatory connection of customer A and B in $\tau_B$. The possibility to
again choose the connection to customer A is important because then customer B can be also only connected with a single feeder. Otherwise, only meshed grids will be provided. In this case, customer B is not connected with a single feeder only to customer A but meshed with a connection to customer D. The choices for customer C are now limited (see $\tau_C$). A connection to customers A and B is not possible as they are on the taboo list (red lines in $\tau_C$). Only a connection to the substation or customer D remains for customer C and the latter is chosen. For customer D, the ant must have a connection to customer B and C. By contrast, a connection to customer A is excluded as well as a connection to itself (see $\tau_D$). In this case, the ant chose a connection to customer C. As a result, customer D is connected to customers B and C and no additional node is added.

![Figure 3.16: Example of ACS for a five node system. The black, dashed arrow indicates a possible choice which has not been chosen in this example. The blue arrow indicates the chosen connection. The bold, black line depicts a possible choice, the red line a choice on the taboo list and the green line a choice, which is already chosen in a previous step.](image)

As mentioned above, the probability that a path is chosen is dependent on the pheromone density and the distance to other nodes ($d_{mn}$). The first factor has already been discussed. The second factor is considered with the visibility $\eta_{mn} = 1/d_{mn}$. For a customer, all distances to other nodes are contained in vector $v = \{\eta_{A,sub}, \eta_{A,B}, \cdots\}$. As a result, the probability for a connection to be chosen is the product of
elements of vectors $t_{k,A}$ and $v$ where $k$ denotes ant $k$. As an example, the probability for customer A to connect to customer B is hence:

$$p_{k,AB} = \frac{[\tau_{k,B}]^\alpha \cdot [\eta_B]^\beta}{\sum_{n=1}^{[\tau_{k,n}]^\alpha \cdot [\eta_n]^\beta}}$$

(3.46)

The parameters $\alpha$ and $\beta$ influence the importance of the pheromone trail and the visibility, respectively. The probability for customer A to connect to customer B is obtained by the division of the resulting pheromone which leads to B (nominator) with the sum of the pheromone which lead to all nodes (denominator). When there are four nodes, the possible connections comprise the substation, customer B and customer C.

A solution to accelerate the efficiency of the ACS is to reformulate (3.46). In order to find a radial grid, the probability of choosing a path should include the information of the radial grid with minimal line length. As mentioned above, this information can be efficiently obtained by a heuristics. The suggested adjusted formula includes the previous knowledge factor $\kappa$:

$$p_{k,AB} = \frac{\delta ([\tau_{k,B}]^\alpha \cdot [\eta_B]^\beta) + \gamma [\kappa_{k,B,rad}] + \gamma [\kappa_{k,n,rad}]}{\sum_{n=1}^{[\tau_{k,n}]^\alpha \cdot [\eta_n]^\beta}}$$

(3.47)

The factors $\gamma$ and $\delta$ determine the weight of the radial solution and the general ACS formulation on the probability of choosing a path.

Another version, where the pheromone trail indicating the radial path is formulated in the fashion of the other two factors.

$$p_{k,AB} = \frac{([\tau_{k,B}]^\alpha \cdot [\eta_B]^\beta \cdot [\kappa_{k,B,rad}]\gamma)}{\sum_{n=1}^{[\tau_{k,n}]^\alpha \cdot [\eta_n]^\beta \cdot [\kappa_{k,B,rad}]\gamma}}$$

(3.48)

The TSP formulation can be ignored and the radial path prioritized if $\alpha = \beta = 0$. 
For meshed grid, a general formulation can be made. If the location of the optimal solution is assumed, e.g., with a visual inspection, the connections can be implemented in the algorithm by using the previous knowledge factor $\kappa$:

$$p_{k,AB} = \frac{\delta([\tau_{k,B}]^\alpha \cdot [\eta_B]^\beta) + \gamma[\kappa_{k,B,meshed}]}{\sum_{n=1}^{[\tau_{k,A}]} \delta ([\tau_{k,n}]^\alpha \cdot [\eta_n]^\beta) + \gamma[\kappa_{k,n,meshed}]} \quad (3.49)$$

Also in this case, a second version can be formulated analogously to (3.48):

$$p_{k,AB} = \frac{[\tau_{k,B}]^\alpha \cdot [\eta_B]^\beta \cdot [\kappa_{k,B,meshed}]^\gamma}{\sum_{n=1}^{[\tau_{k,A}]} [\tau_{k,n}]^\alpha \cdot [\eta_n]^\beta \cdot [\kappa_{k,B,meshed}]^\gamma} \quad (3.50)$$

In the program, all customers are implemented as agents containing several parameters. For each customer, its coordinates, the current pheromone trail, the suggested pheromone trail (\(3.47\) or \(3.49\)), the newly chosen path, the consumption, name, and the vector with its visibility are organized in a struct.

### 3.7.4 Constraints

The constraints are examined as follows: first, it is checked whether the found topology is configured that all customers have a direct or indirect connection to the substation. If this is not the case, the solution is rejected. If the topology passed the first test, a power flow is conducted to check whether the physical limits are violated. Also at this point the solution is rejected if limits are exceed. When also the second test is successfully passed, the costs of the topology are determined applying the objective function. The result is compared to the previously found optimum. If the new result is closer to the optimal result than the old value, the old value is replaced by the newly found topology. Furthermore, the number of repeated result is set to zero and the pheromone trail updated.

The power flow analysis is conducted with BFS or Matpower [50]. The BFS is extended to calculated also meshed grid [32, 33]. Matpower is chosen when the grid is strongly meshed and the BFS fails to converge. In this case, the power flow is calculated applying Newton’s method.
3.7.5 Objective Function

The topologies are evaluated according the cable costs. Therefore, the same objective function is used as discussed in 3.5.3. For every solution found, (3.22) is calculated:

\[ f(L) = L \cdot \pi, \quad L \in \mathcal{L} \]  \hspace{1cm} (3.22)

3.7.6 Termination of ACS

The ACS is terminated when one out of two conditions is fulfilled. The first is when a maximal number of iterations is conducted and the second when the algorithm fails to find a better solution for a predefined number of times. As mentioned above, an iteration comprises the search of the whole ant colony. A maximal number prevents an infinite search and it indicates that an optimal solution is not found. The second condition is more favorable. If the ant colony fails to find a better solution it indicates that an optimum is found. However, the solution might be a local optimum and not the global. Every time, a better solution is found, the variable counting the number of repetition is reset to zero.

The ACS can be accelerated if soft constraints concerning evaluation of the optimal result are applied. As mentioned above, every result is compared to the previously found optimum. If the new result is closer to the optimal result, the old value is replaced by the new topology and the number of repeated result is set to zero and the pheromone trail updated. However, if the new value is close to the previously found optimum, i.e. within a predefined tolerance, the repeated result variable is not set to zero. As a result, the termination condition is reached more quickly.
Chapter 4

Application of Optimization Algorithms

The three optimization methods (complete search, MILP, ACS) are applied in case studies and discussed. The solution, computational time and individual parameters are analysed. The evaluation shows that only the MILP and the heuristic optimization are able to find a solution within a time frame of several hours.

4.1 Comparison of Search Methods

An evaluation of the three search methods is conducted to reveal the most appropriate method for the final case studies. The investigation compares the results, the computational time and discusses the topology search problem. The same electric parameters are used for all studies (table 4.1) and the location of the customers is chosen according to section 2.4.3 on page 31. For all three methods, the optimal topology costs should be equal or within a predefined tolerance. The topology itself can differ provided that the costs are minimal. An impact on the costs is expected from the two metric (Euclidian (2.6) and Manhattan (2.7)). The required individual parameters of all methods are identified and discussed.

The parameters of the three search methods describe or influence the speed of the algorithm. They are different for the complete search, the
MILP and the ACS. For the complete search, the size of the incidence matrix is shown. For the MILP the required number of variables and computational times are shown. For ACS, all parameters and the number of iterations are investigated.

### Table 4.1: Parameters used in the simulation (1$ = 1CHF)

<table>
<thead>
<tr>
<th>Input Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ [Failure per km and year]</td>
<td>0.0042</td>
</tr>
<tr>
<td>C [$ per m]</td>
<td>200</td>
</tr>
<tr>
<td>Nominal Voltage [V]</td>
<td>22000</td>
</tr>
<tr>
<td>Cable type</td>
<td>3*150H</td>
</tr>
<tr>
<td>$I_{max}$ per Cable [A]</td>
<td>300</td>
</tr>
</tbody>
</table>

## 4.2 Four Node System

In this case study, a system with four nodes is investigated. It consists of a substation and three customers. The substation ”Katz” is placed at node 1 which acts as the slack node. Node 2, 3 and 4 contain customer A, B and C, respectively (see section 2.4.3). There are six connections and 42 topologies possible in this system (3.18). In this case, all physical limits can be kept within the boundaries. Therefore, the power flow analysis does not restrict the search. As the objective is to minimize the cable length, the solution must be radial. The optimal solution for both metrics is depicted in fig. 4.1. The costs are kCHF 280 for a direct connection and kCHF 387 for the Manhattan metric (dashed lines). It can be observed that the costs, when following street routes, can be expected to be closer to the direct connection.

### 4.2.1 Complete Search

The complete search provided the results for the four node system within a time frame of less than 0.1. The range can be explained with computer processes which are running in the background. As discussed in section
3.5 on page 51, the complete search is formulated to find a radial grid and can be extended to find also weakly meshed grids.

Figure 4.1: Optimal solution for a four node system. An Euclidean (dashed lines) and a Manhattan metric are shown.

4.2.2 MILP

The number of variables and constraints required for the formulation of the MILP are already considerable for the four node problem. 21 variables denoted by $W_1$ and 42 constraints are needed ($W_2$). The variables describe the capacity of the slack node, the demand of the four nodes, the six power lines, the four angles and the six switch indicator variables. The constraints comprise the demand at the four nodes, the capacity and angle of the slack node, the four equations for fulfilling Kirchhoff’s first law, the six required power flow equations and six equations which define the line capacity (see section 3.6.5 on page 62). Table 4.2 shows the relevant parameter numbers.

The computational time is 0.2497 seconds and hence comparable to the
complete search.

Table 4.2: Number of parameters required in a four node system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Number of parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>V(G)</td>
</tr>
<tr>
<td>$</td>
<td>E(G_c)</td>
</tr>
<tr>
<td>$</td>
<td>W_1</td>
</tr>
<tr>
<td>$</td>
<td>W_2</td>
</tr>
</tbody>
</table>

4.2.3 ACS

The ACS requires various input variables which can be freely chosen (see section 3.7). An overview of the used parameters is shown in table 4.3.

Table 4.3: ACS input values for a four node system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Number of parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximal repeated results</td>
<td>18</td>
</tr>
<tr>
<td>maximal iterations</td>
<td>$10^6$</td>
</tr>
<tr>
<td>ants</td>
<td>20</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.9</td>
</tr>
<tr>
<td>$\tau_{min}$</td>
<td>0.2</td>
</tr>
<tr>
<td>$\tau_{max}$</td>
<td>2</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.9</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.65</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.065</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>1</td>
</tr>
<tr>
<td>$\delta$</td>
<td>0</td>
</tr>
<tr>
<td>Tolerance [kCHF]</td>
<td>50</td>
</tr>
</tbody>
</table>

The parameters maximal repeated results and maximal iterations de-
4.2. Four Node System
termin the time the ACS has to find a solution, whereas the remaining have an impact on the search performance. The higher the limits of the first two parameters are, the more attempts are made to find a better solution. Given enough time, the ACS should be able to find the optimal solution. The other parameters can accelerate the search if appropriately chosen.

Fig. 4.2: Performance example of ACS for a four node system. The red circles indicate a solution found by the ACS. The local optimum is depicted by the blue line. Many solutions for a local optimum are found.

Fig. 4.2 shows the performance of the ACS when (3.46) is applied. This means that the search is conducted with the TSP formulation. The blue line depicts the progress of finding a new result which is closer to the optimum compared to the previous results and the red circles the costs found after a search. If the ants succeeded to find a better solution, the number of repeated results is reset to zero. In this example, the ants can try about 60 times to improve the result (iteration 16-72). The optimal result (kCHF 280) was found 9 times whereas a local optimum (kCHF 375) was found even more often. The value of kCHF 370 was the local optimum for about 12 iterations. The next better found value is already the optimum result which is confirmed the required 60 times. It can be concluded that this number is too high and reduces the search performance unnecessarily. Most likely, 15 repeated result will lead to the optimum which in fact can be confirmed by conducting several searches. However, it is also possible that the ACS fails to find the
optimum. One example of an suboptimal topology is shown in fig. 4.3. The resulting costs of kCHF 375 are about 50% higher than the costs of the optimal solution and the computational time could be reduced from 0.3 seconds to 0.1243 seconds which is significant.

Figure 4.3: Example of a suboptimal solution of ACS for a four node system when result is only 15 times confirmed. Costs are about kCHF 100 higher.

Interesting values are the pheromone trails which determine the probability that a customer is connected to another specific customer. When the ACS starts \((k = 1)\), \(\tau_{An}\) is 1 for all \(n\) choices which results in a probability of choosing connection for A \([p_{1, ASub}, p_{1, AB}, p_{1, AC}] = [0.1627, 0.4557, 0.3816]\), for B \([0.2084, 0.4859, 0.3057]\) and for C \([0.1868, 0.4644, 0.3488]\). The distance to the other nodes is the only influence as there is no history of previous searches yet. Therefore, the following connections are the most probable: customer A connected to B and C, customer B to A and C and customer C to A and B. As formulated in (3.46), the shortest distances lead to the most probable connection. The total probability per customer is as required 1 \(\left(p_{1, ASub} + p_{1, AB} + p_{1, AC} = 1\right)\).

When the ACS terminates, the final pheromone trails are in this example for A \([4.4, 9.9, 6.4]\), for B \([5.4, 8.4, 5.4]\) and for C \([5.4, 5.4, 3.4]\) and result in a probability of choosing for A \([p_{30, ASub}, p_{30, AB}, p_{30, AC}] = \)
4.2. Four Node System

[0.2178, 0.4653, 0.3168], B [0.2813, 0.4375, 0.2813] and for C [0.3803, 0.3803, 0.2394] that customers are connected. The values can be different for other searches as they are based on probability.

The most likely configuration is that the three customers are connected to each other without a connection to the substation. When the ACS terminates, the probability is slightly adjusted towards the optimal solution. However, it is still not found often compared to other results as shown in fig. 4.3. Already this simple example shows that the TSP is only partially comparable to a problem where a radial grid has to be found. As discussed in section 3.3.1, efficient heuristics exist which are able to efficiently find an optimal radial where no physical limits are violated.

The ACS (3.46) is formulated to find an efficient solution of the TSP (see section 3.7 page 68). As mentioned in the same section, additional information concerning the optimal topology can be integrated in (3.47) or (3.46) and used to accelerate the search. Obviously, it is senseless to use the optimal radial grid to eventually find the same optimal radial with ACS. However, the radial grid can be a reasonable start to find a meshed grid.

4.2.4 Discussion

All three search algorithms succeeded to find the optimal solution within a short time frame. In this case, all physical limits can be kept within the boundaries. As the objective is to minimize the cable length the solution must be radial. Table 4.4 shows the computational time of all methods. For this problem, a heuristic as discussed in section 3.3.1 is more appropriate to find a solution.

<table>
<thead>
<tr>
<th>Method</th>
<th>Computational time [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete Search</td>
<td>0.1</td>
</tr>
<tr>
<td>MILP</td>
<td>0.2497</td>
</tr>
<tr>
<td>ACS</td>
<td>0.1243</td>
</tr>
</tbody>
</table>
Chapter 4. Application of Optimization Algorithms

The elapsed time and the solution obtained by the ACS depends strongly on parameters whereas the complete search method and MILP always find the optimum for a four node system.

4.3 Ten Node System

For this case study, a more complex system with a total of ten nodes is investigated. The additional six nodes compared to the previous section result in a total of 45 possible power lines and $3.5184 \cdot 10^{13}$ possible topologies. Fig. 3.5 on page 48 depicts the number of topologies depending on the number of used power lines. The optimal solution obtained by the MILP if no physical limits are violated is depicted in fig. 4.4 by the blue lines. This time, only the Euclidean metric is shown. The red line indicates a topology close to the optimum where instead of a connection of customer F and I a connection between G and I is chosen. This results in a slightly longer total cable length.

4.3.1 Complete Search and MILP

The complete search and the MILP have varying degrees of success in this case study. The investigation with the complete search method was aborted after two hours. It is concluded that this method is not appropriate for finding the result as the problem is too complex. The MILP has shown to efficiently find a solution also in this case. It was found within a time frame of 0.99051 and 2.2634 seconds.

4.3.2 ACS

The ACS shows considerable differences of the performances. The previous knowledge has, as expected, a large impact. Without previous knowledge, the search is extremely slow. When the formulation of the TSP is applied (3.46), the search failed to find a reasonable result within two hours. If only radial grids are allowed, the optimal grid could once be found within 115.7 seconds. The result is found immediately if the radial grid with minimal line length is used and (3.47) is used to calculate the choice probabilities. A condition is that $\gamma$ is bigger than $\delta$. 
4.3. Ten Node System

Figure 4.4: Optimal solution for a ten node system is depicted with the blue line (Euclidean metric). The red line indicates a solution conceived by an engineer. A connection between customers G and I is chosen instead of F and I. This topology can be used (previous knowledge factor $\kappa$) as a starting point for the search of the optimal solution.

otherwise, the information of the input topology might not be considered enough.

In a realistic scenario, a design engineer might conceive a grid topology which is close to the optimum. The question is if the ACS is still able to find the optimal solution and hence what the impact of the given information is when not optimal. As a simple example, the situation is chosen as depicted in fig 4.4 with the red dotted line. As mentioned above, the connection $GI$ is chosen instead of the optimal $FI$. The parameters used are listed in table 4.5 and the resulting performance in fig. 4.5.

With the chosen settings of the various ACS parameters, the result can be found within 26 seconds. The ACS finds the suboptimal solution of the engineer and other solutions more often than the actual optimal result. The number of iterations is eventually about 5300 and it took about 2000 iterations until the demanded number of repeated results
was reached. Per iteration, a maximum of 100 number of repeated results can be obtained (number of ants $|A| = 100$). However, this maximum is only the case when a valid solution is found and one which is less optimal than the previous found optimum.

### Table 4.5: ACS input values for a ten node system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Number of parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximal repeated results</td>
<td>$4.6 \cdot 10^3$</td>
</tr>
<tr>
<td>maximal iterations</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>ants</td>
<td>100</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.9</td>
</tr>
<tr>
<td>$\tau_{\text{min}}$</td>
<td>0.2</td>
</tr>
<tr>
<td>$\tau_{\text{max}}$</td>
<td>1</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.4</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.65</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.065</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>1</td>
</tr>
<tr>
<td>$\delta$</td>
<td>2.5</td>
</tr>
<tr>
<td>Tolerance [kCHF]</td>
<td>50</td>
</tr>
</tbody>
</table>

It is possible that with an another choice of the ACS parameters, the optimal solution can be found even more quickly. Nevertheless, the main objective to obtain the optimal result within a short time frame is fulfilled.

#### 4.3.3 Twenty One Nodes

The last case study comprises 20 customers with a supplying substation. The complete graph has 210 edges and Matlab yielded a warning that it is not able to calculated the resulting number of topologies. The estimate is $1.6455 \cdot 10^{63}$ topologies. As the complete search already failed to find a solution within a reasonable time frame for ten node system, it is not considered for this example. Only the MILP and ACS remain for solving the problem.
4.4 Conclusion

Additional tests by the author have revealed that from the three search algorithms, only the ACS is able to find a solution for a system with more than thirteen nodes. The complete search already fails to find a solution for a ten node system and the MILP requires more than two hours for a grid with 21 nodes. The ACS requires a good estimate of where the solution is in order to find a solution within less than two hours. If no previous knowledge exists, the ACS is also not able to provide reasonable results. Therefore, the main advantage of the ACS is that it can be accelerated with the input values of the engineer which designs a grid. The precondition is that a topology is given which is close to the optimum.

The MILP requires a total of 463 variables and 907 equations. Apparently, this problem is too extensive to be solved and the attempt to find a solution was aborted after several hours. For this problem, only the ACS is able to provide a solution within a time frame of two hours. The quality of the results depend strongly on the restriction if meshed grids are allowed or not. For radial grid, the performance is satisfying and a good result can be provided after roughly one hour.

Figure 4.5: Performance example of ACS for a ten node system. The red circles indicate a solution found by the ACS. The blue line depicts the local optimums found. The topology suggested by the engineer (fig. 4.4) is found more often than the optimal result.
Chapter 5

Reliability Analysis

This chapter discusses the reliability analysis, various assessment techniques and proposes a new method to plan a grid. Since conventionally installed components are used in the reserve grid and replaced regularly, a time independent reliability distribution is assumed. A difficulty to analyze the reliability of many different topologies is that the reliability assessment method must be programmed dynamically. Three different approaches are discussed which can solve the problem. This dynamic reliability assessment program allows a new method to plan the grid where reliability is a design parameter instead of an output parameter.

5.1 Probability Distribution in Reliability Evaluation

Typically, the reliability of a component changes during its life time. Three phases can be used to model this behaviour by applying different hazard rates denoted by $\lambda$. Phase one is the debugging or commissioning phase, phase two the useful life and phase three the abrasion [51]. Fig. 5.1 depicts the bathtub shape which describes the time dependent hazard rate. The debugging phase has a higher hazard rate compared to the useful life due to manufacturing errors or faulty installations. This can often lead to a quick failure of the component. However, the longer
the component is in use the lower the hazard rate becomes. At some point, it is quasi-constant for a long time period which corresponds to the useful life. Failures can still occur if e.g. third parties are damaging the components. Towards the end of the service life, the hazard increases. This is due to aging, e.g. aging of cable isolation.

Figure 5.1: Example of a time dependent hazard rate $\lambda$ ([51] modified)

In this thesis, the reliability of the used equipment is modeled for the normal operation of the system. This assumption is valid when a proper commissioning is conducted and components are replaced before the end of life time. Both can be expected for a reserve grid built, as it is an EPS. Therefore, the hazard rate is assumed to be constant which determines its distribution. In general, the hazard rate is found by examining the survivor function $R(t)$ which is also shown in fig. 5.1. The survivor function describes the probability that a component is operating successfully after a time $t$. The sum of the survivor function and the cumulative failure distribution $Q(t)$ must be one ($R(t) + Q(t) = 1$). The derivative of $Q(t)$ is known as the failure density function $f(t)$:

$$f(t) = \frac{dQ(t)}{dt} = -\frac{dR(t)}{dt}$$  \hspace{1cm} (5.1)

The survivor function can be found with:

$$R(t) = 1 - \int_0^t f(t)dt = \int_t^\infty f(t)dt$$  \hspace{1cm} (5.2)
The difference between the hazard rate and the failure rate is that the hazard rate only describes the time frame greater than \( t \). Therefore, it can be calculated with [51]:

\[
\lambda(t) = \frac{f(t)}{R(t)} = \frac{f(t)}{1 - R(t)} = - \frac{1}{R(t)} \cdot \frac{dR(t)}{dt} \quad (5.3)
\]

The relation between the survivor function and the hazard rate hence is (\( R(0) = 1 \)):

\[
\int_{1}^{R(t)} \frac{1}{R(t)} \cdot dR(t) = \int_{0}^{t} -\lambda(t) dt \quad (5.4)
\]

which is equivalent to:

\[
R(t) = exp \left( - \int_{0}^{t} \lambda(t) dt \right) \quad (5.5)
\]

When \( \lambda \) is a constant, (5.5) becomes:

\[
R(t) = e^{-\lambda t} \quad (5.6)
\]

Therefore, the reliability function with a constant hazard rate has an exponential distribution.

### 5.2 Reliability Evaluation in Electric System Planning

Reliability analysis in grid planning is often used to find a balance between costs and reliability. The objective of this tradeoff is that only the required grid reinforcements are conducted and the system reliability is increased without affecting the costs [44]. For the design of the reserve grid, the formulation of a tradeoff is not appropriate. As the reserve grid is an EPS and not a primary grid, the reliability requirements of the customers must be necessarily fulfilled.
5.3 Reliability Evaluation Techniques

As the objective of the reserve grid planning is to obtain a topology which meets the customers’ requirements, the needed reliability of each customer is an input value of the reserve grid design. This is a significant different approach than the normal grid planning and henceforth denoted as the *a priori* approach. The reason is that the reliability has an influence on the required redundancy. With the N-1 principle, the reliability is calculated after the topology design and is hence an *a posteriori* approach.

By applying the *a priori* approach, the topology is not given and hence the question is how to calculate the reliability for each customer efficiently. The manual calculation cannot be applied when thousands of topologies are tested. Therefore, a dynamic evaluation must be found. The solution to determine the reliability chosen here is the same approach as in section 3.6 on page 56 where the reliability function for a fully meshed grid is calculated and then reduced to construct the situation for the individual customer. This reduction is conducted for each customer in the grid.

5.3.1 Analytical Techniques for Complex Systems

The reliability analysis of power systems can be organised in two categories: simple or complex systems [51]. Simple systems consists only of seriell and parallel connections which can be easily calculated. A summary for simple system reliability analysis can be found in appendix E.5. By contrast, complex systems cannot be reduced to only seriell or parallel connection. A typical example are bridge-type systems which have a meshed configuration as shown in fig. 5.2. These kind of systems require more sophisticated algorithms to find a solution. Various techniques are capable to assess the reliability of a fully meshed system and three of them have been evaluated: the conditional probability method, a software solution and the tie set method.
5.3.2 Conditional Probability Method

In [52], a visual inspection of the system is discussed which results in an illustrative reliability assessment of a meshed grid. The goal is to simplify the meshed system to obtain subsystems consisting only of series and parallel connections. The subsystems occur under certain conditions and hence the conditional probability method can be applied. For a four node system as shown in fig. 3.1, the reliability for node 4 (customer C) is:

\[
 r_{C,4} = 1 - (1 - ((1 - Q_{12} Q_{13})(1 - Q_{24} Q_{34})R_{23} + (1 - (1 - R_{12} R_{24})(1 - R_{13} R_{34}))Q_{23}))Q_{14} \tag{5.7}
\]

where \( R_{mn} \) is the probability of success and \( Q_{mn} \) is the probability of failure for the line between node \( m \) and \( n \). This solution is complicated for a system with more than four nodes as it cannot be simply automated.

5.3.3 Software Solution

Another method to evaluate the reliability of a system is the application of a software solution also used in industry. In this thesis, BlockSim® has been tested which is a product of Reliasoft [53]. The reliability is computed by using a block diagram where each block represents a power line or a node. Fig. 5.3 shows as an example the required modelling for a four node system.

BlockSim provides an analytical calculation of the reliability of the system. A drawback of the program is that only unidirectional connections...
Figure 5.3: BlockSim model for a complete graph with four nodes. The reliability of the power lines are denoted by $R_{mn}$ and the reliability of the nodes by $R_i$.

are allowed. As a result, the same nodes and power lines must be drawn multiple times and identified as such. For a four node system, 15 blocks must be used in the BlockSim model to calculate the reliability of a completely meshed grid. The reliability of the system can be depicted as a symbolic or a numerical result. The symbolic equation can be copied and included in the program. Alternatively, it is possible to connect the BlockSim model to Matlab by an application programming interface (API). This method allows a dynamic use of the model, i.e. the parameters of the blocks can adjusted in a search algorithm.

The drawback of this method is that it requires a graphical programming of the grid and hence it cannot be simply automated. Already for a five node system, the BlockSim model is complex because more than 40 nodes are required.
5.3.4 Tie Set Method

Several methods exist to obtain the reliability equation of a complex system with a software [54–59]. The third method implemented in this thesis applies the tie set method. It is a complement of the cut set method [52]. When all minimal paths are found, the reliability can be easily calculated. As an illustrative example, the four node system shown in fig. 3.1 can be used. Node 1 is chosen as the starting node and node 4 as the end node. Five minimal paths exist which connect the start and the end node with each other: [1,4], [1,2,4], [1,3,4], [1,2,3,4] and [1,3,2,4].

One possibility to calculate all shortest paths is by employing Yen’s algorithm [60]. It is able to find all loopless shortest paths from node \( m \) to \( n \) in a given graph. It is a general solution and can be applied to any graph without negative edge costs. In a power grid, this condition is always fulfilled as negative costs for a power line do not exist. Alternatively, an algebraic method was implemented which exploits the symmetry of a fully meshed grid. The aim of the second method to calculate all shortest paths was to reduce the computational time.

The advantage of the tie set method compared with the other methods is that it can be programmed dynamically. It can also be easily combined with the complete search method and the ACS.

5.3.5 Application Example Reliability Equation

In this example, the reliability equation of a fully meshed four node system (5.7) is applied to the topology shown in fig. 5.4. The configuration could be obtained during the complete search or ACS. The individual position of the customers is considered by the three times repeated application of the reliability equation. The customer of interest is placed at node four, i.e. customers A, B and C are each once modeled as node four. In this example, customers A and B are directly connected to the substation and customer C is connected to customer B. The reliability of the customers is calculated by setting all reliability values of the power lines to zero except from the power line used. For customer A, only the reliability of the power line directly connecting him to the substation is nonzero (\( R_{Sub,A} \Rightarrow r_{A,4} = R_{14} = 1 - Q_{14} = e^{-l_{Sub,A} \cdot \lambda} \neq 0 \)) and analogously for customer B (\( R_{Sub,B} \Rightarrow r_{B,4} = R_{14} = e^{-l_{Sub,B} \cdot \lambda} \neq 0 \)). For
customer C, the calculation is more difficult as it connected to customer B and not directly to the substation. This means that also the power line connecting customer B with the substation must be considered ($R_{Sub,B} \Rightarrow R_{13} = e^{-l_{Sub,B} \cdot \lambda} \neq 0$ and ($R_{B,C} \Rightarrow R_{34} = e^{-l_{B,C} \cdot \lambda} \neq 0$)). The resulting reliability is $r_{C,A} = R_{13} \cdot R_{14} = e^{-l_{Sub,B} \cdot \lambda} \cdot e^{-l_{B,C} \cdot \lambda}$.

\[ \text{Slack} \quad \text{G} \quad \text{Substation} \quad \text{Customer A} \quad \text{Customer B} \quad \text{Customer C} \quad \text{Power line} \]

Figure 5.4: Topology example of four node system

## 5.4 Application on Reserve Grid

The planning of the grid can be conducted with the conventional \textit{a posteriori} or the new proposed \textit{a priori} approach. For both approaches, the reliability of power supply for each customer can be calculated with the reliability equation obtained by the tie set method. With the \textit{a posteriori} method, the reserve grid is similarly designed as the distribution grid and can hence be a radial or a meshed grid. Usually, the meshed MV grid is limited to N-1 security, i.e. one power line is redundant. For the \textit{a priori} approach, the required reliability values of each customer must be known and be used in the grid design. Since the requirements can differ, the resulting topologies can have another configuration than radial or N-1 secure.
5.4. Application on Reserve Grid

5.4.1 *a posteriori* Approach

The *a posteriori* is the normal approach where experience with power systems is used to design the grid. This subjective and qualitative assessment can result in a reliable grid. However, this does not quantify a precise reliability value which can be illustrated by the often applied N-1 security: medium voltage distribution systems are often built in rings to increase the reliability of supply. The advantage of rings is the ability to maintain the power supply even by the failure of one power line. Hence, an interruption of power supply can be prevented or the duration of the interruption shortened. The difficulty of this simple concept is to compare different topologies when all are fulfilling the N-1 criterion as the reliability for each customer can differ with each topology. Therefore, a discussion of various versions is required.

In the search algorithms, the N-1 security is ensured by the constraint that all nodes must have at least two connections (5.8). This is valid when the loss of a power line does not lead to an overload of the remaining power lines.

\[
\sum_{m=1}^{n} \sum_{n>m} s_{mn} \leq 2 \quad (5.8)
\]

For finding the grid topology with minimal costs while fulfilling a required redundancy, the search methods discussed in chapter 3 and the reliability assessment method must be merged. The suggested algorithm is depicted in fig. 5.5.

It starts with defining the required redundancy which can be N (radial), N-1 or any other redundancy. The value influences the constraint how many connections to a node must exist (5.8).

The next step is to find the grid topology with the minimal costs while fulfilling the required redundancy. All three searches discussed in chapter 3 can easily be extended with this constraint. For the complete search and the ACS it is an additional check which determines whether a found topology is valid. The MILP is extended with this additional inequality constraint. It will only find topologies with the required redundancy.

The final step is to calculate the reliability of each customer based on the optimal found grid topology. This is achieved by applying the sym-
metrical reliability equation obtained with the tie set method discussed in section 5.3.5. The reliability parameters must be chosen according to the found grid topology, i.e. unused power lines have a reliability of zero and used power lines according to the line length.

The reliability is a result depending on the required redundancy. The desires of the customers are not directly considered in the design and as mentioned above, the N-1 criterion does not precisely quantify the reliability of power supply for a customer. This is the approach applied in the MV grid which results in different reliability values for all customers. It is discriminating as customers closer to substations have a higher reliability of power supply compared to customers further away.

Figure 5.5: Flow chart of the \textit{a posteriori} approach. The reliability is an output of the algorithm.

5.4.2 \textit{a priori} Approach

With the \textit{a priori} approach, all customers can specify a minimal reliability which is denoted by $r_{c,min}$. This value is chosen by the customer
5.4. Application on Reserve Grid

according to their individual requirements and is an additional constraint in the grid topology search methods. The specific reliability of power supply of all customer is contained in $r_{c,\min}$:

$$r_{c,\min} \in \mathcal{R} = \{r_{1,\min}, r_{2,\min}, \ldots, r_{|C|,\min}\}$$

(5.9)

The individual reliability of power supply of each customer calculated for a grid topology is in $r_c$:

$$r_c \in \mathcal{R} = \{r_1, r_2, \ldots, r_{|C|}\}$$

(5.10)

The reliability requirement denoted by $R_R \in \{0, 1\}$ is fulfilled if for all customers $r_c$ is greater than $r_{c,\min}$:

$$R_R = \begin{cases} 
1 & \text{if } \forall r_c \in \mathcal{R}: r_c \geq r_{c,\min}, \\
0 & \text{otherwise} \end{cases}$$

(5.11)

Also for the a priori approach, the grid topology search methods must be extended to consider the additional constraints. In fig. 5.6, the flow chart of the extended ACS is depicted.

It starts with the available grid information, e.g. number of nodes, customer location etc. These values are the base of the search algorithm. The second step which initializes the search is the construction of the reliability equation of the fully meshed grid. Also in this case, the tie set method discussed in section 5.3.5 is applied.

In the next step, a grid topology is determined with the ACS. The methods discussed in section 3.7.3 on page 66 can be applied to calculate the probability of a customer to connect to another node. The probability can be based on the TSP formulation (3.46) or the formulation containing previous knowledge (3.49) or (3.50). This step has to be conducted for each customer.

When a grid topology is found, it has to be checked whether the physical limits are maintained. This is only the case when all customers are connected to the substation and hence supplied with power. Otherwise, the topology is rejected which means that the ant failed to find a valid solution. In this case, the search algorithm continues with the next ant or the next iteration if the stopping criterions are not met yet.
If the power flow constraints are fulfilled, the reliability constraints have to be investigated. This step is explained in more detail. For each customer, the reliability equation of the fully meshed grid must be applied to calculate its individual reliability of power supply. As discussed in the *a posteriori* approach, the unused power lines have a reliability of zero and the used power lines a length dependent reliability. If the grid topology results in an insufficient reliability power supply for any customer, the grid topology is discarded and the search of this ant stops.

Only one last step is missing before the search terminates. At this point, valid solutions have been found and it has to be checked whether one or both stopping criterions are fulfilled. This can be the maximal number of iterations or the maximal number of failed attempts to find a more optimal result.

The search algorithm might be accelerated if first it is investigated whether a radial topology can already fulfill the reliability requirements of the customers. As discussed in section 3.2, the number of radial grids is low compared to the number of meshed configurations.

### 5.4.3 Hierarchical Clustering

The problem of finding the optimal grid can be facilitated when hierarchical clustering is applied on the customer’s location. The search algorithms is first conducted based on the clusters and second within the clusters. In Matlab, three steps are required to obtain clusters \(^1\) [61]:

1. Calculate the distance between the customers’ locations.
2. Apply the linkage function based on the distance matrix from step 1 to create binary clusters.
3. Apply the cluster function with the output of the linkage function and a chosen inconsistent value.

For the situation in the city center shown in fig. 2.11 on page 30 the corresponding dendrogram is depicted in fig. 5.7. The node numbering corresponds to the customer identification letter in the alphabetic order (customer A is at node 1, etc.).

\(^1\)An introduction to hierarchical clustering can be found in appendix F
5.4. Application on Reserve Grid

In Matlab, the inconsistency is calculated based on the output matrix \( Z \) created by the linkage function. The result is the matrix \( Y \) which contains in the first column the mean heights of all the links, in the...
Chapter 5. Reliability Analysis

Figure 5.7: Dendrogram of clustering of customer’s location

second the standard deviation of the heights of the links, in the third the number of links and the inconsistency in the fourth and last column. Column three of $Z$ contains the distance between two clusters. The inconsistency is calculated for each link $k$ with (5.12).

$$Y(k, 4) = \frac{Z(k, 3) - Y(k, 1)}{Y(k, 2)}$$  \hspace{1cm} (5.12)

For the dendrogram shown in fig. 5.7, the inconsistency can be grouped to the following vector: $v_c = [0, 0.64, 0.71, 0.75, 1.1167]$. When clustering is generated with $v_c = 0.71$, a total of six clusters are built (black line fig. 5.7). For $v_c = 1.2$ only one cluster is generated. Fig. 5.8 depicts the six clusters for $v_c = 0.71$.

The connection point of a cluster can be determined by several approaches. A possibility is to find the centroid of the area, e.g. by adding the x and the y coordinates and dividing the result with number of customers (5.13).

$$\text{Coord}_{\text{centroid}}(x, y) = \frac{\sum_{n=1}^{\mid C \mid} \text{Coord}_n(x, y)}{\mid C \mid}$$ \hspace{1cm} (5.13)

Another possibility is to choose the customer with the highest load. Also possible is a mixture, i.e. weighting the coordinates with the maximal
5.4. Application on Reserve Grid

Figure 5.8: Hierarchical clustering of customer’s location

load (5.14). The coordinates of a customer are multiplied with the maximal load $L_{n,\text{max}}$ and divided by the number of customers ($|C|$) and the sum of all loads ($L_{\text{tot, max}}$).

$$Coord_{\text{centroid, load}}(x, y) = \frac{\sum_{n=1}^{\left|C_{n}\right|} Coord_{n}(x, y) \cdot L_{n,\text{max}}}{\left|C\right| \cdot L_{\text{tot, max}}} \quad (5.14)$$

The exact connections between the clusters can be obtained by applying a nearest neighbor approach [62]. For this algorithm, the connection of the clusters must be known which also ensures that the physical limits are maintained. The nearest neighbor algorithm starts at the primary substation Sempersteig and finds the nearest node in the nearest cluster. All clusters are connected applying this algorithm.

The total load per cluster (annual maximum of each customer) is $7.0792 \text{ MVA}$, $9.3425 \text{ MVA}$, $2.4444 \text{ MVA}$ and $0.2316 \text{ MVA}$, $4.2480 \text{ MVA}$ and $16.500 \text{ MVA}$. The actual reserve power is expected to be lower as usually
only parts of the electric distribution are connected to EPSs, e.g. via an emergency grid. Furthermore, it is optimistic to expect that all potential customers are ordering a connection to the reserve grid. If for example the reserve grid is planned for clusters 1,2,3,4 and 5, the supplying primary substation can be Sempersteig (Semp). Cluster 6 will not be chosen as it is already connected to Semp for the primary power supply. The potential total load is hence about 23 MVA. If half of the customers require a connection with a reserve power lower than the maximal load (e.g. half of the maximal load), the total load drops below the maximal loading of MV cables (10 MVA). As a result, one MV cable would be enough to supply all customers with power and additional cables are only installed to increase the redundancy. It can be concluded that no physical limits are violated since the overloading of cables was identified in section 2.2 on page 14 as the only limiting factor.

5.5 Discussion

Two different approaches are discussed in this chapter which are able to find an optimal grid topology. The a posteriori search is based on a pre-defined redundancy and the reliability of power supply is calculated for each customer after the grid topology is found. It is the approach typically used for the design of the primary grid. By contrast, the a priori approach is designed according to exact demanded reliability values defined by each customer. The redundancy is hence an output variable. The a priori approach is developed specifically for the requirement of the reserve grid customers.
Chapter 6

System Planning considering Reliability

In this chapter, case studies are presented for the topology search methods including reliability requirements. The a posteriori and a priori approaches are conducted and compared with each other. It is shown that significant cost savings are possible when the a priori approach is applied instead of the N-1 configuration.

6.1 Comparison of Search Approaches

The a posteriori and a priori search methods discussed in the last chapter are investigated for various scenarios. The impact of the two approaches on the topology and the costs illustrates the advantages and disadvantages. The resulting reliability is compared to the value required to obtain a reliability of 0.99999 which is $r_{EPS} > 0.6908$ (see section 2.4.1 on page 28). Analogously to chapter 4, the same electric parameters are used for all studies and the two metrics are applied. The a posteriori approach is conducted for radial and ring-shaped configurations. Both are common in MV grid design. The a priori investigation comprises reliability higher than provided by the radial grid with minimal line length. Eventually, the resulting reliability of the parallel connection of the primary and reserve grid is discussed. All studies are conducted with the ACS.
6.2 Four Node System

In this first case study, the same locations of the customers and the primary substation are chosen as in 4.2. As mentioned above, the radial and ring-shaped configurations are investigated. The results are used as a benchmark for the a priori approach. The reliability equation of the complete graph is shown in (5.7) on page 87. The total load is assumed to be 8 MVA, i.e. no power lines are overloaded.

6.2.1 Radial Grid Topology

The optimal solution of a radial topology obtained with the Euclidean metric is shown in fig. 6.1. The costs are kCHF 280 as discussed in 4.2 on page 72. It is the most economic version of a reserve grid with the given conditions. The reliability of power supply provided by the reserve grid customer A, B and C is 0.995484, 0.996540 and 0.994129, respectively. All values are higher than $r_{EPS} > 0.6908$ which corresponds to a reliability of power supply of 99.999%.

Figure 6.1: Radial topology of a four node system
6.2. Four Node System

6.2.2 N-1 Secure Topology

The optimal reserve grid topology of a N-1 secure grid is shown in fig. 6.2. The requirements are formulated using (5.7) on page 87, i.e. every node must have at least two connections. The resulting reliability of power supply provided by the N-1 secure reserve grid is for customer A, B and C 0.999972, 0.999975 and 0.999972, respectively. The total costs are kCHF 511.72 and almost double as high compared to the radial reserve grid discussed above.

![N-1 secure topology of a four node system](image)

Figure 6.2: N-1 secure topology of a four node system

6.2.3 a priori Approach

The a priori approach is investigated for the case that customer C requires a higher reliability of power supply compared to the value obtained with a radial connection ($r_{\text{rad},3} = 0.994129$). Two scenarios are
chosen: in the first scenario, only customer C requires a higher reliability than 0.6908 which is sufficient for a 99.999 % reliable power supply. The demanded reliability provided by the reserve grid is \( r_{3,min} = 0.995 \). The resulting vector containing all minimal reliability values is hence \( r_{c,min} = [0.6908, 0.6908, 0.995] \). The second scenario is the case when all customers obtain the same minimal reliability of power supply from the reserve grid which \( r_{c,min} = [0.995, 0.995, 0.995] \).

The optimal topology for the first scenario is depicted in fig. 6.3. The reliability of customers A, B and C is in this case 0.9938, 0.99274 and 0.99515. As wanted, the reliability of customer C is higher than 0.995. However, the reliability values of the other customers are slightly lower. Furthermore, by applying the Manhattan metric, this solution does not reach the required reliability. The costs are for the Euclidean metric kCHF 346.68 and hence about kCHF 60 higher compared to the radial grid and kCHF 165 lower than the N-1 configuration.

Figure 6.3: Example of \textit{a priori} approach with three customer. Reliability of customer C must be at least 0.995
The second scenario can be used as a comparison to the first scenario. The optimal reserve grid for this case is shown in fig. 6.4. The reliability of power supply provided by the reserve grid is for customer A, B and C 0.996536, 0.996540 and 0.996535, respectively. Therefore, it is higher than 0.995 for all customers. The costs are kCHF 376.92 which means they are 8.7\% higher than the costs obtained in the first scenario.

![Diagram of four node system with three customers.](image)

Figure 6.4: Example of \textit{a priori} approach with three customer. Reliability of all customers must be at least 0.995

### 6.2.4 Discussion

The four node system has been investigated for a radial, N-1 and two versions applying the \textit{a priori} approach. The results were obtained with the ACS and are listed in table 6.1. The computational time was for all cases less than 1 second.

The lowest and highest costs are obtained with the radial and N-1 configuration, respectively. Both belong to the \textit{a posteriori} approach which is mostly used in system planning. The N-1 secure grid has the benefit
that planned disconnection of the grid do not lead to an interruption of reserve power supply. By contrast, the other two results are calculated applying the *a priori* approach. Both scenarios have the goal to increase the reliability of power supply of customer C and have similar costs. In the second scenario, the reliability of power supply is higher for all customers. The cost savings compared to the N-1 secure grid are about 30%.

Table 6.1: Results of four node system and various planning approaches

<table>
<thead>
<tr>
<th>Planning approach</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>Costs [kCHF]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial</td>
<td>0.995484</td>
<td>0.996540</td>
<td>0.994129</td>
<td>280.31</td>
</tr>
<tr>
<td>N-1</td>
<td>0.999972</td>
<td>0.999975</td>
<td>0.999972</td>
<td>511.72</td>
</tr>
<tr>
<td>( R_{\text{min},3} = 0.995 )</td>
<td>0.993800</td>
<td>0.992740</td>
<td>0.995150</td>
<td>346.68</td>
</tr>
<tr>
<td>( R_{\text{min},1−3} = 0.995 )</td>
<td>0.996536</td>
<td>0.996540</td>
<td>0.996535</td>
<td>376.92</td>
</tr>
</tbody>
</table>

### 6.3 Clustering of Nineteen Node System

In this case study, the reserve grid for eighteen customers is investigated as discussed in section 2.4.3 on page 31. The example load of customers B, E, F, G, I, J, K, L, M, N, O, P, Q, R, S, T, U, V is depicted in fig. 2.12. The primary grid of all customers is supplied either from primary substation Katz or Zeughaus (Zeug). Therefore, the reserve grid can be fed by substation Sempersteig (Semp). Four clusters are built according to the hierarchical clustering method discussed in section 5.4.3 on page 94. The centroid has been chosen according to (5.13). The total load per cluster is 7.0792 MVA, 9.3425 MVA, 2.4444 MVA and 0.2316 MVA. The physical limits are usually not considered for reasons discussed in section 5.4.3 and it also facilitates the studies. The impact of reliability on grid topology is the only remaining factor which can result in additional required cables.
6.3. Clustering of Nineteen Node System

6.3.1 Radial Grid Topology

The minimal radial topology of the four clusters is the first study to be conducted and can be used as a benchmark for the other topology versions. It is also the base for the ACS which is applied in the N-1 and a priori method investigations and indicates the optimal grid to the ants. Figure 6.5 depicts the grid topology for the centroids of the clusters. The costs are kCHF 408.42. The reliability of the centroids 1, 2, 3 and 4 is $r_{c,\text{rad}} = [0.99733, 0.99531, 0.99344, 0.99333]$. The reliability is the lowest for centroids 3 and 4 because the distance to the substation is longest. The weakness of this topology is the importance of the power line between Semp and cluster 1. If this power line fails or is disconnected for maintenance, the whole reserve grid is not operational.

Figure 6.5: Radial grid of a clustered nineteen node system

Radial Grid Topology considering Limits

If physical limits are considered, the costs of the optimal radial topology are in this case higher (kCHF 519.52). The reason is that an overloading of cables must be prevented which requires different routings of the
cables as shown in fig. 6.6. The loads of cluster 1 and 3 is 9.52 MVA and the loads of cluster 2 and 4 is 9.57 MVA. The loading of the cables is in this close to the maximum of 10 MVA.

![Figure 6.6: Radial grid of a clustered nineteen node system considering physical limits](image)

**6.3.2 N-1 Secure Topology**

The N-1 secure topology is as mentioned in previous studies the most common configuration of MV primary grids. The main advantage is that during planned disconnection of a power line, the power supply is still possible which is in the primary grid operation a typical problem. However, a N-1 secure grid has also higher costs compared to the radial grid. In this case, they are kCHF 645.7534, i.e. about 50 % higher. The reliability for all cluster centroids is \( r_{c,N-1} = [0.99997, 0.99996, 0.99995, 0.99996] \). It is considerable higher compared to the values obtained with the radial grid. The centroid of cluster 3 has the longest distance to the primary substation and hence the lowest reliability. Fig. 6.7 shows the minimal N-1 secure grid topology. The costs and the individual reliability of power supply \( r_{c,N-1} \)
can be considered for both values as an upper limit. When the \textit{a priori} approach finds similar values, then the advantage during maintenance should be considered.

![Image of N-1 secure grid of a clustered nineteen node system]

Figure 6.7: N-1 secure grid of a clustered nineteen node system

### 6.3.3 \textit{a priori} Approach

The \textit{a priori} approach is applied for two scenarios with the objective to increase the reliability of power supply for the customers with the lowest reliability provided by the radial reserve grid. In one case, the \textbf{BFS} failed to converge. Apparently, a grid topology was found with too many meshes for the algorithm to handle. Therefore, also Newton’s method is applied. After several searches it was observed that the \textbf{ACS} applying Newton’s method was slightly faster than the \textbf{ACS} applying the \textbf{BFS}. A reason can be that the construction of the incidence matrix required for the \textbf{BFS} is slower than generating the input parameters required for Matpower. The average computational time for the \textbf{BFS} and Newton’s are 38 seconds and 36 seconds, respectively.
Scenario 1

In this scenario (S1), the objective is to increase the reliability of power supply with the lowest value obtained by the radial reserve grid with minimal line length (see section 6.3.1). Therefore, the reliability of cluster four is targeted to be 0.994 which results in a minimal required reliability vector of $r_{c, \text{min}, S1} = [0.6908, 0.6908, 0.6908, 0.994]$. Fig. 6.8 depicts the solution found by the ACS.

![Map showing cluster reliability](attachment:cluster_reliability_map.png)

Figure 6.8: Reliability must be at least 0.994 for cluster 4

The resulting costs are kCHF 431.95 and the reliability of $r_{c, S1} = [0.99481, 0.99683, 0.99497, 0.99486]$. The main difference compared to the radial topology obtained with minimal radial grid is that cluster 2 is connected to the primary substation instead of cluster 1. This change in topology increased the reliability sufficiently for cluster 4. The mean value is $\mu_{r, S1} = 0.9954$ and the maximal deviation from $\mu_{r, S1}$ is $\text{dev}_{\max, r, S1} = 0.0014$. By comparison, the mean value and the maximal deviation of the minimal radial grid are $\mu_{r, \text{rad}} = 0.9949$ and $\text{dev}_{\max, r, \text{rad}} = 0.0024$, respectively. As the standard deviation is lower for the scenario S1, the grid is less discriminating. However, the costs are about 5% higher.
Another aspect is that the power line connecting Semp and cluster 1 is replaced by a connection to cluster 2. This means that this power line has a high importance as a disconnection would lead to a power loss for all clusters. Additionally, the centroid of cluster 2 becomes an essential node since all other clusters are connected to it. The failure of this node would also lead to a power loss of all clusters. This problem can be mitigated with splitting of the node that only three connections are allowed. However, the probability of the failure of a switch gear is low compared to a failure of cables. Therefore, several connections to one node are acceptable.

**Scenario 2**

In the second scenario ($S_2$), the objective is that the reliability of all customers is higher than 0.9955. The vector containing the minimal required reliability is hence $r_{c, \text{min}, S_2} = [0.995, 0.995, 0.995, 0.995]$. The resulting topology obtained by the ACS is shown in fig. 6.9.

![Figure 6.9: Reliability must be at least 0.995 for all clusters](image)

The costs are kCHF 549.48 and hence 15 % lower than the N-1 secure grid and 35 % higher than the radial grid. The reliability is $r_{c, S_2} =$
Chapter 6. System Planning considering Reliability

[0.99733, 0.99531, 0.9953, 0.9953]. The mean value is $\mu_{r,S2} = 0.9958$ and the standard deviation $dev_{max,r,S2} = 0.0015$. Even though the required reliability is equal for all customers, the maximal deviation is higher compared to scenario 1. Therefore, a topology with less discriminating reliability indices is not necessarily obtained by requiring equal reliability of each customer.

6.3.4 Discussion

The four investigations have revealed that the radial grid has the lowest costs and the N-1 secure the highest costs. For the two a priori scenarios, the costs were 5% - 35% higher than the radial and 15% - 32% lower than the N-1 topology. The N-1 configuration was the most nondiscriminating concerning reliability with a mean value of $\mu_{r,N1} = 0.99996$ and maximal deviation of $dev_{max,N1} = 1 \cdot 10^{-5}$. From the radial grids, scenario 1 is less discriminating compared to the radial grid with minimal line length. This might be used as an argument in favor of scenario 1 despite the higher costs. On the other hand, the reliability of reserve supply might be used as an influence on the resulting customer costs, i.e. customer with a higher reliability have higher costs per kVA. As the individual customer prices are out of scope of this theses, the last conclusion can be understood as an input for price discussions. Furthermore, it has been shown that nondiscriminating reliability cannot be simply obtained by requiring the same minimal reliability of each customer.

6.4 Optimization within Cluster 1

The optimal radial grid within cluster 1 ($S1$) depends on the supplying node. In the radial grid with minimal length, it is the primary substation Semp. By contrast, by applying the a priori method it is Cluster 2. In this case study, the cluster 1 is supplied by cluster 2 ($S1$). At this point, a specific node in cluster 2 has to be found which serves as the connection and thereby as the power source. The optimal node is found by applying the nearest neighbor algorithm as discussed in section 5.4.3 on page 94. Afterwards, the ACS is applied to find the optimal reserve grid within cluster 1. The reliability of the supplying node in cluster
2 has to be considered in the reliability evaluation of the customers of cluster 1.

### 6.4.1 Nearest Neighbor of Cluster 1

The nearest neighbor search is conducted by comparing the coordinates of the customers within clusters 1 and 2. Table 6.2 lists the input values of the search where each value corresponds to a node. The order of list is according to the alphabetic order of the customer labels. The Euclidean metric is applied for finding the shortest paths. The result of the Matlab function is that for nodes I, L, M, and R from cluster 2 is closest to node F of cluster 1 and for N, O, P and S it is G. The second output is the list with the distances between the nodes. The shortest distance is between node F and L which is 209.24 m.

<table>
<thead>
<tr>
<th>Cluster 1</th>
<th>Cluster 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Y</td>
<td>X Y</td>
</tr>
<tr>
<td>683226</td>
<td>247955</td>
</tr>
<tr>
<td>682960</td>
<td>247842</td>
</tr>
<tr>
<td>683027</td>
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<tr>
<td>683043</td>
<td>247375</td>
</tr>
<tr>
<td>683126</td>
<td>247331</td>
</tr>
</tbody>
</table>

### 6.4.2 ACS within Cluster 1

Cluster 1 comprises 5 nodes and is supplied by node L as discussed above. The radial grid with minimal line length obtained by the ACS is depicted in fig. 6.10. The search was considerably slower because of the evaluation of the reliability. An explanation is that the reliability equation generated with the tie set method contains for a 6 node system
more than 15,000 terms. Another explanation is the reliability equation has to be applied to five nodes instead of four in the previous cases. A cluster containing five nodes can hence be considered as an upper limit for this method.

![Figure 6.10: Radial grid of a cluster 1](image)

### 6.5 Conclusion

In this chapter, the two approaches discussed in the previous chapter, the search method considering reliability and the two metrics are applied in the case studies. The *a posteriori* and *a priori* approach can provide grid solutions which satisfy the various requirements. The results are obtained for both methods with the ACS including reliability assessment. When the reliability of power supply obtained by the Euclidean metric is close to the required minimal reliability, then it is possible that the Manhattan metric does not satisfy the reliability requirement.

It is shown that cost savings of about 30% are possible when the *a priori* approach is applied instead of the N-1 configuration. The resulting grid topology is either another radial version than the version with minimal
6.5. Conclusion

line length or it contains meshes without fulfilling the N-1 criterion. It is shown that the reserve grid can be less discriminating when the a priori approach is applied. However, simply requiring the same reliability for each customer is not sufficient for a nondiscriminating topology. In order to obtain a nondiscriminating topology, additional investigations are required. Various topologies are obtained which have advantages and disadvantages compared to the others. All can be considered in the final design of the reserve grid.

In general, a system with up to five nodes can be obtained within one minute. For larger systems, the reliability analysis is computationally expensive and a reduction of the problem should be considered. The ACS including reliability assessment while using hierarchical clustering for reduction of the problem has shown to be applicable for large systems.

The two metrics can lead to different topologies. The Manhattan metric leads to higher distances and hence lower reliability. If an a priori method is applied, the required reliability of the individual customers might not be satisfied with the same result using the Euclidean metric. Different routing or additional redundancy is required which results in higher costs. If this is the case, a more precise metric or the exact situation can be helpful for making a decision.
Chapter 7

Aspects of a Self-Sufficient Reserve Grid

In this chapter various requirements to build a self-sufficient reserve grid are discussed. Possible power sources, protection issues and the generation capacity are investigated. The power sources comprise PV combined with energy storage, EDG and existing power production. The maximal short circuit current has to fulfill the protection requirements. The adequacy of the generation capacity is assessed by evaluating the loss of load expectation for a system supplied by a battery energy storage system and a system supplied by EDG.

7.1 Difference to Reserve Grid

The reserve grid discussed in the previous chapters cannot replace an EDG if the primary and reserve substation experience an outage. If the reserve grid is equipped with power production which allows self-sufficiency, also this shortcoming can be eliminated. The questions are: what power sources are available and what is the corresponding impact on reliability of power supply. It has to be ensured that a reliable operation is possible. Furthermore, it is an additional layer to improve the reliability of power supply and the costs have to be covered by the customers. It is possible that certain customers do not require this increased reliability and are not willing to pay for the power sources or
their connection to the reserve grid. If this is the case, an interruption has to be identified as an event which can be handled with the reserve grid which is not self-sufficient or an event where island operation is required. If the latter is the case, only customers must be supplied with reserve power which ordered it. The other customers must be remotely disconnected. Therefore, an intelligence is required which is able to make these decisions.

7.2 Power Sources

The potential power production for the reserve grid in Zurich is investigated for photovoltaics (PV) combined with energy storages, EDG and existing power production. Other technologies as e.g. wind power are assumed to lack the potential for providing sufficient power. Since the reserve grid is operated with medium voltage, also the production is required to feed in on this voltage level.

7.2.1 PV and Energy Storage

In this subsection the potential of PV production and energy storages is investigated. PV plants are scalable and can be mounted on buildings which makes them suitable for power production in the city center. The production performance of PV plants can be divided into two parts: location dependent or location independent. Location dependence comprises the global radiation, shading and the orientation of the panels. By contrast, the power factor and the round trip efficiency are calculated location independent and under laboratory environment [63]. The efficiency factor is about 15% and the performance ratio, which is a quality factor which considers e.g. conduction losses and thermal losses, is usually about 80%.

As a contribution to reach the 2000 Watt Society, Zurich has created a solar land registry [64]. It uses a 3D model of Zurich to estimate the roof area usable for PV production and the possible annual production. The total area is according to the solar land registry 5.5688 million square meters. The efficiency factor is chosen to be 15% and the performance ratio 78% [64]. The overall possible peak power is hence about 700 MWp.
A restriction of the PV potential is the protection of historical buildings. There are three kinds of protection with the objective to preserve historical buildings or areas: protection of historical monuments, core zone and quarter conservation area.

The protection of historical monuments is divided into three levels: under protection, in inventory and no protection. Under protection is the most strict setting. It means that PV plants most probably will not be permitted. In inventory means that the building is on a list of future under protection buildings and hence permission for PV plants is unlikely. If a building is not under protection, not in the inventory, not in a core zone or quarter conservation area, the authority of protection of historical monuments will not make any restrictions. Fig. 7.1 shows an overview of buildings under protection (red marks) or in inventory (blue marks) in city center of Zurich [65].

Figure 7.1: Overview of buildings under protection or in inventory in the city center of Zurich. For both categories, PV plants will not be permitted. Buildings under protection are depicted with red marks and buildings in inventory with blue marks.

It can be observed that the city center of Zurich has many buildings un-
under protection. If protection is considered, the potential PV energy production is reduced from 3,200 MWh (28MWp) to 920 MWh (8MWp). The impact on the potential PV production is hence considerable. The question is whether enough is produced to supply the customers during the whole year. In the case that production is sufficient all customers will be supplied with reserve power for any power interruption duration. If all MW customers in this area are connected to the reserve grid, this is not the case as the consumption is 150,000 MWh with a maximal power of 33 MW. If only one quarter of the load is required as discussed in section 5.4.3, the consumption reduces to 35,500 MWh with a maximal load of 8.25 MW. The energy demand exceeds in both cases the production, whereas the potential power can be sufficient. Figure 7.2 shows the reserve grid customer load and the potential PV production in 2012 by using irradiation measurement of MeteoSwiss [66].

![Figure 7.2: Potential load and PV production in city center of Zurich in 2012](image)

For obvious reasons, PV production only occurs during daytime. For the time, when PV production is not providing enough power, a storage is required until the PV production is sufficient again. In Zurich, a battery energy storage system (BESS) is being tested for the evaluation
of this technology [67]. First results are expected end of 2015. Also other technologies with the potential to have an installed power in the MW range have been investigated [69]. The main interest of ewz in storage technologies is the integration of renewables or other smart grid applications including ancillary services. The implementation of PV and a BESS in the reserve grid can hence be considered as one of their applications. Only in case of an emergency, they supply reserve grid customers. This is an advantage because during a blackout, islanded operation is allowed and income is still possible. Furthermore, only the costs and impact on the environment related to the connection of the two systems to the reserve grid have be covered by reserve grid customers. The only exception is when the size of the BESS has to be increased to cover a longer interruption. In order to reduce switch operation, it is recommended that the systems are always connected to the reserve grid instead of to the primary grid.

7.2.2 EDG in Substation

An obvious power generation source are EDGs. An appropriate location is in the primary substation feeding the reserve grid. If all substations experience an interruption of power supply, the EDGs can be started to produce reserve power. Instead of using the power from the transmission grid, it is locally produced in the primary substation. The advantage for customers is in this case among others that ewz is responsible for the proper testing of the units. This is considered as beneficial as ewz is more familiar with power production than their customers. However, several disadvantages of using EDG exist. One drawback of EDGs located in the primary substation is that the power losses are higher compared to an installation at the customer’s site. Furthermore, the high maintenance costs and the risks discussed in the introduction remain (see chapter 1.2 on page 2). An additional drawback is that the sole application of the EDG is to provide reserve power whereas other sources can also be used on a daily basis. As a result, the impact on the costs and on the environment is higher for EDGs compared to the other technologies. This issue might be mitigated if EDGs are combined with other power sources.

1 Also other utilities, as e.g. the electric utility of the canton of Zurich (EKZ), are investigating a BESS [68]
7.2.3 Existing Power Production in Zurich

Nowadays, existing power sources in Zurich are hydro power, waste-to-energy and CHP. The location of the first two is depicted in fig. 7.3 and the area used in the previous case studies is indicated with the red line. Hydro power is produced with run-of-the-river hydroelectricity (Letten and Höngg) or drinking water power plant (Glaubten and Strickhof). The hydro power plant Letten has a rated power of 4 MW and Höngg 1 MW. The rated power of Glaubten is 44 kW and Strickhof 148 kW. The waste-to-energy power plants are Hagenholz and Josefstrasse. Hagenholz can provide 16 MW electric power and has a distance to the red marked area of about 5 km. Considering the cable costs for supplying the reserve grid, Hagenholz is an interesting option if the reserve grid is built in its vicinity, i.e. the reserve grid is also built in Oerlikon and connected to the reserve grid in the city center. The power plant Josefstrasse is not considered as it will be decommissioned in the next years. In a suburb of Zurich, a fuel cell is installed with a rated electric power of 230 kW and 170 kW and operated heat-led. Analogously to PV, CHPs can be built which produce power on a daily basis. In case of an outage, the operation must be changed to current-led to supply enough electric power.

7.2.4 Impact on Topology

The power sources should also be considered in the design of the reserve grid when an overloading of the cables is possible. When e.g. the total load is 16 MW and the waste-to-energy power plant Hagenholz is used as a power source, it has to be ensured that the 16 MW can be transmitted.

7.3 Protection

The reserve grid is an EPS, which has during outage of the primary grid an island character. Also in islanded mode, the protection of the system has to be ensured. A power system supplied primarily by renewable production is a new concept and hence has risks. In La Graciosa [70] and Germany [71], projects are conducted which have the goal to demonstrate the feasibility of micro-grids. It is suggested that the conclusions
7.4 Generation Capacity Assessment

Figure 7.3: Power production in Zurich. Hydro power plants are marked with a blue pin and waste-to-energy power plants with a brown pin. The area discussed in the previous case studies is indicated with the red line.

of these and additional projects are awaited and a similar grid tested in Zurich before it is sold as a reliable system.

7.4 Generation Capacity Assessment

In this section, the adequacy of the generation capacity of an EDG and a BESS are assessed with the loss of load expectation (LOLE) [52]. The analysis is conducted for a customer load of 8 MW which is one quarter of the maximal load in the city center (see section 5.4.3 on page 94). The EDG is investigated for a 10 MVA unit and the BESS for nine systems with 1 MVA rated power. As a result, the EDG has no redundancy and the BESS solution has one unit more than required to supply the load. Production from PV is not considered as it is assumed that the
BESSs are fully charged and the PV supports the BESSs by charging them during a long interruption of power supply. During nighttime, no production from PV is possible and the BESS is solely responsible for the power supply. For the EDG and the BESS a capacity outage probability table is generated. It contains all capacity levels and the correspondence probability of occurrence.

7.4.1 Emergency Diesel Generator

For the EDG, the same probability of success is chosen as in (2.3) on page 29. It is the reliability for an EDG with limited correct maintenance. When an electric utility is responsible for the operation of the EDG, a higher reliability can be expected. Therefore, the value of $r_{EDG} = 1 - q_{EDG} = 0.875$ can be considered as a worst case. The corresponding capacity outage probability is simple in this case. The probability that 0 MW are out of service is 0.875 and the probability that 10 MW are out of service is 0.125. Other capacities are not possible when a single 10 MV unit is used.

7.4.2 Battery Energy Storage System

For the BESS the reliability of success is chosen according to ewz statics of UPS installed in primary substation. All nine BESSs are assumed to be installed with the same design and have the same reliability ($r_{BESS} = 0.99$). Furthermore, it is assumed that they are always charged with enough energy to fulfill their tasks. Therefore, the binomial distribution can be applied and the probability that $s$ successes occur in $n$ trials when the probability of success is $p = 1 - q$ is [52]:

$$P_s = \frac{n!}{s!(n-s)!} p^s q^{n-s} \quad (7.1)$$

Fig. 7.4 shows the probability that generation capacity is in service. For a system comprising nine BESSs with a reliability of 0.99 each, the probability that all systems are operational is $P_9 = 0.9135$, that only eight (one has a fault) is $P_8 = 0.0830$, that only seven (two have a fault) is $P_7 = 0.0034$ and that only six (three have a fault) is $P_6 = 0.0001$. The probability that more systems are failing is negligible.
7.4.3 Customer Load

The customer load data is organized to assess whether it is provided with sufficient electric power or a loss of load occurs. The load data for 2012 given in 15 minute values is grouped in seven clusters which represent a defined maximal load which occurred the most. The k-means clustering function of Matlab is applied to obtain these clusters\footnote{[72]}. The number of occurrences \(|O|\) are for a load between 7 MW and 8 MW \(|O_8| = 3589\), between 5 MW and 6 MW \(|O_6| = 5723\), between 4.1 MW and 5 MW \(|O_5| = 5781\), between 2.8 MW and 3.5 MW \(|O_{3,5}| = 5032\), between 6 MW and 7 MW \(|O_7| = 3624\), between 3.5 MW and 4.1 MW \(|O_{4,1}| = 6405\) and between 2 MW and 2.8 MW \(|O_{2,8}| = 4982\). As mentioned above, the maximal load has to be supplied with power and is hence of interest. Fig. 7.5 shows the seven clusters of the load.

7.4.4 Loss of Load Expectation

The LOLE is calculated by applying the generation capacity outage probability and the load data. A loss of load only occurs if the generation outage leads to a system state where the load exceeds the available production. Therefore, it has to be investigated in which cases and how
often a generation outage results in a loss of load. The LOLE of the EDG and the BESS are hence calculated differently. The loss of the EDG always results in a total loss of load whereas the loss of a single BESS has no impact on the power supply. When more than one BESS fail, a loss of load can occur. The LOLE of the EDG is shown in (7.2).

\[
LOLE_{EDG} = |O_{10}| \cdot q_{EDG} = 35136 \cdot 0.125 = 4392 \text{ 15min/year} = 45.75 \text{ days/year} \tag{7.2}
\]

The LOLE of the reserve grid supplied by nine BESSs is dependent on the probability of \( n \) failures of all BESSs denoted by \( P(n) \):

\[
LOLE_{BESS} = 3589P(2) + 5723 \cdot P(4) + 5781 \cdot P(6) + 5032 \cdot P(7) +
+3624 \cdot P(3) + 6405 \cdot P(5) + 4982 \cdot P(7) =
3589 \cdot 0.0034 + 5723 \cdot 0 + 5781 \cdot 0 + 5032 \cdot 0 +
\]

Figure 7.5: Customer load sorted in a descending order. Seven clusters of customer load represent a defined maximal load which occurred the most (indicated with the dashed lines).
$$+3624 \cdot 0.0001 + 6405 \cdot 0 + 4982 \cdot 0 =$$

$$= 12.5650 \text{ min/year} = 0.1309 \text{ days/year} \quad (7.3)$$

The BESS has a lower LOLE compared to the EDG for two reasons: the first is that failure of the EDG leads to a total loss of loads and second is that the EDG has a lower reliability. However, this investigation is only a rough estimate. A reserve grid supplied by only BESS would have a pilot character as discussed in section 7.3 whereas the EDG is a conventional and often applied power source. Furthermore, analysis concerning the organization of the operation is not conducted which can have an impact on the reliability of a power source. More communication system and intelligence is expected in a grid where BESS and PV are installed compared to a system of a single EDG unit. An additional method to improve the $LOLE_{EDG}$ is to install two EDGs with a rated power of five MW instead of a single ten MW unit.

### 7.5 Conclusions

In this chapter, various aspects of a self-sufficient reserve grid are addressed. It has been shown that the required power can be fed by a BESS, an EDG or existing power plants. The disadvantage of the EDG is that its sole use is reserve power supply whereas the other technologies can be applied for constant power production or smart grid applications. Furthermore, the large number of BESSs can have a positive effect on the reliability of power supply and the expected loss of load can be lower compared to an EDG. However, more investigations are required for a profound conclusion and also a cost analysis of a project must be conducted. As the reserve grid is an EPS, the use of EDG is recommended as it is an often applied and tested system whereas a BESS is nowadays a research object. In future, also a BESS can be a valuable option. Already existing power productions have also a huge potential especially when the reserve grid is constructed in the whole city. Otherwise, the distance from the power plants to the reserve grids might result in high installation costs due to the required cable lengths.
Chapter 8

Conclusions and Outlook

In this chapter, conclusions are drawn and an outlook on further research is provided.

8.1 Conclusions

In this thesis, a cost based planning of an electric reserve grid regarding reliability is investigated. Topologies obtained with conventional and new design approaches are investigated. The investigated conventional approaches comprise radial and N-1 secure configurations which are common on the MV level. The redundancy is hence given and the resulting reliability is calculated \textit{a posteriori}. By contrast, the new proposed design approach considers reliability \textit{a priori} and provides the required grid topology and redundancy.

The reliability values of a power supply differs for all grid topologies. The N-1 secure configuration yields the highest reliability for all customers and the radial design the lowest. If certain customer required a more reliable power supply than others, cost savings of about 30 % are possible when the \textit{a priori} approach is applied instead of the N-1 configuration. The resulting grid topology is either another radial version than the version with minimal line length or it contains meshes without fulfilling the N-1 criterion. The main reason for the cost savings is that the requirements of the customers are considered more precisely in the grid design.
It is shown that the reserve grid can be less discriminating when the *a priori* approach is applied instead of finding the radial grid with the lowest costs. However, simply requiring the same reliability for each customer is not sufficient for a nondiscriminating topology and several investigations might be required. In the final design of the reserve grid, the discrimination and the costs to reduce it can be considered. An additional aspect is that the N-1 secure grid has the advantage that the disconnection of a cable due to a planned or unplanned switch operation does not lead to an interruption of reserve power supply. If the reserve grid is not N-1 secure, interruption of the reserve power supply will occur and have to be considered in the contract with the customer.

The comparison with the EDG has shown that the reserve grid is competitive concerning reliability of power supply, costs and environmental impact. The reliability is higher for all discussed reserve grid topologies compared to the EDG. An explanation is that the reserve grid is simpler than the EDG since only a switch operation at the customers’ site is required. By contrast, the EDG is a high maintenance unit which is only used for emergency supply and often not properly tested. The fear of an unsuccessful test and the resulting interruption of power supply often exceed the increased reliability of the EDG if tested thoroughly. The costs for the reserve grid and the EDG are comparable when the reserve grid is installed in the city center and few customers are connected. When installed in the outskirts or many customers are connected, more cables are required. The applied Manhattan metric can also have an impact through the reduced reliability due to the assumption of longer cable length. Therefore, in the real case, the exact cable lengths have to be considered. The environmental analysis is conducted with simple assumptions. It has been shown that the materials used to built the reserve grid and the EDG have a similar environmental impact. However, the monthly test of the EDG is the dominating factor compared to the materials and makes the reserve grid more environmental friendly considering both the greenhouse effect and the ecological scarcity method.

Three optimization methods (complete search, MILP, ACS) are formulated which can be applied to find the reserve grid with minimal power line length. Provided that enough time is given, all methods yield the optimal result. For a large number of nodes, the computational time is identified as an important factor and only the ACS has the potential to find the optimal result within a reasonable time period. The ACS can be significantly accelerated if previous knowledge is considered which
8.2. Outlook

shows the assumed optimal solution of an engineer. This helps to reduce the tendency of the ants to generate grid topology with many loops when nodes are close to each other.

The reliability is assessed with a reliability equation of a complete graph. This equation is generated prior to the topology search algorithm and be applied to evaluate the reliability of every customers. Therefore, the reliability equation has to be generated only once instead of individually every time for each customer. The drawback is that for systems with more than 6 nodes, the computational time to generate and apply the reliability equation in the ACS increases considerably. This problem can be mitigated when the problem is reduced by conducting hierarchical clustering. The optimization problem is first solved for the clusters and then in a second step within the cluster until the grid topology is determined for the whole area of interest.

A self-sustaining reserve grid has the advantage to provide power supply also in the case that all primary substations experience a failure. This scenario is possible if the transmission grid fails which is responsible for the power supply of the primary substations. In Zurich, a BESS, an EDG or already existing power plants are identified as potential power sources. The advantage of the EDG compared to the BESS is that is a well known and often used concept. A power system fed only by BESS is considered as a research project and hence inappropriate for EPS. The remaining technologies are EDG and the already existing power plants. The advantage of the EDG is that it can placed where it is needed and the existing power plants only can be connected economic when close to the reserve grid. The drawback of the EDG is that its sole use is emergency power supply and has a huge impact on the environment. By contrast, the other power sources can be used for power production on a regular basis or smart grid applications. Therefore, it is recommended for a reserve grid built in the city center that it is primarily planned nowadays with EDGs and where possible existing power plants. However, when economic feasible and properly tested in future, the BESS should be considered as an alternative to EDGs.

8.2 Outlook

The case studies of the optimal reserve grid design are conducted for the MV level. As low voltage customers can also have an interest in a
connection to the reserve grid, an analysis how to design the connection efficiently has to be conducted. The same search methods could be applied but it has to determined whether they are adequate to find the optimal solution.

As the objective of the thesis is to discuss the reserve grid design and not to specifically to find the most efficient search algorithms, more efficient search methods might exist. They could be based on heuristics and can help the engineers to design the reserve grid. Furthermore, the program can be further developed to be more user friendly, e.g. by using a graphical user interface.

The search algorithms should also be considered in other applications, e.g. in the primary grid planning. Possible future studies are the investigation whether the 150 kV in Zurich is optimally installed or, for other locations, how off-shore wind power plants should be connected to the transmission grid.

The reliability model is based on the assumption that the hazard rate is constant which is valid for a system in the useful phase of its lifetime. For the commissioning of the reserve grid, a time dependent model could be applied to assess the reliability in the first phase of the reserve grid life time.

The results of the reserve grid topology obtained by the \textit{a priori} and \textit{a posteriori} provide different results. For customers, especially the resulting impact on the reliability and the costs are interesting. Therefore, the resulting topologies should be discussed and the priorities of the customers evaluated. Furthermore, it has to be decided if the reserve grid should be constructed nondiscriminating. If this is the case, the search method should be extended to find grid topology with similar reliability of power supply for each customer while minimizing the costs.

The investigation of the self-sufficient reserve grid is preliminary and requires additional studies. The installation of a \textbf{BESS} is promising because of the synergies with other applications. A feasibility study could reveal if the reserve grid can be supplied by a \textbf{BESS} from an operational and economic point of view. The required communication and protection system must be evaluated and a system built on a small scale to obtain the know how required to operated a micro grid in Zurich.
Bibliography


[69] R. La Fauci, B. Heimbach, E. Kaffe, F. Kienzle, and L. Küng, “Feasibility study of an electrothermal energy storage in the city of
Zurich,” 22th International Conference on Electricity Distribution (CIRED), 2013.


Curriculum Vitae

January 16, 1983  Born in Zurich, Switzerland
1989-1995       Primarschule Böswisli Bülach
1995-1998       Sekundarschule Mettmenriet Bülach
1998-2002       Kantonsschule Büelrain Winterthur
2003           Military Service
2003-2010       ETH, Zurich
2010-today      ewz, Zurich
2010-2015       Ph.D. student at ETH Zurich
Appendix A

Grid Structure

Power grids consist traditionally of two categories: the transmission grid and the distribution grid. The transmission grid transports energy over long distances - originally from the production area to the area where the consumers are located. The use of high voltages (in Europe 110 - 400 kV) reduces the line losses. The task of the distribution grid is to bring the energy from the transmission grid to the consumer. Fig. A.1 shows the traditional structure of a power grid.

In Zurich, the distribution grid is organized by three grid levels, the 150 kV (HV), the 22 kV (MV) an the 0.4 kV (LV) grid. The transformers placed in the primary substations transform the high voltage to medium voltage. MV power lines are often built ring-shaped in order to increase the security of supply (N-1 security). The advantage of rings is the ability to compensate the failure of one power line by using the remaining power lines. Usually, the rings are only fed by one substation.
Appendix A. Grid Structure

Transmission Grid  
380/220 kV  
(Meshed)

Subtransmission Grid  
150 kV  
(Meshed)

Distribution Grid  
22 kV  
(Ring-shaped,  
N-1 safe)

Distribution Grid  
0.4 kV  
(Radial,  
N safe)

Primary substation

Secondary substation

Figure A.1: Traditional grid structure from production to customer [73] modified.
Appendix B

Grid Component Data

B.1 Cable Data

Table B.1: Cable data of a PPB 3x150H

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R \ [\Omega \ km]$</td>
<td>0.124</td>
</tr>
<tr>
<td>$X \ [\Omega \ km]$</td>
<td>0.097</td>
</tr>
<tr>
<td>$C \ [\mu F \ km]$</td>
<td>0.34</td>
</tr>
<tr>
<td>$I \ [A]$</td>
<td>300</td>
</tr>
</tbody>
</table>
B.2 Reliability Values

The reliability values listed in table B.2 are obtained from ewz statistics (2015). They are annually updated.

Table B.2: Reliability values of grid components

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV single busbar [#/a]</td>
<td>0.00205</td>
</tr>
<tr>
<td>MV cable [#/a/km]</td>
<td>0.0042</td>
</tr>
<tr>
<td>Transformer 150/22 kV [#/a]</td>
<td>0.0088</td>
</tr>
<tr>
<td>HV single busbar [#/a]</td>
<td>0.0339</td>
</tr>
</tbody>
</table>
Appendix C

Model for Preliminary Investigation of Reserve Grid

Table C.1 lists the reliability index for MV customers. Here, $H$, denotes number of outages of a state space diagram with two states ($H = \frac{\lambda}{\lambda T + 1}$).

<table>
<thead>
<tr>
<th>Index</th>
<th>Prim. Grid</th>
<th>MVRG A</th>
<th>MVRG B</th>
<th>MVRG C</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV H (#/a)</td>
<td>0.2159</td>
<td>0.2113</td>
<td>40.2113</td>
<td>0.2114</td>
</tr>
<tr>
<td>MV T (min/a)</td>
<td>82.3200</td>
<td>1.5960</td>
<td>1.9800</td>
<td>2.4120</td>
</tr>
<tr>
<td>MV P (min/a)</td>
<td>17.7729</td>
<td>0.3372</td>
<td>0.4184</td>
<td>0.5099</td>
</tr>
</tbody>
</table>
Appendix C. Model for Preliminary Investigation of Reserve Grid

Figure C.1: Reliability model of MVRG A

Figure C.2: Reliability model of MVRG B
Figure C.3: Reliability model of MVRG C
Appendix C. Model for Preliminary Investigation of Reserve Grid
Appendix D

Prim’s Algorithm

In this chapter Prim’s algorithm is summarized based on [27].

Prim’s algorithm can be used to find a minimal spanning tree in a weighted, connected, undirected graph. The algorithm starts with an arbitrary vertex $v \in V$ of the graph. Then, a greedy method is applied to find the edges of a minimum spanning tree, i.e. an edge with minimal weight is chosen, which is a connection to a vertex not contained in the graph yet. The algorithm continues until all vertices are connected.
Appendix D. Prim’s Algorithm
Appendix E

Basics of Reliability Analysis

In this chapter basics of reliability analysis is summarized based on [51].

E.1 Permutation and Combination

E.1.1 Permutation

According to [51] the number of permutations of \( n \) different items is the number of different ways these items can be arranged.

\[
{nP_r} = \frac{n!}{(n - r)!}
\]  

(E.1)

E.1.2 Combination

The same as permutation with the difference that the order of items in the group is disregarded. Hence, the number of combinations is equal or less than the number of permutations.

\[
{nC_r} = \frac{n!}{r!(n - r)!}
\]  

(E.2)
Appendix E. Basics of Reliability Analysis

E.1.3 Application in Power Systems

Combinations are usually more interesting than permutations as it is more important to know which combined events lead to a system failure. The order is not of interest.

E.2 Rules for Combining Probabilities

**Rule 1 - Independent events**  Coin and die are independent events. In reality, be careful whether events are indeed independent or not.

**Rule 2 - Mutually exclusive events**  If something happens, the other cannot. Head or tail.

**Rule 3 - Complementary events**  When something does not occur, the other does. Also coin: when not head than tail. With to events:

\[ P(A) + P(B) = 1 \text{ or } P(B) = P(\overline{A}) \]  \hspace{1cm} (E.3)

**Rule 4 - Conditional events**  An occurring under the condition that another event has occurred. Spoken: Conditional probability of A occurring given that B has occurred.

**Rule 5 - Simultaneous occurrence of events**  Intersection of two sets.

(a) Events are independent

\[ P(A|B) = P(A) \]

\[ P(A|B) = \frac{P(A \cap B)}{P(B)} \leftrightarrow P(A) = \frac{P(A \cap B)}{P(B)} \leftrightarrow P(A \cap B) = P(A)P(B) \]  \hspace{1cm} (E.4)

(b) Events are dependent

\[ P(A|B) = \frac{P(A \cap B)}{P(B)} \leftrightarrow P(A \cap B) = P(A|B)P(B) \]  \hspace{1cm} (E.5)
Rule 6 - Occurrence of at least one of two events  
A or B. (a) Events are independent but not mutually exclusive
Consider the event that A and B occurs simultaneously only once.

\[ P(A \cup B) = P(A) + P(B) - P(A \cap B) \]  \hspace{1cm} (E.6)

(b) Events are independent and mutually exclusive
\( P(A \cap B) \) is zero by definition.

\[ P(A \cup B) = P(A) + P(B) \]  \hspace{1cm} (E.7)

(c) Events not independent

\[ P(A \cup B) = P(A) + P(B) - P(A|B) \cdot P(B) \]  \hspace{1cm} (E.8)

Rule 7 - Application of conditional probability

\[ P(A) = \sum_{i=1}^{n} P(A|B_i) \cdot P(B_i) \]  \hspace{1cm} (E.9)

E.3 Probability Distributions

The summation of all probabilities must equal unity. The outcome \( i \) is denoted by \( x_i \).

\[ \sum_{i=1}^{n} P(x_i) = 1 \]  \hspace{1cm} (E.10)

A representation method is the cumulative probability distribution function.
Appendix E. Basics of Reliability Analysis

E.3.1 Density

The probability density function $f(x)$ is obtained by differentiating the probability distribution function $F(x)$

$$f(x) = \frac{dF(x)}{dx} \quad (E.11)$$

$$F(x_1) = \int_{-\infty}^{x_1} f(x)dx \quad (E.12)$$

E.3.2 Mathematical Expectation

The mathematical expectation does not necessarily need to be a physical feasible solution. See expected number of dots of a die. However, it is probably the most important distribution parameter.

$$E(x) = \sum_{i=1}^{n} x_i p_i \quad (E.13)$$

$$E(x) = \int_{-\infty}^{\infty} xf(x) \quad (E.14)$$

E.3.3 Variance

Underlying shape is lost using only the expected value. Use the variance to keep more information. It contains the dispersion of a distribution.

$$V(x) = E(x^2) - E^2(x) \quad (E.15)$$

or

$$V(x) = \sum_{i=1}^{n} (x - E(x))^2 P_i \quad (E.16)$$

or

$$V(x) = \sum_{i=1}^{n} (x_i^2 P_i) - E^2(x) \quad (E.17)$$
Usually, the standard deviation is applied:

\[ \sigma = +\sqrt{V(x)} \]  \hspace{1cm} (E.18)

### E.4 Probability Distribution

Probability distribution is necessary as most application of electric devices are lacking a clear operation time. Usually, they fail obeying a probability distribution. The value is obtained by testing or constant data collection.

The cumulative distribution function increases from zero to unity as the random variable increases from its smallest to its largest value. This behavior is equivalent to the characteristic of the failure rate as all components are defined to be working at \( t = 0 \) and not working at \( t = \infty \), respectively. This means that the probability of failure at \( t = 0 \) is zero and unity at \( t = \infty \). The cumulative failure distribution function is known as the cumulative failure distribution \( Q(t) \). The reliability evaluation is known as the survivor function and denoted by \( R(t) \):

\[ R(t) = 1 - Q(t) \]  \hspace{1cm} (E.19)

The derivative of the failure distribution of a continuous random variable gives the failure density function \( f(t) \). The area under the failure density function must be unity.

\[ f(t) = \frac{dQ(t)}{dt} = -\frac{dR(t)}{dt} \]  \hspace{1cm} (E.20)

or

\[ Q(t) = \int_0^t f(t)dt \]  \hspace{1cm} (E.21)

or

\[ R(t) = 1 - \int_0^t f(t)dt = \int_t^\infty f(t)dt \]  \hspace{1cm} (E.22)

The hazard rate \( \lambda \) is the transition rate of components from working to failure.

\[ \lambda = \frac{\text{number of failures per unit time}}{\text{number of components exposed to failure}} \]  \hspace{1cm} (E.23)
At $t = 0$ all components are in operation, i.e. none failed. Components will not be repaired. $N_s(t) =$ number surviving components at time $t$. $N_f(t) =$ number failed at time $t$

### E.5 Reliability Analysis of Power Systems

In this section, the reliability analysis of simple power systems is discussed. The variables $R_A$ and $R_B$ denote the successful operation of two components $A$ and $B$. The failure of operation is denoted with the notation $Q_A$ and $Q_B$. The following equation ensures that the components are either in operation or in a failure state:

$$R_A + Q_A = 1 \quad (E.24)$$

#### E.5.1 Simple Series System

When two components are connected in series as depicted in figure E.1, both must be operable to obtain a success.

![System with two components in series](image)

Figure E.1: System with two components in series

Therefore, the probability of success of a system with $n$ components is multiplied:

$$R_S = \prod_{i=1}^{n} R_i \quad (E.25)$$

On the other hand, the probability of failure for a system with $n$ components in series is:

$$Q_S = 1 - \prod_{i=1}^{n} R_i \quad (E.26)$$
E.5.2 Simple Parallel System

When two components are connected in parallel as depicted in figure E.2, both must be operable to obtain a success.

\[ R_P = 1 - \prod_{i=1}^{n} Q_i \] (E.27)

On the other hand, the probability of failure for a system with \( n \) components in series is:

\[ Q_P = \prod_{i=1}^{n} Q_i \] (E.28)

E.5.3 Simple Series-Parallel System

A simple system as depicted in figure E.3 is reduced by combining the components as shown in the two previous subsections E.5.1 and E.5.2. The two components in parallel \( A \) and \( B \) appear in series with component \( C \). Therefore, the reliability in this case is:

\[ R_P = (1 - Q_A \cdot Q_B) \cdot R_C \] (E.29)
Figure E.3: Simple Series-Parallel System
Appendix F

Hierarchical Clustering

In this chapter an introduction to hierarchical clustering is summarized based on [61]. The objective of hierarchical clustering is to group data containing objects with a defined location. The distance between the objects is used to generate a dendrogram (binary cluster tree) which indicates the objects and also groups of objects closest to each other.

F.1 Problem Description

In this dissertation the situation shown in fig. 2.11 on page 30 is analyzed with hierarchial clustering in section 5.4.3 on page 94 (in order to increase the readability, the situation is displayed again in fig. F.1). The question is how the objects, here the customers or a cluster of customers, can be grouped to obtain clusters containing the objects closest to each other. The process is based on the geographical coordinates of the customers.

F.2 Algorithm

Three steps are required to obtain the clusters. First, the distance between each customer is calculated and the information formatted into a matrix. The elements $i$ and $j$ of the matrix contain the distance between
Appendix F. Hierarchical Clustering

customers $i$ and $j$. Second, clusters containing two objects closest to each other are built (binary clusters). This process is also called linking of two objects and in Matlab implemented with the ”linkage function”. The algorithm starts with the two customers with the minimal distance. These two customers build the first cluster. For the situation shown in fig. F.1, customers D and H build the first cluster. From this moment, this cluster can be used to generate a cluster containing itself and an additional cluster or a customer (another binary cluster). For the example in fig. F.1, customer C is the next close customer and hence used to build a cluster including itself and the cluster with customers D and H. The algorithm continues to form clusters by considering the minimal distances until all objects are linked in a so called hierarchical tree. This tree is often depicted with a dendrogram. It contains on the horizontal axis the customer information and on the vertical axis the distance between the objects (customers or cluster of customers). Fig. F.2 shows the dendrogram of the customers of the situation discussed in this thesis. The third and last step is to choose an appropriate number of clusters. A method is to compare the distance between clusters with the distance within the cluster (below the cluster). If the distances (also called height of the cluster) are comparable, it is called consistent and otherwise inconsistent. A high inconsistency coefficient indicates that the objects are not close to each other. The ”inconsistent function” of Matlab generates a list of the inconsistency coefficients for the whole tree. Each link in the cluster is compared with the links below the cluster which are maximally two levels below (depth of the comparison). Nodes which do not have any nodes below them have an inconsistency coefficient of zero.

The algorithm is summarized in the following list:

1. Calculate the distance between the customers’ locations.
2. Apply the linkage function based on the distance matrix from step 1 to create binary clusters.
3. Apply the cluster function with the output of the linkage function and a chosen inconsistent value.
Figure F.1: Map with potential customers. The color indicate the supplying substation of the primary grid.

Figure F.2: Dendrogram of clustering of customer’s location. Node 4 (customer D) and 8 (H) are closest to each other and build the first cluster (node numbering is conducted in alphabetic order). The next close node is 3 (C) which builds together with the cluster of 4 and 8 a cluster with a higher hierarchy.
Appendix G

Backward/Forward Sweep

In this chapter the BFS is summarized based on [74].

BFS for radial power flow

The BFS can be used to calculate the radial load flow. The BFS consists of two stages:

- Backward stage: the complex branch currents are calculated by using the load data and the nodal voltages. The first iteration begins with a flat start, i.e. all nodal voltages are set to 1 per unit (p.u.). The nodal voltages allow the calculation of the nodal current vector $i_S$ which consists of the current induced by the load and the shunt susceptance at the node. When $i_S$ is found, the branch current vector $i_B$ can be constructed. The individual branches supply the loads of the networks with power. Therefore, the branch currents of line $l$ are the superposition of the nodal currents connected to branch $l$.

- Forward stage: the voltage drop on the lines can be calculated using the branch currents. Beginning at the slack node, the nodal voltages are calculated. When all the voltages are found, they are compared to the voltages of the previous iteration. The iterations must be repeated until a tolerance condition, which must be predefined, is fulfilled.

The convergence of the iterative process is discussed in [74].
Backward stage: calculation of the different types of nodal currents
As mentioned above, the nodal current vector $i_S$ has to be constructed for the backward stage. The calculation of the nodal current depends on the types of load (constant power (PQ), constant impedance (Y) and constant current (I)). For the three types of load and the shunt susceptance, a nodal current vector is built. The vector containing the nodal currents of constant power loads for iteration step $k$ is denoted by $i_{S\{PQ,k\}}$, for constant impedance loads it is $i_{S\{Y,k\}}$, for constant current $i_{S\{I,k\}}$ and for the shunt susceptance $i_{S\{BC,k\}}$. One element of such a vector represents a node. The sum of the vectors provides the total nodal currents. Figure G.1 shows the building of $i_S$ for node $m$ at iteration step $k$. The values of the nodes are transformed in p.u using the base values $S_b$, $V_b$, $Z_b$ and $I_b$ which are defined on page 167.

![Diagram of load model](image)

Figure G.1: Load model. The various type of loads are: constant power (PQ), constant impedance (Y), constant current (I) and the current caused by the shunt susceptance $\frac{B}{2}$ of all lines connected to node $m$. The shunt susceptance is considered to 50% at the receiving node and 50% at the sending node. The sum of these currents build the nodal current $i_{S\{k\}}$.

As mentioned above, the nodal currents of constant power loads are stored in $i_{S\{PQ,k\}}$. Its component at node $m \in \mathcal{N}$ is defined as:
\[ i_{S(PQ,k,m)} = \frac{S_m^*}{v_{k-1,m}^* \cdot S_b} \]  

(G.1)

The variable \( k \) indicates the iteration step, \( m \) the node number and \( S_m^* \) the complex conjugate of the demand \( S_m \).

The constant impedance loads have been transformed to constant admitances \((G.17)\). Therefore, the components of \( i_{S(Y,k)} \) are calculated by using:

\[ i_{S(Y,k,m)} = v_{k-1,m} \cdot Y_m \]  

(G.2)

The constant current nodes have a constant amplitude and a constant phase \((G.18)\), which is as mentioned calculated using the rated voltage and are stored in \( i_{S(I,k)} \). The change of the voltage angle \( \delta_{(k-1,m)} \) at node \( m \) has to be considered:

\[ i_{S(I,k,m)} = i_{load} \cdot e^{(\delta_{(k-1,m)} - \phi_m)i} \]  

(G.3)

The current caused by the shunt susceptance \( i_{S(BC,k)} \) is calculated similarly to the constant impedance load \( i_{S(Y,k)} \) by using \((G.16)\):

\[ i_{S(BC,k,m)} = b_m \cdot v_{k-1,m} \]  

(G.4)

The elements of the various vectors introduced are zero if there is no load. E.g. if node \( n \) is a constant current node, \( i_{S(PQ,k,n)} = 0 \), \( i_{S(Y,k,n)} = 0 \) and \( i_{S(I,k,n)} \neq 0 \). The nodal current caused by the shunt susceptance is nonzero when a branch is connected to the node. For a three phase system each node has for all three phases a current. The desired current vector \( i_S \) is the sum of all mentioned currents:

\[ i_S(k) = i_{S(PQ,k)} + i_{S(Y,k)} + i_{S(I,k)} + i_{S(BC,k)} \forall m \in N \]  

(G.5)

The required branch current vector \( i_B(k) \) is found by \((G.6)\). This calculation concludes the backward stage.

\[ i_B(k) := \Gamma^T \cdot i_S(k) \]  

(G.6)
Forward stage: calculation of nodal voltage

The nodal voltage vector $v_k$ is calculated using the following equation:

$$v_k = V_0 \cdot 1 - \Gamma \cdot Z_B \cdot i_{B(k)} \quad (G.7)$$

The variable $V_0$ contains the initial nodal voltages which is 1 p.u. for all nodes. For a single phase calculation, $1 = [1, 1, \cdots, 1]^T$ is a $|N| \times 1$ column vector, where $|N|$ denotes the number of nodes. The multiplication $V_0 \cdot 1$ results in the nodal voltages for a system without any voltage drops caused by the branch currents. Therefore, it remains constant for all iterations. The voltage drop on the branches is found by using the second part of $(G.7)$: $\Gamma \cdot Z_B \cdot i_{B,k}$. Hence, the nodal voltage vector $v_k$ is obtained by the subtraction. The matrix $\Gamma$ transforms the branch impedances which are the elements of the diagonal matrix $Z_B$. As a result, the branch impedances are placed in the new impedance matrix at position of the branches they belong. This is a general formulation and hence also allows negative loads, i.e. power generation.

Merging of the backward and forward stage

The backward and forward stage ($(G.6)$ and $(G.7)$) can be combined to the following equation:

$$v_k = V_0 \cdot 1 - \Gamma \cdot Z_B \cdot \Gamma^T \cdot i_{S,k} \quad (G.8)$$

$(G.1)$ - $(G.4)$ show that the nodal currents depend on the voltages at the same node of the previous iterations:

$$i_s = g(v_{k-1}) \quad (G.9)$$

It is concluded that the BFS method can be regarded as a Gauss-type numerical method. The reason is that in the Gauss method, the nodal voltages depend on the nodal voltages of the previous iterations:

$$v_k = f(v_{k-1}) \quad (G.10)$$

The similarity of the two methods is also indicated by the same definition of the convergence criterion which is explained in the next paragraph.
Convergence criterion  The last step in the iteration is to check whether the solution fulfills the tolerance criterion. As the BFS method calculates the nodal voltages, the difference of the voltages of each node between two iteration steps ($k$ and $k-1$) $v_{k,m} - v_{k-1,m}$ is used in the definition of the convergence criterion:

$$\tau_1 = \max_{\forall m} \left( \frac{|v_{k,m} - v_{k-1,m}|}{v_{k,m}} \right) < \varepsilon$$  \hspace{1cm} (G.11)

where $m$ are the nodes.

If $\tau_1$ is smaller than a predefined tolerance named $\varepsilon$ (here $\varepsilon=10^{-5}$), the BFS procedure ends.

Figure G.2 shows the flow chart of the BFS method.

![Flow chart of BFS method](image)

**Figure G.2: Overview of BFS**

Construction of the impedance and susceptance matrices

The power flow is conducted in p.u. for practical reasons. The base values used are:
• Base power $S_b$ [MVA]

• Base voltage $V_b$ [V]

The base impedance $Z_b$ and base current $I_b$ are calculated using:

\[
Z_b = \frac{V_b^2}{S_b} \quad (G.12)
\]
\[
I_b = \frac{V_b}{\sqrt{3} \cdot Z_b} \quad (G.13)
\]

The series impedance of the branches are stored as the diagonal elements of the matrix $Z_B \in C^{\vert N \vert \times \vert N \vert}$:

\[
Z_B = \begin{bmatrix}
Z_1 & & \\
& Z_2 & \\
& & \ddots \\
& & & Z_{NL}
\end{bmatrix} \quad (G.14)
\]

The shunt susceptance per line are contained in matrix $B_{ct}$:

\[
B_{ct} = [B_1, B_2 \cdots, B_{NL}]^T \quad (G.15)
\]

The shunt susceptance per line has to be considered to 50% at the receiving node and to 50% at the sending node. This way, the shunt susceptance for each node $B_n$ is calculated. The general equation which is valid for all nodes is shown in eq. (G.16). The function $column_n(\vert L \vert)$ extracts the column $n$ in a single phase network. In a three phase system, the dimension is increased and $column_n(\vert L \vert)$ extracts a $3 \cdot N_N \times 1$ matrix.

\[
B_n = \sum_{n=1}^{N_N} \frac{column_n(\vert L \vert)^T \cdot B_{ct}}{2} \quad (G.16)
\]
Preparation of the load data

A general network model includes many different aspects of a power grid such as: unbalanced spot and distributed loads, in-line transformers, shunt capacitor banks and overhead and underground lines with variety of phasing. The load data given in MW and Mvar is converted by assuming rated voltage (1.0 p.u.). The equation used to calculate the admittance is:

\[ Y = Z^{-1} = \frac{S^*}{V^2 \cdot S_b} \quad (G.17) \]

Constant current loads are converted to a constant current analog to the constant impedance loads by assuming rated voltage (1 p.u.) as shown in figure G.3.

![Figure G.3: Model of constant current load](image)

It can be observed in figure G.3 that the current lags behind the voltages which indicates the load is inductive. The magnitude \( I_{load} \) and the angle \( \phi \) between the current and the rated voltage must be maintained constant during the power flow calculation:

\[ I_{load} \cdot e^{\phi \cdot i} = \frac{S}{|V| \cdot S_b} \quad (G.18) \]