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Analysis of Fuse Dimensioning in Low Voltage Networks

A case study based on low-voltage network of Schleswig Holstein

Master Thesis

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Matriculation number: 557509
Submission date: August 16th, 2024

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Acknowledgements

I would like to express my special thanks to my supervisors at Europa-Universität Flensburg, Prof. Dr. Bernd Möller, and Prof. Dr. Ingmar Leiße, for their guidance and support during this research. Also, I would like to express my sincere gratitude to my industrial supervisor, Mr. Lucas Hamann, at the Schleswig-Holstein Netz GmbH (SH Netz) for proposing this topic and providing helpful guidance during my research. Finally, my special thanks to my family and friends for their unwavering support.

Abstract

This research primarily focuses on the analysis and dimensioning of power fuses in low-voltage (LV) networks, with more emphasis on ensuring reliability and safety in the LV grid infrastructure of Schleswig-Holstein. This research also highlights the complexity of fault management and protection systems as the penetration of distributed renewable energy resources are increasing in LV networks. This study develops a methodology to accurately dimension power fuses, thereby ensuring that they can effectively disconnect faulted areas in the network without causing extensive outages.

In the beginning of the chapters, the research focuses on the issues arising from the bidirectional power flow caused by distributed generation, such as voltage fluctuations and reverse power flow, which complicate the operation of traditional protection devices like power fuses. Subsequently in the second chapter of this study includes a comprehensive review of the current state of low-voltage networks in Europe, the regulatory frameworks governing them, and the technological advancements in fault detection and protection systems.

The primary part of this research involves the development and then the implementation of a Python-based algorithm that integrates with PSS SINCAL and SQLite to perform single-phase short circuit analysis and execute queries on the datasets. This algorithm tries to evaluate the dimensions of installed power fuses by simulating fault conditions in various scenarios, including LV networks with high, medium, and low population density areas. Then the analysis identifies underperforming fuses that require replacement, and which can’t comply with stringent grid regulations as given by the DSO. The final findings of this research have been validated through case studies, providing a practical framework for optimizing fuse dimensioning and improving the resilience of low-voltage networks.

Overall, this study offers an in-depth methodology for enhancing the safety and reliability of LV networks in the light of energy transition. The research also opens opportunity for future studies, including cost estimations of grid outages and sociological impact assessment, to further support the ongoing energy transition.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AC	Alternating Current
ANN	Artificial neural networks
DG	Distributed Generators
DBMS	Database Management System
DFIM	Doubly-fed induction machine
DSO	Distribution System Operator
EEG	Erneuerbare-Energien-Gesetz
EnWG	Energiewirtschaftsgesetz
EU	European Union
IEC	International Electrotechnical Commission
LCT	Low Carbon Technologies
LV	Low Voltage
MsbG	Messstellenbetriebsgesetz
NAV	Niederspannungsanschlussverordnung
PV	Photovoltaic
RE	Renewable Energy
SH	Schleswig Holstein
SC	Short Circuit
SM	Smart Meters

TAB	Technische Anschlussbedingung
VoLL	Values of Lost Load

Nomenclature

kWp	Killo watts peak
kV	Killo volts
OC	Over Current
MV	Medium Voltage
GW	Giga watts
Ithmax	Maximum thermal limiting current
Ith	Thermal limiting current
Isc	Short-Circuit current
Vph	Phase Voltage
Zsc	Total Short-circuit impedance
Rsc	resistive component of the impedance
Xsc	reactive component of the impedance
θsc	Phase Angle of Short Circuit Current

1 Introduction

1.1 Background

Germany has planned for huge development of grid infrastructure planning under the Grid Development Plan 2030 which highlights necessary development up to 2030. (Strom, 2019) The electricity grid infrastructure of Germany has been sub-divided into two segments transmission grids (maximum voltage) and distribution grids (high, medium, and low voltage). The main transmission grid is spread across 37,000 kilometers in total length and connected to the European grid at various interconnection points. Further, the distribution grids are divided into high voltage (60 kV to 220 kV with the grid length approx. 94,000 km), medium voltage (6 kV to 60 kV with the grid length approx. 5,20,000 km), and low voltage (230 V or 400 V with the grid length approx. 1,19,000 km) (BMWK, 2020).

In the past few decades, the conventional grid system has been going through some major development changes, such as growth in renewable energy resources connected in the low-voltage network. In the low-voltage grid, consumers such as private households, small industrial companies, small enterprises, and office premises opt for RE resources for their individual consumption.

Although the growth in these small-scale renewable energy projects shows a positive impact, they also come with certain challenges, i.e., previously the grid was designed to transmit electricity in only one direction (source to load), but these days the grid must withstand transmitting electricity bidirectionally (source to load as well as load to source).

While the integration of small-scale renewable energy resources offers several benefits such as they help in reducing electricity bills, make consumers more energy independent etc. But the integration of these technologies can also introduce certain challenges into the low voltage electrical grid networks (Nicholas Etherden, 2014). Additionally, some of the challenges that can happen in low voltage networks due to renewable energy resources includes voltage fluctuations, harmonic distortions, reverse power flow etc. which leads to damage of electrical equipment. These faults might occur due to variability in solar and wind generations, which can lead to voltage fluctuations and frequency deviations, which can lead to equipment damage or power quality issues in electrical networks.

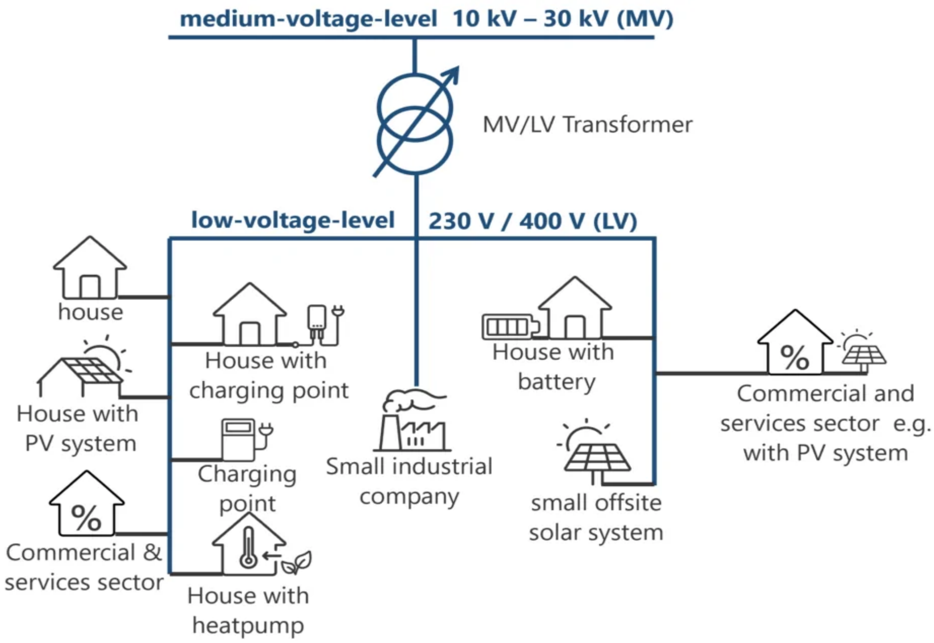

Figure 1-1: Consumers and generators connected to the low-voltage grid (Elisabeth Wendlinger, 2023)

Apart from these faults, frequency deviations beyond permissible limits can disrupt the operation of sensitive electrical equipment and may necessitate corrective measures to maintain system stability. These faults also lead to safety hazards and could damage the electrical equipment connected to the distribution grid. Sometimes, during periods of high renewable penetration, low electricity demand and excess power generation from RE generators can lead to reverse power flow leads voltage regulations issues. Henceforth, the distribution system operator needs to define basic principle guidelines for connection of RE resources with the distribution network.

The electrical fuses play a crucial role in low-voltage networks and are essential for ensuring an effective and reliable protection of electrical systems against various types of faults. In the low voltage network, electrical fuses are installed in the outgoing cable outlets of cabinets, at the connection point to the households and secondary substations. The foremost task of an electrical fuse is to safely disconnect so that a small area of the network in case of any fault condition occur and make sure continue to supply as many customers as possible and avoid further damage to the grid equipment.

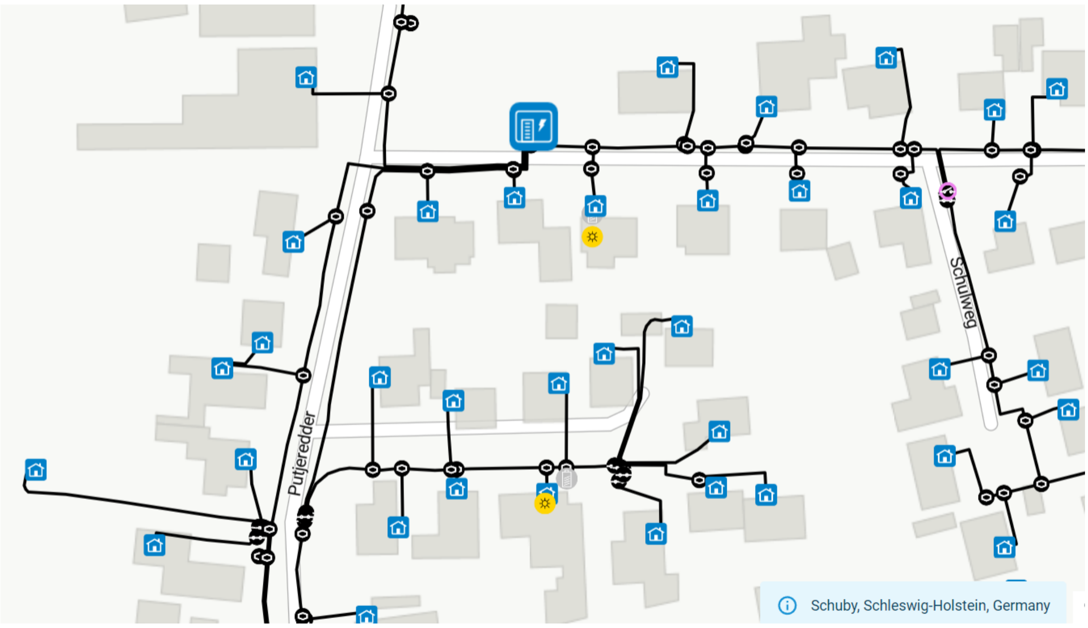

Figure 1-2 : LV Distribution Network in Germany

This figure above represents a part of a low-voltage network in Germany, though the common topology of the LV network of the European distribution grid is designed as a radial network (GmbH, 2022). It consists of distribution transformers which are located along the feeders connected by a bus bar. The operating voltage of a European low voltage network occurs between 220-240V, and these networks can cover large areas in rural and urban locations.

Furthermore, power fuses or electrical circuit breakers are installed at the LV side of each secondary substation to avoid any system failure. The time required to melt or break down the power fuse is inversely proportional to the magnitude of the current flows in the circuit. A power fuse is an over-current protective device, and its working principle depends on the heating effect of current.

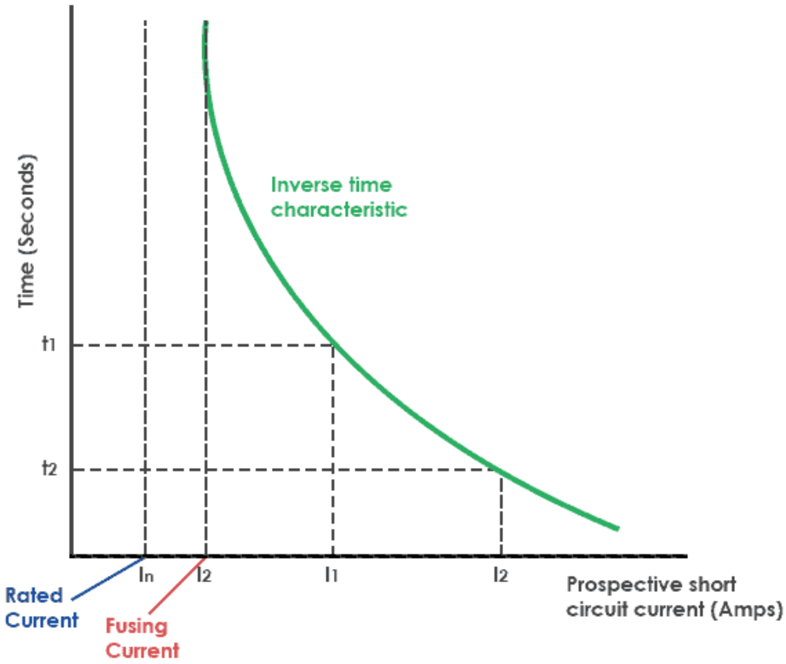

Figure 1-3: Time-current characteristics curve of a fuse

The figure above represents time current characteristics that are vital to understanding the technical behavior of an electrical fuse. It shows the relationship between the current and melting time of the fuse element. The curve shows the response as inverse time-current characteristics of a fuse element in case of over current condition (Codrey, 2020). The low voltage fuses follow the IEC 60269 (formerly IEC 269, equivalent to EN 60269 and VDE 0636) (Comission I. E., 2024) which are used in electricity distribution systems, industries, and by end-users (fuse boxes).

Overall, the thesis project provides a comprehensive approach for fault analysis, fuse functionality, selectivity considerations, short circuit calculations, and Python programming implementation for network analysis, while ensuring reliability and safety in low-voltage networks. Also, ensuring a constant power supply to the various types of consumers which are connected to low-voltage networks in the distribution system.

Further, the research dives into focusing specifically on single-phase errors, phase-to-ground faults, and their significance in the context of fuse size dimensioning. Additionally, this project addresses the selectivity of compatible fuses and the functionality of right fuses low voltage analysis.

1.2 Problem Statement

Overall, the distribution network in Germany is expanding, and new low-carbon technologies (LCT) such as electric vehicles, heat pumps, etc. Henceforth to accommodate future loads the distribution system must be prepared to tackle any future challenges and provide reliable support for the integration of these technologies. The problem statement of this project also lies in the similar criteria to make the existing grid more technically resilient to accommodate future scenarios.

In line with the overall task, Schleswig-Holstein Netz GmbH (SH Netz), manages the distribution of electricity and gas across numerous municipalities in Schleswig-Holstein and serves approximately 2.5 million customers. SH Netz has facilitated the integration of thousands of wind turbines and solar installations into the power grid and plays a vital role in contributing to the energy transition.

Currently, the organization is performing innovation in the development of renewable energy network navigation systems, marking a significant change in digitalization within electrical network computation. This innovative tool aims to assess connection capacities across approximately one million low-voltage and medium-voltage nodes and restructure the management of renewable energy resources. One of the key parts of this energy network navigation tool requires accurate dimensioning of power fuses in low-voltage networks. In the low voltage network, fuses are installed in the outgoing cable outlets of cabinets and secondary substations and at the connection point to the households.

The main task of household fuses is safely disconnecting in case of an overcurrent scenario while the cabinet fuses which have higher overcurrent protection tries of these safely disconnect a small area of the network in case of fault conditions to avoid further damage and continue to supply as many customers as possible. It implies that the electrical utility must avoid economic losses from power outages while ensuring a consistent supply of electricity to keep customers satisfied with the service.

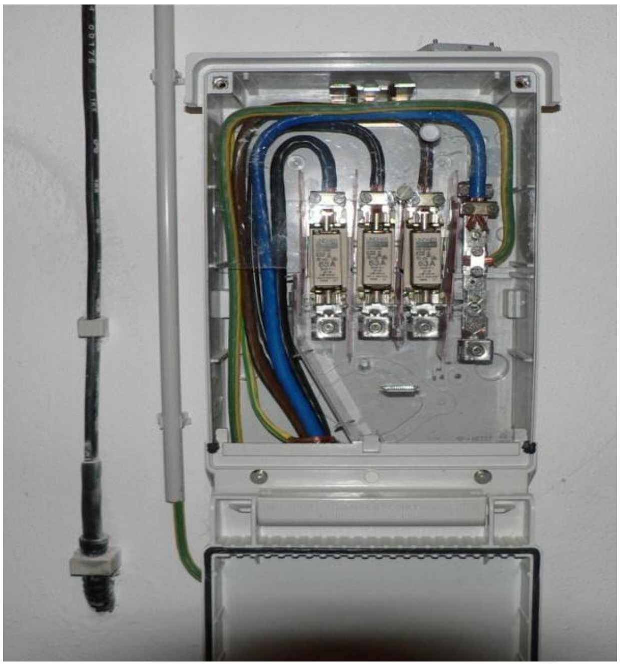

Figure 1-4: A power fuse panel in the household

During a normal operating condition, a fuse allows the flow of nominal current flows without tripping (melting of fuse wire) (PHBB, 2009). However, in case of flow of overcurrent during the transient state (high flow of current during a short period of time which is close to 0.2 to 0.5 secs), the fuse must disrupt the flow of overcurrent. The selectivity of a fuse is dependent on current rating, nominal current, ambient temperature, melting integral, short circuit current, etc. The following table shows regulations as per the low voltage grid connections code for basic protection of the grid connection for standard household loads.

Table 1-1: Grid Connection Power Ratings for standard household loads

Mains Connection in cable cross section	Fuse Protection	Transferable Power (kVA)	Transmittable power (kW) with cos θ =0.9
NAYY 4 x 50 mm^2(up to 100m)	3 x 25 A	17	16
	3 x 35 A	24	20
	3 x 50 A	34	30
	3 x 63 A	44	40
	3 x 80 A	55	50
	3 x 100 A	69	60
NAYY 4 x 150 mm^2 (up to 150 m)	3 x 125 A	87	75
	3 x 160 A	111	100
	3 x 200 A	139	125
	3 x 250 A	173	150
NAYY 4 x 240 mm^2	3 x 315 A	218	195
	3 x 355 A	246	220

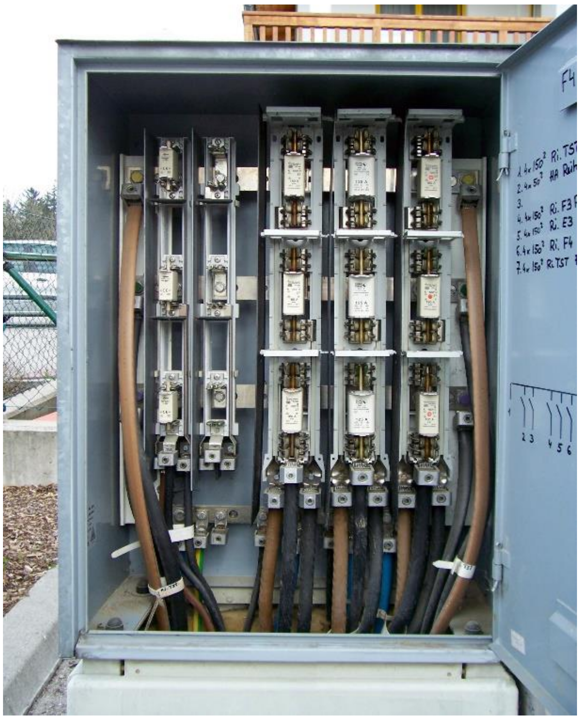

Figure1-5: Cabinet fuses at the terminal of multiple lines

While the household power fuses can shut down when there an overcurrent conditions in case of fault occurs with a lower nominal current breaking point, the fuses at the cabinet have higher nominal current ratings. They are the combination of several lines joining at one terminal point and forming a cluster inside a cabinet box. Generally, the function of these cabinet fuses is to disconnect a focused area where the fault occurs, and it also needs to make sure that while one area is disconnected but rest of the part of the LV network gets a consistent electricity supply. The following table shows regulations as per the low voltage grid connections code for non-household loads such as generation systems, heating systems, storage systems and charging of electric vehicles.

Table 1-2: Grid Connection Power Ratings for non-household loads

Grid connection in cable cross section	**Fuse Protection**	**Transferable Power kVA**	**Transmittable power kW with cos θ =0.9**
NAYY 4 x 50 mm^2 (up to 100 m) 2)	3 x 80 A	50	45
NAYY 4 x 150 mm^2 (up to 100 m) 2)	3 x 200 A	100	90
NAYY 4 x 240 mm^2 (up to 50 m) 2)	3 x 315 A	176	158

The power fuse characteristics vary based on the cable type, type of connection box, operating class of the fuse, rated current, and power rating. (Wikimedia, 2012). The Table 1-3 (Netz, Low Voltage Grid Connection, 2020) below shows the mains connection cables must be made of 35 mm^2 (for standard house connections up to 100 A) or 50 mm^2, depending on the standard materials available from the grid operator. The following fuse protection table is based on the general performance approaches according to planning principles for electricity by SH Netz (with the phase angle of $\cos\varphi=0.9$).

Table 1-3: General fuse protection approach by SH Netz

House connection cable	**House connection box**	**Recommended number of residential units**	**Size/ operating class (fuse)**	**Rated current (Amps)**	**Power rating (kVA)**
NAYY-J 4x35 mm² or NAYY-J 4x50 mm² (130 A at m=0.85)	1x3xNH00	1 to 2 WE	NH 00 gG	50 A / 63 A	35 kVA/ 44 kVA
NAYY-J 4x35 mm² or NAYY-J 4x50 mm² (130 A at m=0.85)	1x3xNH00	3 to 5 WE	NH 00 gG	100 A	69 kVA
NAYY-J 4x50 mm² (130 A at m=0.85) or NAYY-J 4x150 mm² (248 A at m=0.85)	1x3xNH2	6 to 8 WE	NH 2 gG	125 A	87 kVA
NAYY-J 4x150 mm² (248 A at m=0.85)	1x3xNH2	9 to 12 WE	NH 2 gG	160 A	111 kVA

Some terms expalined below which are mentioned in the table above:

*NAYY-J: European aluminum conductor power distribution cables
*WE: Wohneinheiten (Housing units)
*NH: Hausanschlusskasten (House connection box)
*gG: Betriebsklasse (Operating Class)

1.3 Research Question and Objective

This research project addresses an industrial-level problem by developing and implementing a Python-based program to automate the analysis for single-phase short circuit analysis. This analysis also includes identifying the underperforming power fuses in the LV network as per the grid codes provided by the DSO. The goal is to ensure that these power fuses can safely disconnect in case of fault conditions in the LV network. Moreover, this research project aims to understand the LV network of Schleswig Holstein and develop answers to the following questions:

1. Optimal design of a power fuse using an algorithm for dimensioning and identifying the power fuses that are performing low and need to be replaced from the low voltage network?

2. Develop a methodology for performing single-phase short circuit current analysis and advance an understanding of the simulation and database tools that can be utilized to effectively analyze a substantial portion of the low voltage network and replicate similar analysis across other sections of the LV network in SH Netz.

3. Lastly, perform model validation of the designed algorithm and run multiple queries to extract out input and output datasets and conduct graph analysis on one of the LV network models, considering all traversed fuses and the current characteristics of this analysis.

The purpose of this research is to explain the importance of power fuses in low voltage (LV) networks through a comprehensive case study of LV networks in the Schleswig Holstein area. The subsequent chapters are tailored for professionals engaged in research review, network analysis, and selectivity analysis of fuses. These subsequent chapters offer in-depth insights into case studies of resilient LV networks, methodologies for conducting single-phase short circuit current analysis, and techniques for visualizing LV networks using graph analysis.

2 Research review

The literature review explores three critical areas relevant to the research questions: a) Constraints and regulations on feed-in power in low-voltage networks, b) Fault Detection and Protection Systems for Distributed Generation in Distribution Networks, and c) A techno-economic analysis of European low-voltage distribution networks. Furthermore, this section provides a comprehensive understanding of the context, a detailed analysis of the methodologies, and an insightful interpretation of the findings presented in the research papers.

2.1 Feed in power limitations and regulations in low voltage networks

In Germany, low-voltage grid planning assumes constant minimal consumption as base load case, but an installed generation capacity of around 30% of annual consumption may cause reverse power flows during the day and increases magnitude of voltage in the distribution grid. This is causing DSOs to reconsider traditional voltage band divisions. The peak power per household ranges from 2 to 6 kW for households with small electrical demand to 7 to 13 kW for households with full electrical demand and electric heating demand. A surge in penetration of small PV systems led to almost 41 GW of installed capacity by 2016 and mostly 96% has been installed at low-voltage levels in Germany (Ruf, 2018).

This leads to certain system constraints including voltage magnitude, thermal loading of lines and transformers, and losses. In case of high penetration of PV, the electricity grid can lead to high power ramp rates and large feed-in power disrupts voltage thresholds. The feed-in power by PV generation can also cause certain faults flicker, voltage disturbances, and reserve generation requirements.

The DSOs in Germany are regulated by various laws, including the energy industry law(EnWG, German “Energiewirtschaftsgesetz”, EnWG, 2013) (EnWG, 2013)], renewable energy law(EEG, German “Erneuerbare-Energien-Gesetz”, EEG, 2023) (Erneuerbare-Energien-Gesetz , 2023), metering point operation law (MsbG, German “Messstellenbetriebsgesetz,” MsbG, 2016) (Messstellenbetriebsgesetz (MsbG), 2023)].

The low-voltage connection regulation (NAV, German “Niederspannungsanschlussverordnung,”) (Niederspannungsanschlussverordnung, 2006) These laws are crucial for connecting small scale RE resources to the low-voltage grid, ensuring efficient and safe operation of these systems. The connection of residential PV systems to the low-voltage grid requires compliance with these four key laws. The distribution Service Operators (DSOs) are required to establish minimum technical interconnection requirements (German “Technische Anschlussbedingung” or TAB) (Amprion, 2016). for the installation and operation of distribution system components that are linked to their grid.

The low-voltage connection regulation (NAV) governs the terms of grid connection and safety between consumers and DSOs at the low-voltage level, ensuring that the standard voltage at this level is around 230 V with a frequency of approximately 50 Hz. It is the responsibility of the system owner to adhere to these specifications and comply with VDE standards. Typically, there are two TABs applicable to the distribution grid: one for the medium-voltage level and another for the low-voltage level, both forming part of the grid connection agreement between the consumer and DSO. The regulations that enforce these requirements include EN 50160 (Henryk Markiewicz, 2004) which focuses on characterizes voltage parameters of electricity (including supply voltage, voltage variation,, flicker severity etc.) supplied by public distribution networks and VDE AR 4105 (FNN, 2021) for small power generation systems (including PV rooftops) connected to the low-voltage distribution network.

In case, the grid frequency exceeds 50.2 Hz, controllable generators must decrease the feed-in active power by 40% of the nominal power per Hz, in accordance with the current draft of the European network code. Furthermore, if the frequency falls outside the range of 47.5–51.5 Hz, all generators are mandated to disconnect automatically.

2.2 Fault Detection and Protection Systems for Distributed Generation in Distribution Networks

Besides feed-in power constraints and grid regulations, the integration of distributed generation systems could cause various faults in the distribution network or LV network. Some of these faults include short circuit faults, single phase-to-ground faults, phase-to-phase faults, open circuit faults, intermittent faults, etc. These faults could occur due to an increase in penetration due to distributed generators and increased safety risks, power outages, and power quality issues in the distribution grid.

This research (Matin Meskin, 2020) reviewed the impacts of integrating Distributed Generation (DG) systems into distribution networks or LV/MV networks and identify the challenges associated with protection systems. This analysis identified various issues which include changes in fault current values, operational challenges among protective devices, and reduction in system reliability due to these distributed generators. The distributed generators include synchronous generators, induction generators, and inverter-based units which contribute differently to fault currents and create detection problems. The findings of this study highlighted problems such as reverse power flow, failure of protection devices, islanding, and unsynchronized reclosing which all pose significant risks to the distribution network. Furthermore, it also identifies potential solutions which include adaptive protection schemes, multiagent systems for coordinated decision-making, and the use of directional protection and fault current limiters to manage these impacts effectively. Lastly, the study suggests methods to improve protection strategies for maintaining reliable and safe operations in modern distribution networks as the percentage of distributed generators is increasing.

Table 2-1: Proposed techniques to improve protection systems in distribution networks

Method	Advantage	Disadvantage
Disconnecting all DGs during fault	Easy to apply, no need to install new devices or change current protective system	Not reasonable for temporary faults, cannot be applied to DGs installed by the private sector
Disconnecting DGs from faulted area and connecting to other un-faulted parts	-	Needs to monitor and control all CBs remotely, needs a communication channel, difficult to implement
Recalculation/resizing of protective devices	Beneficial but it needs to be evaluated based on the size of network, elements and technical specifications etc.	Finding optimal settings is not feasible since DG units are not always in service; using higher time settings increases fault-clearing time
Directional protection	Maintains coordination	Needs PT to be installed, needs directional OC relays on both ends of feeders, coordination is more complicated
Fault current limiter	Maintains coordination	Reduces contribution of other parts of network to fault current, prolongs operating time of OC protective devices, non-fault transients can trigger SFCL incorrectly
Limiting DG size	Maintains coordination	Restricts customers, other factors like power quality and reliability are not considered

Reducing the inverter current during the fault	Maintain coordination in high fault current	Non-fault disturbances may cause voltage drop at PCC, not necessary in very low fault current cases
Application of fly wheel DFIM energy storage	Improves power quality, emulates synchronous generator response	Only appropriate for OC relays, worsens coordination between fuse-recloser, costly
Pre-calculated (offline)	Maintains coordination, high flexibility	Needs accurate network data, complex calculations, may fail in unforeseen circumstances, inapplicable to fuses

Some research finds innovative approaches to improve fault detection and localization in Low Voltage networks. One notable study introduced a digital twin (DT) model driven by smart meter (SM) data to address the shortcomings of traditional fault detection methods, which often depend on costly micro-Phasor Measurement Units (μPMUs) (Mohamed Numair, 2023). In this project, the authors created a virtual replica of the distribution network which utilized SM voltage-magnitude data and network topology to accurately detect and locate faults. Moreover, the study also used employed machine learning techniques to estimate the Currents Symmetrical Component (CSC) to compensate for the lack of direct current measurements from SMs. The test has been validated on a real-world 41-node LV distribution feeder and shows a fault detection accuracy of 95.77 percent which does not rely on voltage data. Additionally, this method effectively detected high-impedance shunt faults and open conductor faults, providing proactive fault management. Overall, the system shows a significant increase in fault detection accuracy as compared to similar other studies and highlights the benefits and applicability of the digital-based approach in enhancing the reliability of modern distribution networks.

Another study (P. Stefanidou-Voziki, 2022) which tries to identify fault location after using the data of advanced sensors and actuators which enhances the observability and controllability of distribution grids. This study demonstrates the need of transformation of traditional power systems into smart grids. It also highlights a shift towards unconventional methods, particularly artificial intelligence (AI), due to their superior accuracy and efficiency for fault detection, isolation, and restoration. The paper reviews various methodologies for fault location and classification in both medium-voltage (MV) and low-voltage (LV) distribution grids. In the methodology section, the authors examined the advantages, disadvantages, and applications of fault location techniques using five main principles: impedance-based, traveling-wave, AI-based, sparse measurements, and hybrid methods. For example, impedance-based methods use voltage and current measurements to determine fault locations, while AI-based approaches leverage algorithms like artificial neural networks (ANNs) for more sophisticated and adaptable fault analysis. In contrast with modern techniques the paper identifies impedance-based techniques, are simpler but less effective in modern, complex grid environments while the AI and hybrid methods offer significant accuracy and adaptability, they also involve greater complexity and reduce costs.

This study also underlines the importance of database management with potential of AI methods to identify fault diagnosis in increasingly complex distribution grids in the end, the study highlights the need for practical applications of these methods for fault location and classification methods by DSOs, suggesting improvements in grid reliability and efficiency.

2.3 Techno-economic review of European low-voltage distribution networks

The European Union (EU) and other European countries have set ambitious targets for achieving net-zero emissions in the coming decades, which increases the promotion of low-carbon technologies (LCTs) such as heat pumps, photovoltaic systems, and electric vehicles (Rui Guo, 2023). However, the integration of LCTs can considerably influence the traditional load patterns in low-voltage (LV) distribution grids. These LV networks were designed which designed for smaller capacity loads.

This study aims to provide a structured literature review of LV grids in Europe, with a special emphasis on technical and economic parameters, to help academics and distribution system operators (DSOs) comprehensively quantify the impacts of LCT integration and investigate options to mitigate these impacts. The research consists of a three-step framework (1) analysis of grid topologies, (2) review of technical grid parameters of LV grids, and (3) review of economic parameters. During the research data sets were collected from 26 open-access grids and 29 scientific articles/reports covering most of the European countries and zones (rural and urban).

During the study, a typical European LV grid was designed consisting of one MV/LV transformer and several feeders, treated as a three-phase four-wire system. An approach of dummy island was taken to reduce computational complexity. Although, there are significant deviations in technical parameters across European countries and zones. As a result, German LV grids came out to be most well-documented, with data on almost all investigated parameters. The grid in urban areas generally had higher nominal power of transformer shorter average length between consecutive nodes and larger feeder cable cross-sections compared to rural grids.

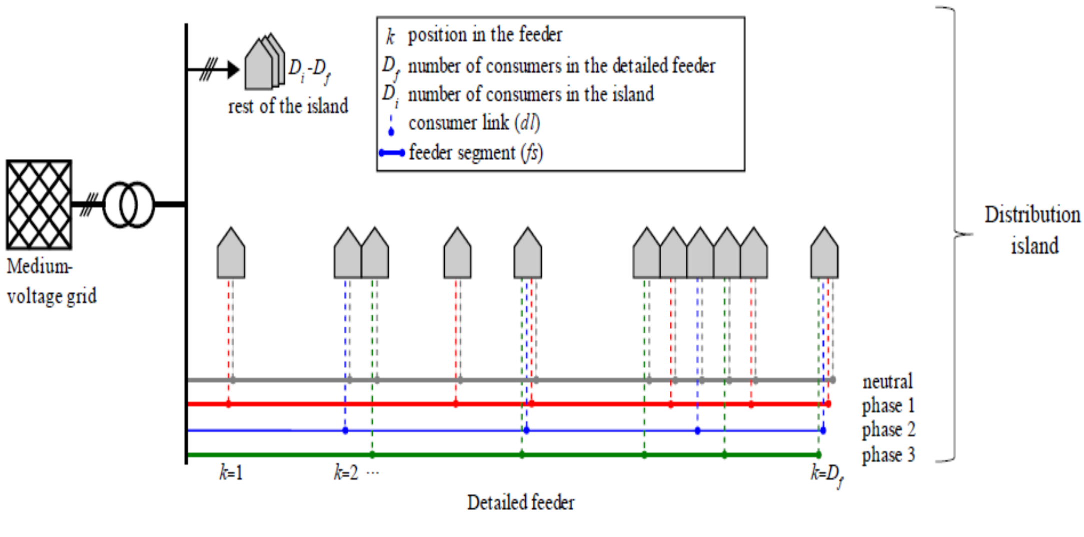

Figure 2-1: A typical European LV grid topology with the dummy island approach

A brief analysis has been created among various countries of Europe based on various criteria such as topology, faults occurring, financial implications associated with maintaining and upgrading, technical standards and strategies to mitigate the impact of faults and other operational challenges in the LV networks (refer to Table 2-2). The recommendations provided in the study enables researchers and DSOs to select appropriate parameters for simulations and analyses related to LCT integration with LV Grid.

Table 2-2: Analysis of LV grids for various European countries

Country	Topology	Types of Faults	Cost Impact	Technical Requirements	Mitigation Measures
Germany	Radial, high underground ratio	Overload, voltage unbalance	High due to extensive underground cables	High-quality insulation, robust protection systems	Extensive use of automation and monitoring
Belgium	Similar to Germany, less underground ratio	Similar to Germany, with harmonics	Similar to Germany, lower cable costs	Moderate, based on local standards	Localized control strategies
Italy	Radial, high underground ratio	Voltage variation, harmonics	Moderate, influenced by undergrounding	Advanced monitoring, robust for DG	Use of power electronics, voltage regulation
UK	Radial, mixture of underground and overhead	Voltage dips, unbalances	Moderate to high, depends on region	High standards for smart grids	Investment in smart grids, automation
Generic Europe	Radial, varied underground ratios	Varied: Overload, voltage issues	Moderate, influenced by country-specific factors	Varies; generally lower compared to Germany	Depends on specific grid challenges

2.4 Research Challenges

While some of the studies point to fault detection and protection strategies for distributed generation systems at LV networks. However, the integration of these technologies also comes with significant challenges including managing the feed-in power voltage disturbances, variable generational patterns of LCT, and exceeding voltage thresholds due to high PV generation in the DSO's portfolio. Henceforth, it becomes necessary to automate the network and adopt advance techniques for fault protection strategies.

This research takes a step towards the monitoring of assets such as power fuses and identifies the underperforming fuses before any failure conditions. Yet, further research can be developed using these case studies as base scenarios and with the AI/ML models, the whole LV network of Schleswig Holstein can be realized. However, due to time availability constraints, this study mainly focuses on model validation of functioning and performance analysis of power fuses in households and cabinets.

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3 Methodology and Tools

The methodology of this research is based on an aligned approach according to the objective function of finding the dimensioning of power fuses in a Low Voltage network. Although these tools are far more complex to elaborate on individually the research tries providing an overall idea and working principle of these tools. Additionally, this research also seeks to contribution to energy transition while making the grid more reliable and resilient for future loads such as heat pumps, electric vehicles, etc.

Step 1

- NEMO acts as a geo-spatial software consists all the data of network elements e.g substation, fuse, lines, breaker, etc.
- Firstly, the low voltage assets data needs to extracted out from NEMO

Step 2

- SQL lite is used to contain all theese information in datasets regarding all the elements.
- It acts as a database repository which was extracted from NEMO

Step 3

- PSS Sincal tool acts as a tool to perform single phase short circuit calculations in the LV network.
- A Sincal file also extracted from NEMO which can be further utilized to perform network analysis.

Step 4

- Python Visual Studio was used to capture all information and perform a single-phase short circuit calculation
- Furthermore, the code can be run on multiple low voltages networks under various substations

Step 5

- Results are shown in a graphical manner using network graph method that could help to visualize major part of the network
- Overall the agenda of ensuring the safety and reliability of the grid will be fulfilled.

Figure-3-1: Steps for finding an accurate dimension of power fuses in a Low Voltage network

3.1 Technical System Information

The system configuration includes a study of multiple low voltage networks which begin from a secondary substation with a capacity of 20kV/0.4kV from the primary to secondary side of voltage. It mainly involves an LV network under these secondary substations which relate to each other with the help of MV lines. Though some of these secondary substations have more consumers connected when compared with others, it varies based on the population density of that area. The LV lines make sure a reliable connection among the elements under the substations which finally connect to loads further down. These loads such as household loads connected to individual power fuses, and there are cabinets shown in the figure below which helps to cluster these meshed networks. The color coding is as follows: black: secondary substations, blue: household along with power fuses, yellow: cabinets, red: LV switches, and green: solar PV rooftops or RE generators.

Figure 3-2 : Geo-spatial view of elements in LV network model

As this study progresses, the identification of suitable dimensioning of fuses became necessary as some of these power fuses are many years old (Dittmann, 2020)and aren't capable enough to work in case of any fault scenario. For identification of suitable dimensioning of power fuse, a methodology has been developed as per the grid codes such that the current ratio between thermal limiting current (exists for a short span in case of fault conditions) and nominal current (rated current) of the power fuses (Netz, Planungsgrundsätze Strom, 2022).

Usually, thermal limiting current and nominal current needs be calculated and simulated in this while performing the single-phase short circuit current analysis and must be stored in the database. Then onwards, the ratios or dimensioning of these fuses will identify the further performance of these fuses installed at the outlet cables of household, at the cabinets and secondary substations.

This study identifies a methodology and designs an algorithm for the dimensioning of the fuses. Yet further this research could help to design a sample network using Python from an LV network and perform a detailed analysis on each node of that LV network. Figure 3-3 provides a sample of an LV network that contains various elements, lines, fuses, cabinets, and secondary substations (SINCAL, 2022)

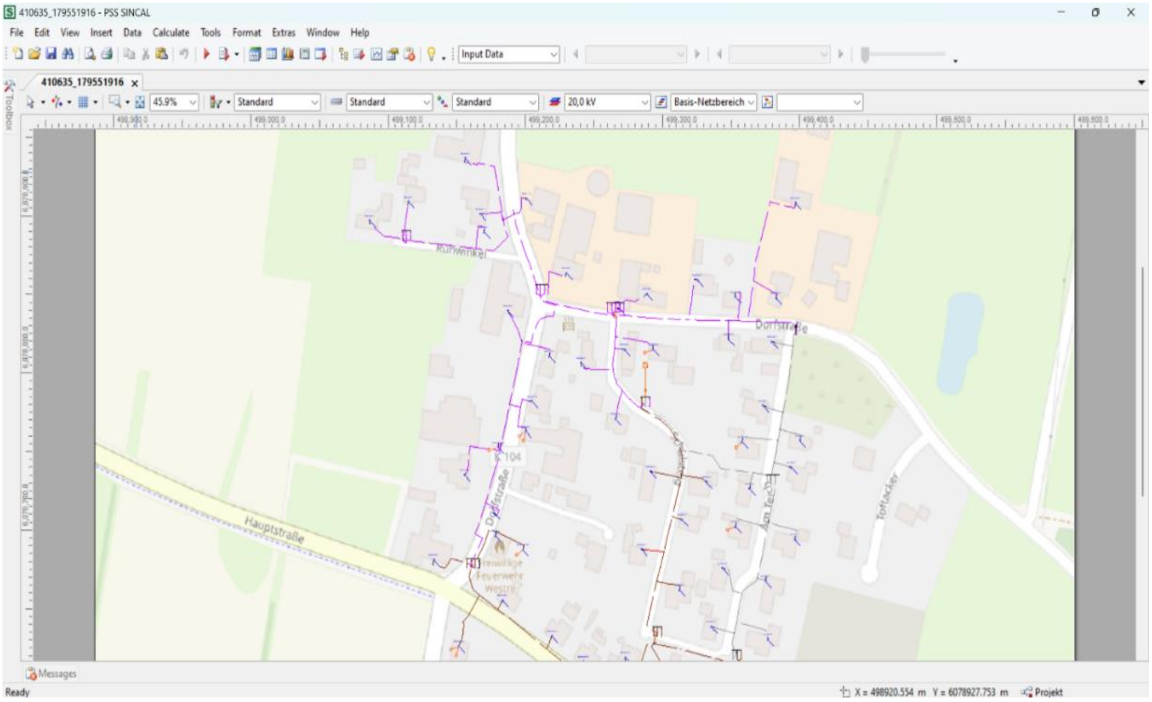


Figure 3-3: LV network model in PSS SINCAL system

3.2 Model Description and Equations for SC analysis

The general complex equation for the short-circuit current is given by:

$$Isc = \frac{Vph}{Zsc} \quad (1)$$

Where:

- *I_sc* is the short-circuit current as a complex number
- *V_ph* is the phase voltage at the fault point as a complex number
- *Z_sc* is the total short-circuit impedance as a complex number

The phase voltage can be represented as a phasor in polar form:

$$Vph = \mathrm{V_{ph}} \angle \, \theta\_V \quad (2)$$

Where:

- *V_ph* is the magnitude of the phase voltage
- *θ_V* is the phase angle of the voltage (relative to a reference)

The total impedance in the circuit from the source to the fault point is expressed as:

$$Zsc = Rsc + jXsc \quad (3)$$

Where:

- *R_sc* is the resistive component of the impedance
- *X_sc* is the reactive component of the impedance
- j is the imaginary unit (j^2=−1), which accounts for the phase difference between the resistive and reactive components.

The complex short-circuit current can be calculated by dividing the complex voltage by the complex impedance:

$$Isc = \frac{\mathrm{Vph} \angle \, \theta\_V}{\mathrm{Z\_sc}} \quad (4)$$

To simplify this complex division, we often convert the impedance Zsc to its polar form:

$$\mathrm{Z_{sc}} = \sqrt{Rsc^2 + Xsc^2} \tag{5}$$

Determine the phase angle of the impedance:

$$\theta_\mathrm{Z} = tan^{-1}\frac{Xsc}{Rsc} \tag{6}$$

Now, the impedance can be expressed in polar form as:

$$Zsc = |\ Zsc\ |\ \angle\theta z \tag{7}$$

Thus, the short-circuit current becomes:

$$Isc = \frac{\mathrm{Vph} \angle \theta\_\mathrm{V}}{\mathrm{Z\_sc}} = \frac{\mathrm{V\_ph}}{|\mathrm{Z\_sc}|} \ \angle\,(\theta_\mathrm{V} - \theta_\mathrm{Z}) \tag{8}$$

The magnitude of the short-circuit current and its phase angle can be calculated as:

$$|\mathrm{Isc}| = \frac{\mathrm{V_{ph}}}{\sqrt{Rsc^2 + Xsc^2}} \tag{9}$$

The phase angle of the short-circuit current indicates the phase shift between the voltage and the current at the fault point.

$$\theta_{Isc} = (\theta_\mathrm{V} - \theta_\mathrm{Z}) \tag{10}$$

The complex equation for single-phase short-circuit current analysis considers both the magnitude and phase of the voltage and impedance (Benoît de METZ-NOBLAT, 2005). The total impedance includes both resistive and reactive components, and the resulting short-circuit current is a phasor that reflects the complex interaction between these components and registered in the form of a matrices within the database file. Overall, this approach provides a more complete picture of the electrical behavior during a fault, crucial for accurate analysis and protective device coordination in power systems.

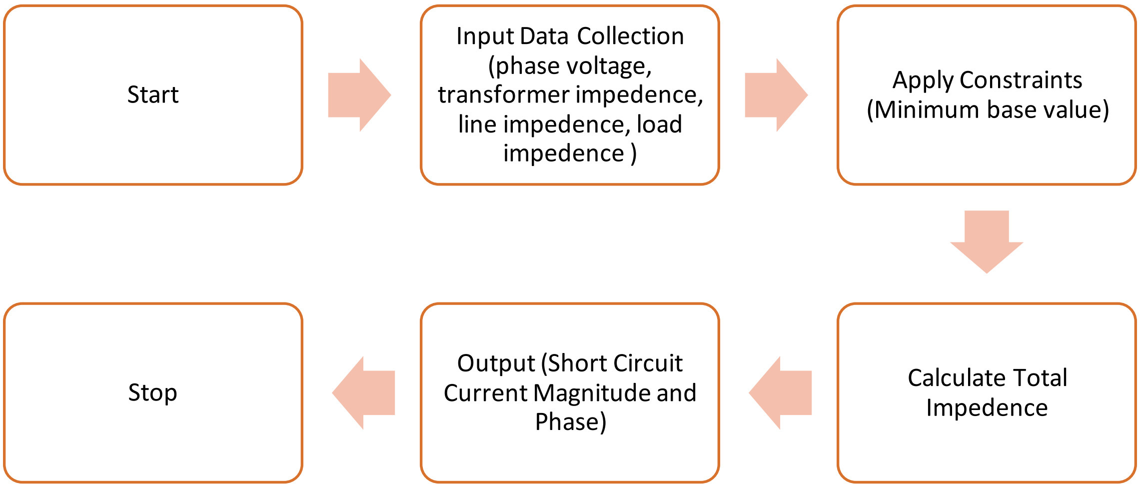


Figure 3-4: Process flow to perform single phase short circuit analysis

3.3 Comprehensive Short Circuit Analysis Simulation using PSS SINCAL

PSS SINCAL Short Circuit is an effective tool for illustrating, simulating and evaluating electrical transmission and distribution networks. In SINCAL Short Circuit calculates the electrical values for current, voltage and power with 1-, 2- and 3-phase short circuits according to the standards VDE or IEC, IEEE C37, Engineering Recommendation G74 or Initial load analogous to VDE or IEC. (SIEMENS, 2020).

The following steps are necessary to perform the SC calculations in PSS SINCAL:

- Define and set parameters in the short circuit procedure in the short circuit calculation settings
- Switch the short circuit calculations ON in the network level data
- Set parameters for the source voltage in the network level data (if required by the procedure)

The speed of the network calculations depends primarily on four factors:

- Network size and topology
- Number of controlled elements

- Calculation type
- Available storage capacity

The short circuit calculations simulate short circuits in an electrical network that has rated series and shunt admittances and rated electromotive generator voltages. The equipment determines the series and shunt admittances. SINCAL searches for currents and node-point voltages when there are short circuits at nodes. The symmetrical components must be used for short circuit calculations in strict compliance with standards such as VDE 0102, IEC 909, IEC 61363, Recommendation G74 and IEEE C37 and GOST given in the interface.

The sum of the currents flowing to the node is equal to the sum of the leakage. Thus, the node equations produce the following set of linear equations:

$$Y \times \varphi = I \tag{11}$$

Where:

Y is node admittance matrix

φ is vector for node potential

I is vector for feed current at respective node

The main diagonal links are equal to the sum of the admittances that lead to the specific node point. The secondary diagonal links are equal to the negative value of the shunt admittance between two nodes.

In a generator node, current I is the product of the generator source voltage and generator admittance. At the fault node, current I is equal to the fault current. For other nodes Current I is equal to zero. To calculate node power, one needs to calculate current I on the right side of the set of equations. It is assumed that the source voltages of the generator have been provided in input. Each generator can have a different source voltage. Thus, compensating currents would already flow before the short circuit occurs.

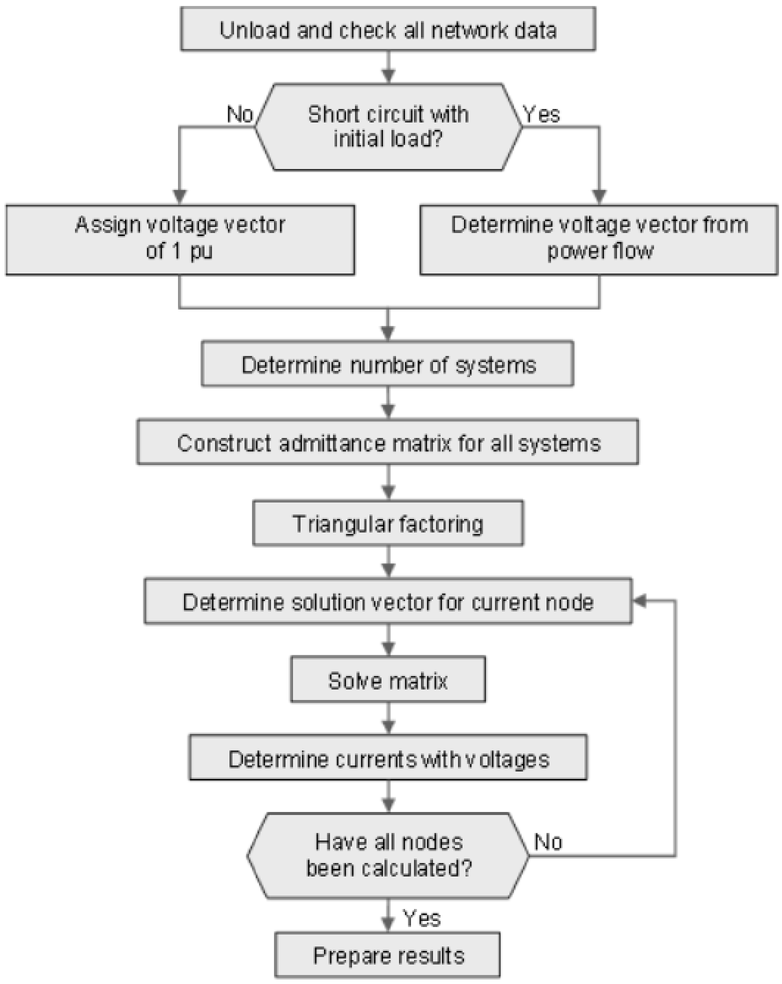


Figure 3-5: Short circuit calculation method in PSS SINCAL

3.3.1 Short Circuit Modeling

The simulation of the LV network elements is conducted based on phase values. When phase value simulation is selected, the network is modeled using phase values, which may be necessary for short-circuit calculations. However, it is important to note that this short-circuits calculation will not fully adhere to standard compliance but rather approximate standard conditions. The phase values for the supply conductors (L1, L2, and L3) and the neutral conductor (N) are derived from the positive-sequence and zero-sequence data of the network elements.

3.3.2 Short Circuit Calculation Settings

Temperature at End of SC converts the active resistance of lines to the indicated temperature in minimum short circuit calculations. During this research the standard VDE102/IEC 909 (Kurzschlussstromberechnung, 2022) was considered in the calculation settings of PSS Sincal.

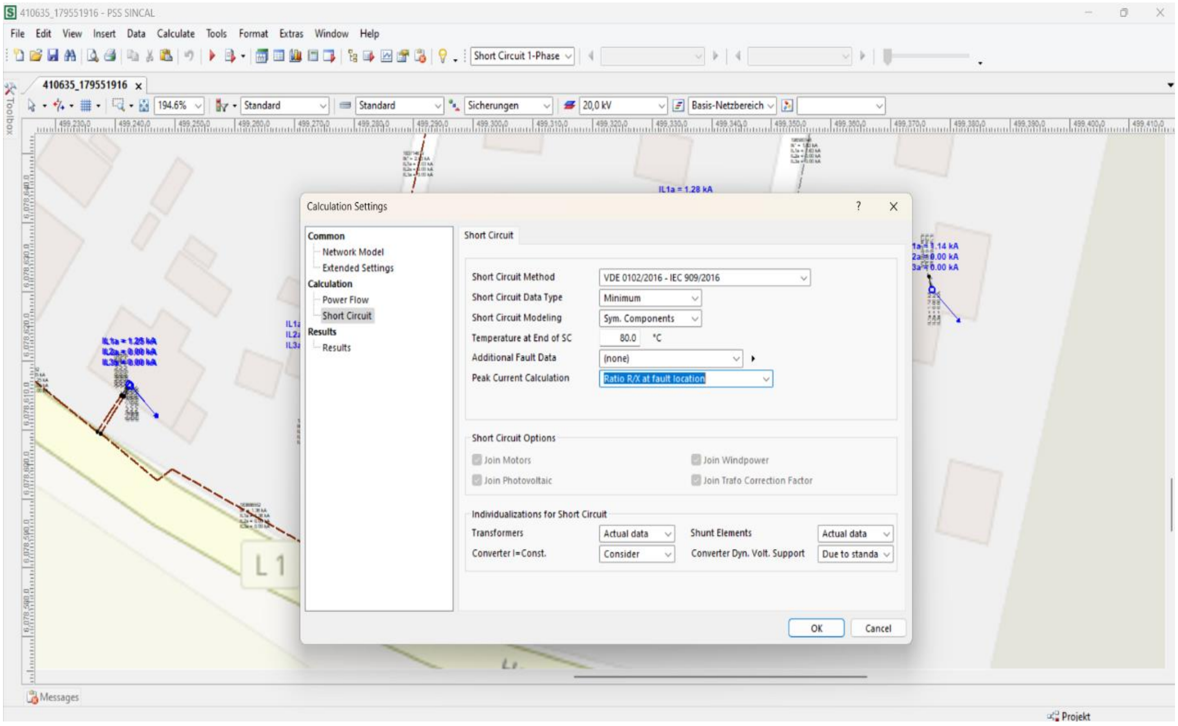


Figure 3-6 Short Circuit Calculation Setting

According to VDE102/IEC 909 (Kurzschlussstromberechnung, 2022) the following assumptions in calculation methods are considered

- Uniform ratio R/X: With this method, the factor kb is defined with smallest R/X ratio.
- Ratio R/X at fault location and Ratio R/X at fault location R/X < 0.3: With this method, factor kb is also multiplied by the factor of 1.15. With the Ratio R/X at fault location < 0.3 method, the factor is only used if R/X stays less than 0.3 in all branches.
- The factor kb is limited to 1.8 in low voltage networks and 2.0 in medium and high voltage networks.

- Equivalent frequency
- Radial network

Furthermore, the Short Circuit Data field also influence the short circuit calculations in the calculation settings can as follows:

- Standard: Current short circuit power with network feeders
- Minimum: Minimum short circuit power with network feeders
- Maximum: Maximum short circuit power with network feeders

Unlike the maximum short circuit current analysis whereby assuming all generating units are online, all lines and transformers are in service, and all potential current sources (like synchronous generators, large motors, etc.) can contribute to the fault conditions.

This analysis assumes the most unfavorable conditions for fault current contribution, such as the outage of significant generating units, or elements being out of service, which increase the system impedance. Moreover, this minimum short-circuit current is vital and helps to set up protective relays and devices at certain values.

The difference between the minimum and maximum single-phase short-circuit current analysis lies in the varying conditions that affect the magnitude of the short-circuit current. These conditions include the system configuration, source impedance, and load conditions at the time of the fault.

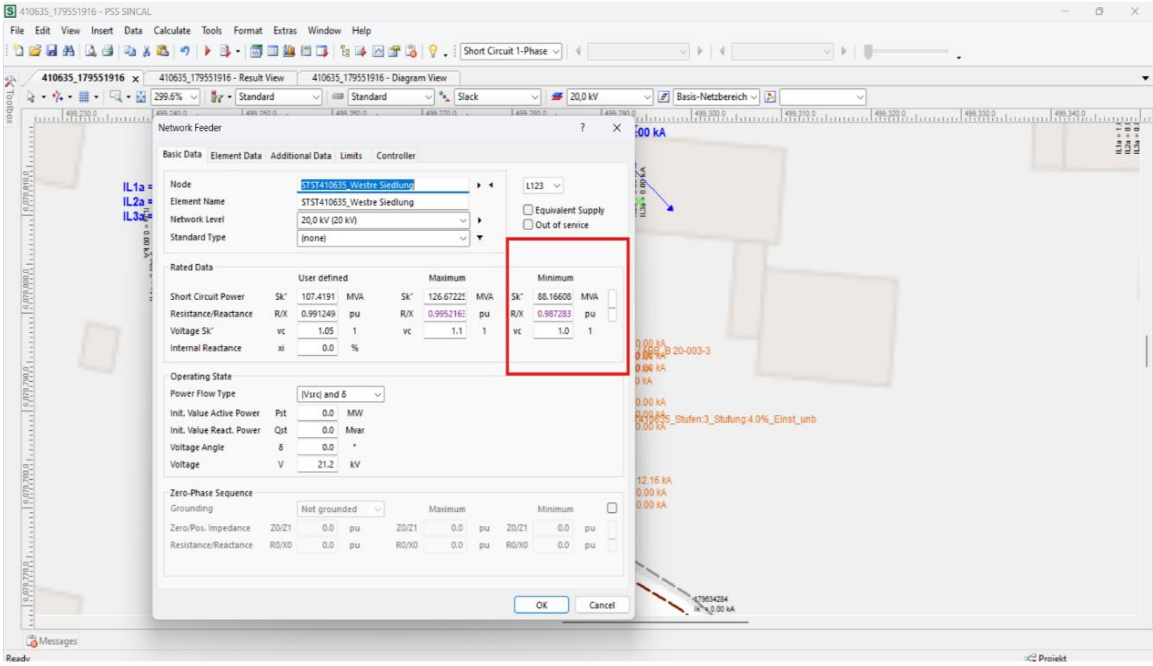
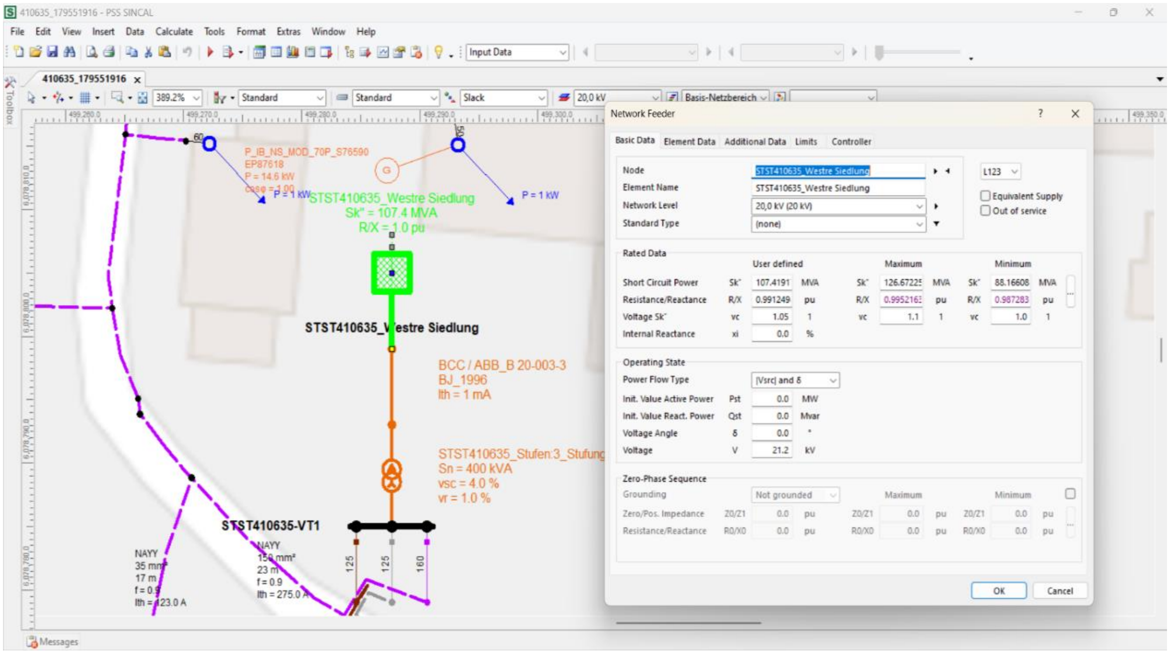
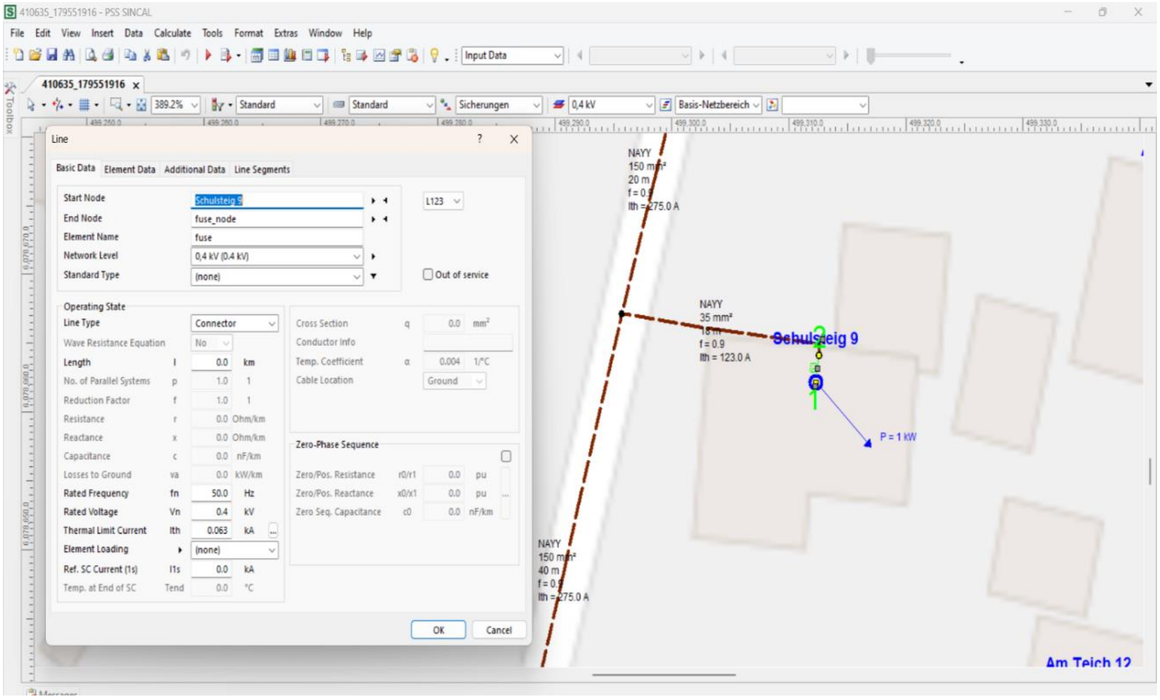


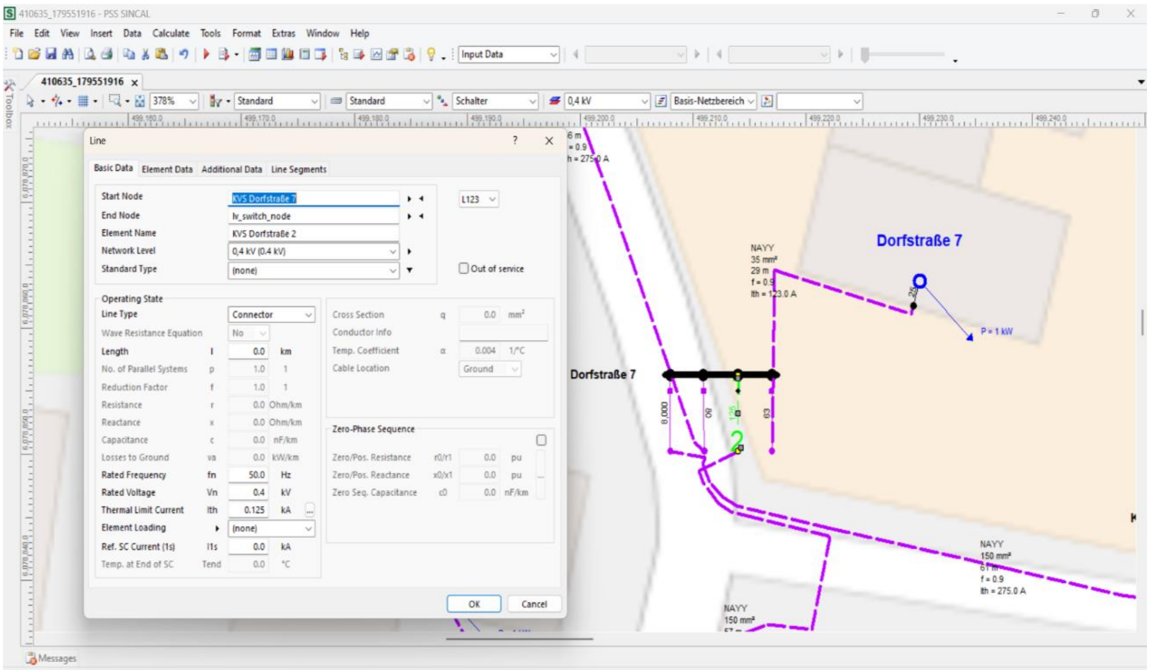
Figure 3-7: Setting up minimum value constraint

Step 1: Check all the input elements of the LV network model (such as lines, nodes)

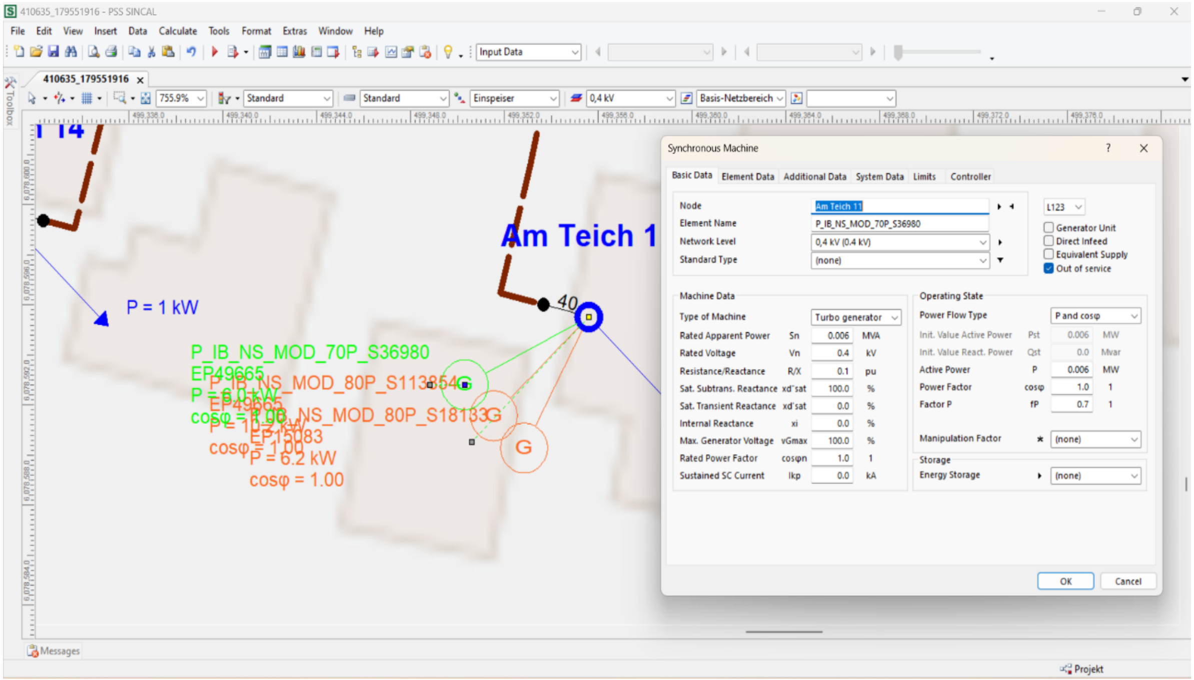


Step 2: Identify all the power fuses (households and cabinets) in the LV network

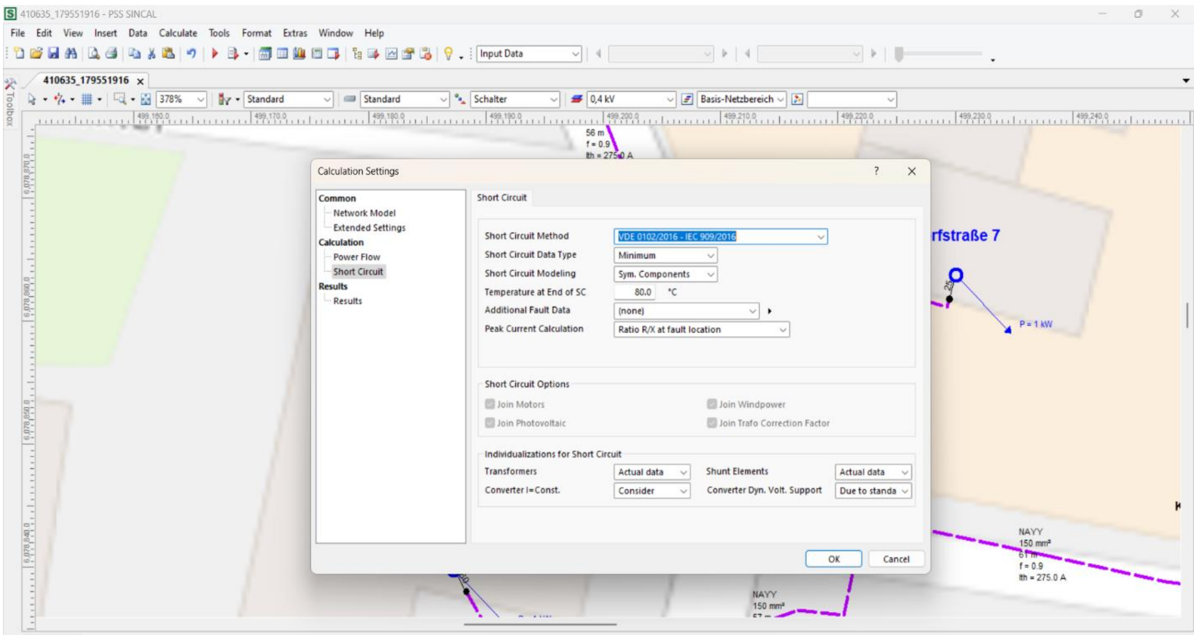




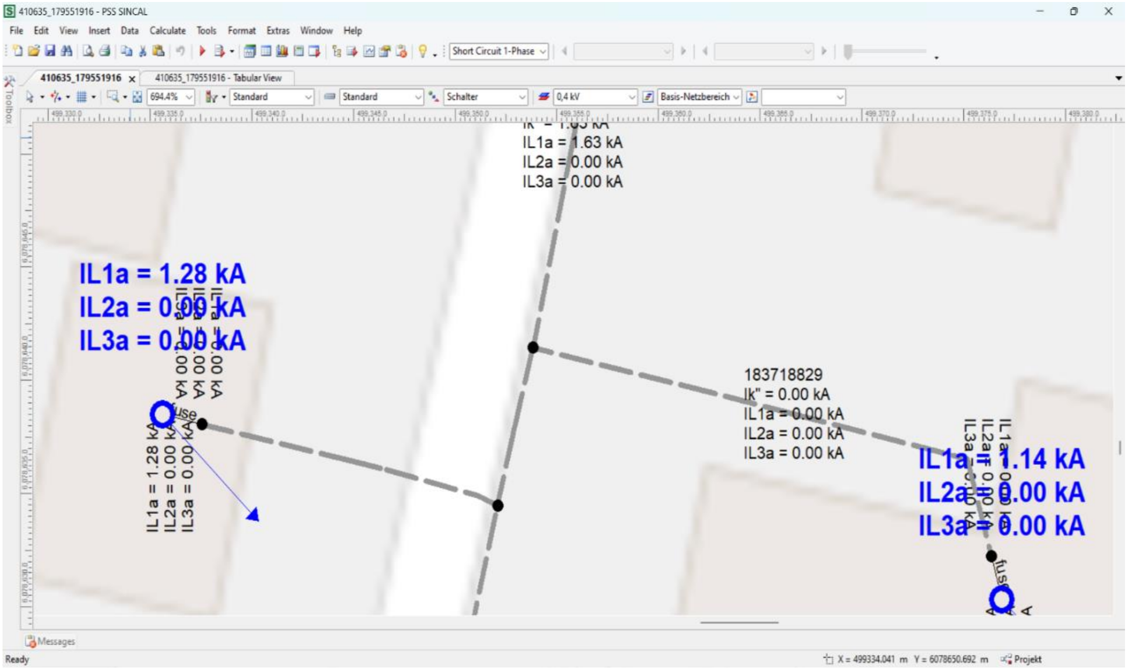
Step 3: Setting all the generators out of order connected in LV the network



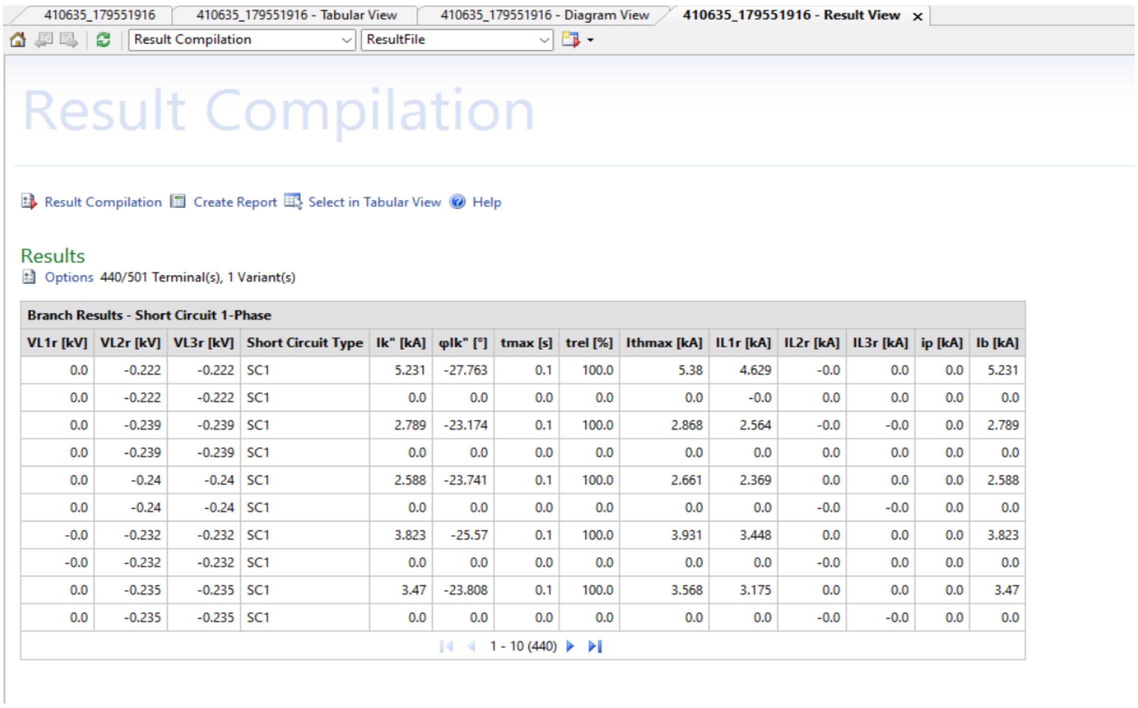
Step 4: Control the paramters to perform single phase SC calculations



Step 5: Run the model and check the magnitude of short circuit current on each fuse (at each households and cabinets)



Step 6: Result Compliation (Branch and Node results and comlied into one table)



410635_179551916 | 410635_179551916 - Tabular View | 410635_179551916 - Diagram View | **410635_179551916 - Result View**

Result Compilation | ResultFile

Result Compilation

Result Compilation | Create Report | Select in Tabular View | Help

Results

Options 440/501 Terminal(s), 1 Variant(s)

Branch Results - Short Circuit 1-Phase

VL1r [kV]	VL2r [kV]	VL3r [kV]	Short Circuit Type	Ik" [kA]	φIk" [°]	tmax [s]	trel [%]	Ithmax [kA]	IL1r [kA]	IL2r [kA]	IL3r [kA]	ip [kA]	Ib [kA]
0.0	-0.222	-0.222	SC1	5.231	-27.763	0.1	100.0	5.38	4.629	-0.0	0.0	0.0	5.231
0.0	-0.222	-0.222	SC1	0.0	0.0	0.0	0.0	0.0	-0.0	0.0	0.0	0.0	0.0
0.0	-0.239	-0.239	SC1	2.789	-23.174	0.1	100.0	2.868	2.564	-0.0	-0.0	0.0	2.789
0.0	-0.239	-0.239	SC1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	-0.24	-0.24	SC1	2.588	-23.741	0.1	100.0	2.661	2.369	0.0	0.0	0.0	2.588
0.0	-0.24	-0.24	SC1	0.0	0.0	0.0	0.0	0.0	0.0	-0.0	-0.0	0.0	0.0
-0.0	-0.232	-0.232	SC1	3.823	-25.57	0.1	100.0	3.931	3.448	0.0	0.0	0.0	3.823
-0.0	-0.232	-0.232	SC1	0.0	0.0	0.0	0.0	0.0	0.0	-0.0	0.0	0.0	0.0
0.0	-0.235	-0.235	SC1	3.47	-23.808	0.1	100.0	3.568	3.175	0.0	0.0	0.0	3.47
0.0	-0.235	-0.235	SC1	0.0	0.0	0.0	0.0	0.0	0.0	-0.0	-0.0	0.0	0.0

1 - 10 (440)

3.3.3 Short Circuit Results (Node Results – Single Phase Short Circuit)

For each node in the short circuit calculations, can calculate following node results for single-phase short circuit.

- Node or network level display the name of the node or the network level for identification.
- The network modelling field shows the way in which the network was modeled for the short circuit calculation. The modeling can either be based on sequence data or phase data.
- The type of fault field shows which fault circuit was used (short circuit, return circuit, ground circuit and return and ground circuit).
- The standard field shows which short circuit method was selected for the calculation.
- The initial SC AC Power is the effective value of the sum of the alternating power expected at the moment the short circuit occurs in the individual conductors. This power is calculated with the rated voltage of the node's network level.
- The initial SC current is the maximum of the effective values of the current expected at the moment the short circuit occurs in the individual conductors. This current is calculated with the source voltage.
- The angle SC current is the negative angle (I = V/Z) of the network impedance based on the initial SC current.
- The peak short circuit current is calculated with the help of the Kappa-factor and the initial SC current. The Kappa factor is calculated according to the norm using the initial ratio R/X or X/R (G74) at the fault location.
- The initial ratio R/X is the ratio real part to imaginary part of the network impedance based on the initial SC current.
- The peak SC current ratio is the ratio peak short circuit current to maximum admissible peak current according to the limit values entered in the network level data or the node calculation data.

- The initial SC current Ratio is the ratio initial SC current to maximum admissible breaking current according to the limit values entered in the network level data or the node calculation data.
- The initial SC Power Ratio is the ratio tripping alternating power to maximum admissible SC alternating power. The tripping alternating power is calculated with the breaking current and the operating voltage listed in the network level data.
- The maximum admissible SC alternating power is calculated with the maximum admissible breaking current from the network level data (or node calculation data) and the rated network voltage obtained from the network level data
- Therm. Equivalent Current for the effective value of a current that displays the same Joule integral from the moment a short circuit occurs until the switch delay as the decaying short circuit current

3.3.4 Short Circuit Results (Branch Results – 1-Phase Short Circuit)

The branch results provide for each branch in the short circuit calculations. The powers, currents, loads and times refer to the terminal assigned to the displayed start node. PSS SINCAL provides the following branch results for 1-phase short circuit.

- Start Node, End Node, Element Name and Network Level are used to identify the terminal.
- The network modelling field shows the way in which the network was modeled for the short circuit calculation. The modeling can either be based on sequence data or phase data.
- The type of fault field shows which fault circuit was used (short circuit, return circuit, ground circuit and return and ground circuit).
- The standard field shows which short circuit method was selected for the calculation.
- The initial SC current is the maximum of the effective values of the current expected now the short circuit occurs in the individual conductors. This current is calculated with the source voltage. The conductor that has the maximum is used as the conductor with the maximum.

- The angle SC current is the angle difference between current and voltage of the conductor with the maximum.
- The peak SC current is the peak value of the maximum possible short circuit current in the conductor with the maximum. The peak short circuit current is calculated with the help of the Kappa-factor and the initial SC current.
- Therm. Equivalent Current for the effective value of a current that displays the same Joule integral from the moment a short circuit occurs until the switch delay as the decaying short circuit current.

3.4 Database Management System (DBMS)

Furthermore, the second part of the analysis focuses on refining, extracting, and testing the datasets from the SQLite database file. The model runs multiple queries on the datasets of these classes of databases because of the complex arrangement of the database files and excessive datasets. Therefore, the algorithm has been developed to just focus on extracting the necessary results after conducting the single-phase short circuit analysis method. Moreover, a detailed information flow to extract inputs (element ID, line ID, terminal ID, nominal current) and outputs (branch and node results) is provided below.

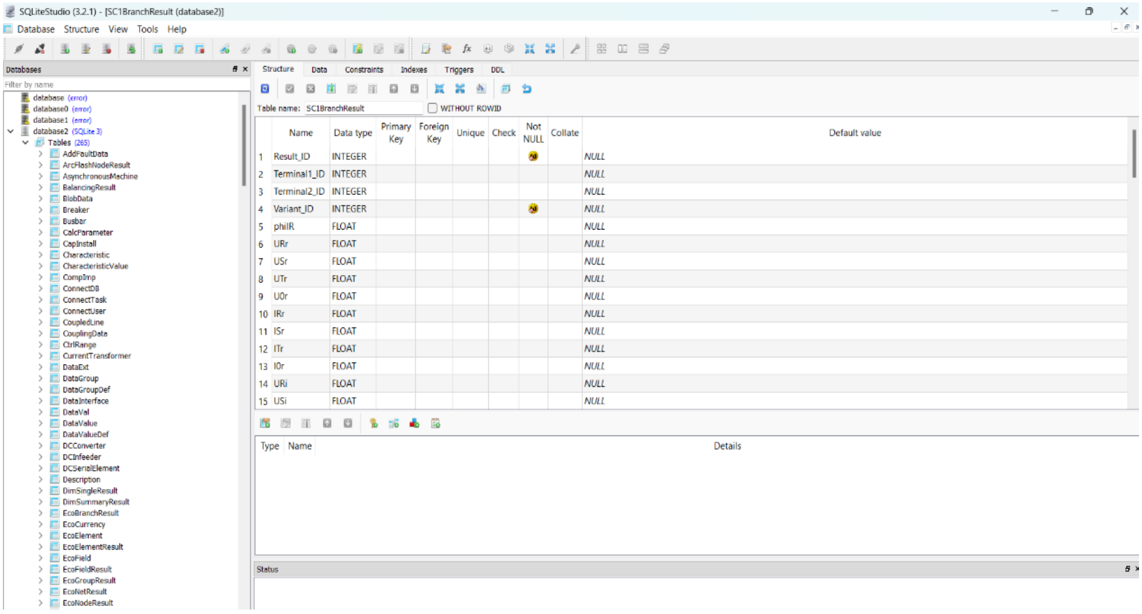


Figure 3-8 SQLite database manager of LV network

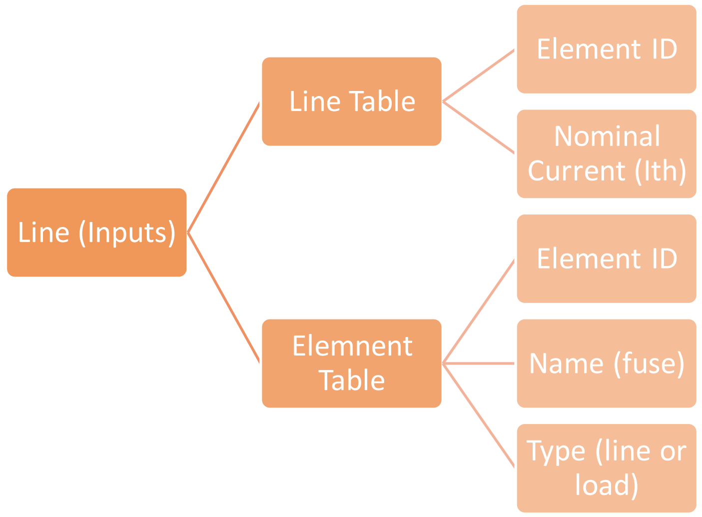


Figure 3-9: Inputs extracted from the SQLite database

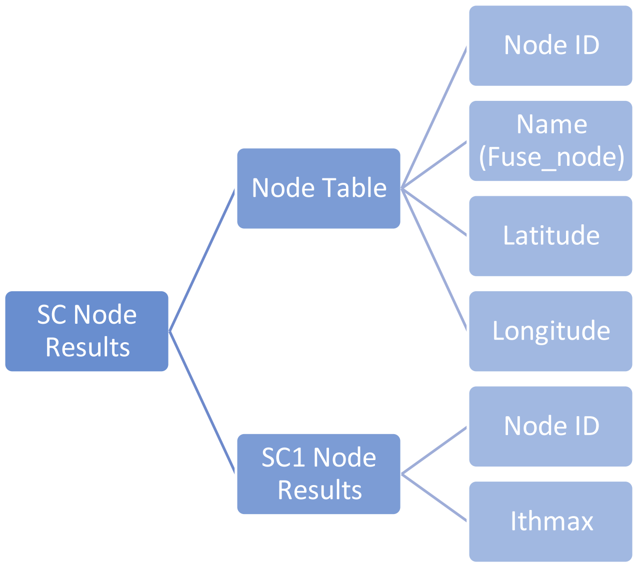


Figure 3-10 Node outputs extracted from the SQLite database

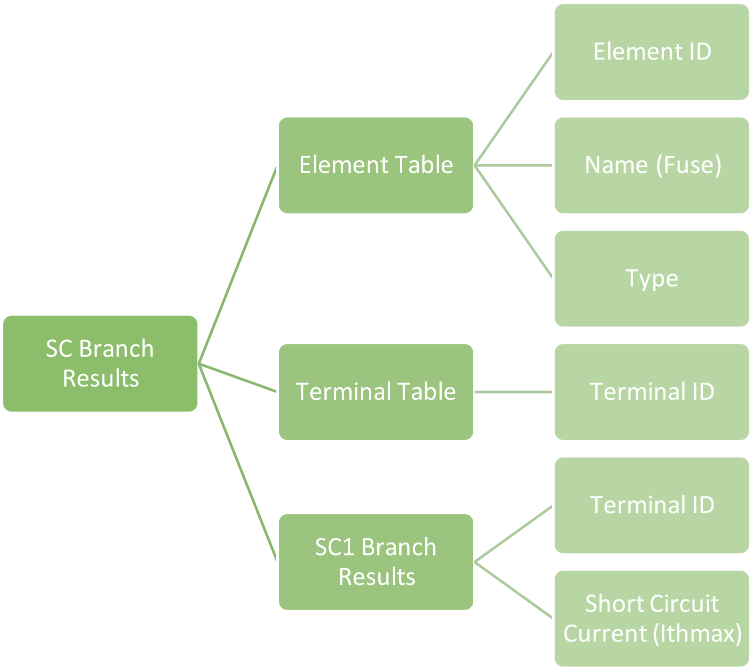


Figure 3-11: Branch outputs extracted from the SQLite database

3.5 Control Logic of Short Circuit Calculations using Python Algorithm

The development of an algorithm for dimensioning power fuses in a low-voltage (LV) network is fundamentally grounded in the control logic diagram for single-phase short circuit calculations. The code was meticulously structured to adhere to these principles, ensuring accurate and reliable results. In alignment with the control flow diagram, two databases were imported: one for accessing the dataset files and another for the PSS SINCAL file. Subsequently, a primary function for power fuse dimensioning was created, within which data from both sources was efficiently retrieved and utilized.

The model initiates by establishing a connection with the SQLite database and retrieving all necessary inputs from the attribute tables. Subsequently, it creates a specialized Sincal application object and opens the Sincal LV grid model document. In the following steps, the model executes a single-phase short-circuit current analysis, adhering to the IEC standard (VDE 0102/2016 - IEC 909/2016) (Comission I. E., 2016), with the base scenario set to minimum short-circuit current conditions.

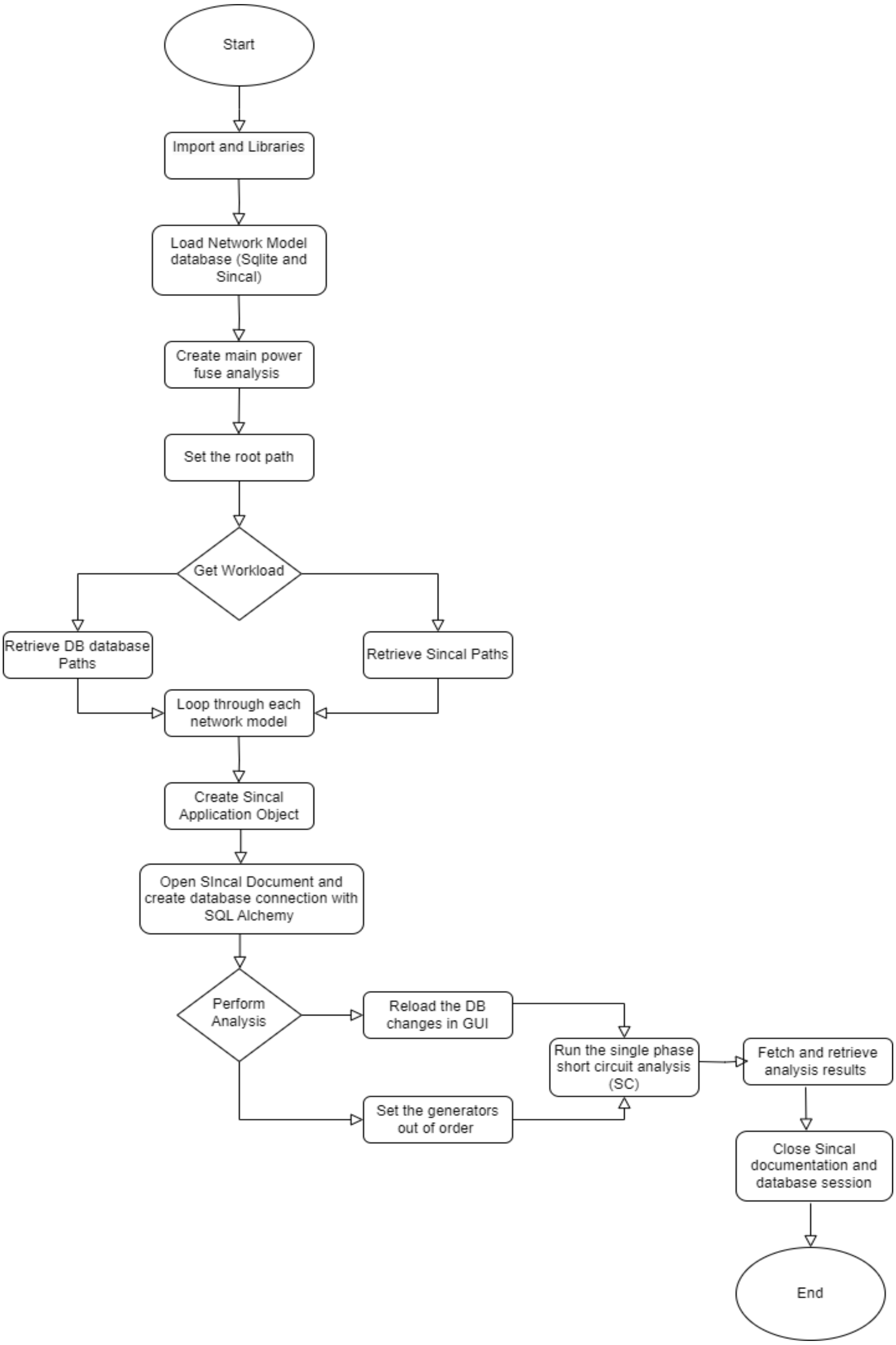


Figure 3-12: Process flow of single phase short-circuit analysis algorithm

Under these conditions, the model deactivates all generators and adjusts the network feeder parameters to reflect minimum short-circuit current characteristics, including the lowest short-circuit power, resistance/reactance values, and per-unit voltage. This approach ensures that the short-circuit current is minimized, thereby determining the lowest possible current that could occur during a fault. This is crucial for ensuring that protection systems remain sensitive enough to reliably detect and respond to faults. The key purpose of designing the algorithm is to protect the LV grid from outages in case of any fault in the LV network. Although it's hard to find and quantify the monetary losses during a fault condition, but some studies estimate the cost of power interruptions.

3.6 Cost estimation of Power Interruptions (Value of Lost Load)

In the case of calculating the grid outage cost for a Distribution System Operator (DSO) is crucial for understanding the economic impact of power interruptions on customers. The cost involves several factors, including the duration of the outage, the number of customers affected, the type of customers, and the value of lost load (VoLL).

This study (Christian Growitsch, 2013) follows a macroeconomic approach and analyzes the economic costs imposed by potential power interruptions in Germany. It focuses on industrial as well as household consumers to estimate Values of Lost Load (*VoLLs*) and associated costs of power interruptions. The hourly outage costs in any federal state of Germany can be calculated by multiplying VoLL by current power consumption. The mathematical equation for the cost estimation of hourly outages in any sector is given below

$$VoLLs, f = \frac{GV\ As, f}{ECs, f} \tag{12}$$

Where:

VoLLs,f is defined as values of lost load sector s in federal state f

GVAs,f is annual defined as gross value added by sector s in federal state f

ECs,f is defined as annual electricity consumption of sector s in federal state f

Moreover, the time-varying outage costs within sector s in federal state f at a specific hour t are

$$OCr,f,t = \frac{GV\ As,f}{ECs,f} \times ECs,f,t = \ GV\ As,f\ \times\ lfs,t \tag{13}$$

Where:

lfs,t is defined as hourly load factor

ECs,f,t is defined as annual electricity consumption of sector s in federal state f with respect to time

The findings of this research underscore the importance of economic efficiency in managing electricity supply shortages. According to economic theory, load shedding, when necessary, should be directed toward customers who incur the least welfare loss from power supply interruptions. Furthermore, a deep dive research on the DSO level can be conducted to estimate cost estimation for grid outages in various areas of the distribution network. In the next section, the project tries to converge into more modeling of the program and validate the results section as per the grid code provided by DSO.

4 Analysis and Results

According to the Planning Principles for Electricity document or grid regulation by SH Netz, it's vital that the rated current of the fuse must be selected so small that in the event of a fault at least the large test current 1.6 * inflows. Or, if a certain rated current of the fuse is required due to the current being transmitted, a correspondingly high cable cross-section or a correspondingly short cable length must be realized so that the current can flow.

Although, the standard requirement short circuit current requirement for a power fuse is Isc > 1.6 x In (inflow of current) should only be used for SHNG in justified individual cases. But as per the stringent grid requirements Isc > 2.5 x following regulations which is used for dimensioning the power fuses and applied to network installations that are older than 40 years. This also provides a certain reserve concerning current-limiting inter-feed effects of arcing faults.

Furthermore, the principles should always apply that a nominal fuse current should be selected as low as possible, and the maximum permissible value should only be exhausted if the (prospective) connected power makes it necessary. During the programming of designing the algorithm for power fuse dimensioning, these regulations provided by the DSO SH Netz have been adhered to. Based on the analysis performed by the program or code, the results are extracted for various LV networks of Schleswig Holstein.

4.1 Case Studies for Model Validation in Low-Voltage Networks

The result section has been divided into various case studies that identify the technical parameters such as secondary substation, test loads, cabinet and household fuses, lines, and RE generators of the LV network. Then the scenarios are segregated based on high, medium, and low population density in the LV network. Finally, the results show scatter plots identify various fuses that are underperforming or need to be replaced from the LV network.

4.1.1 Model validation on high population density area

All the inputs required to validate the Python based algorithm for high population density area are given below in the table 4-1 with a sketch of that particular LV network.

Table 4-1: Specifications of LV network elements

Element Name	Technical Specifications	Value	Quantity
Transformer (STST418108)	Two-winding transformer	20kV/0.4KV	1
Household Fuses	Fuses	25A to 63A	73
Cabinet Fuses	Fuses	63A to 250A	53
RE Generators	Solar PV Rooftop	4.9kWp to 11.8Wp	9
Test Loads	Household Load	1kW	73
Lines	LV Distribution Lines	0.4kV	166

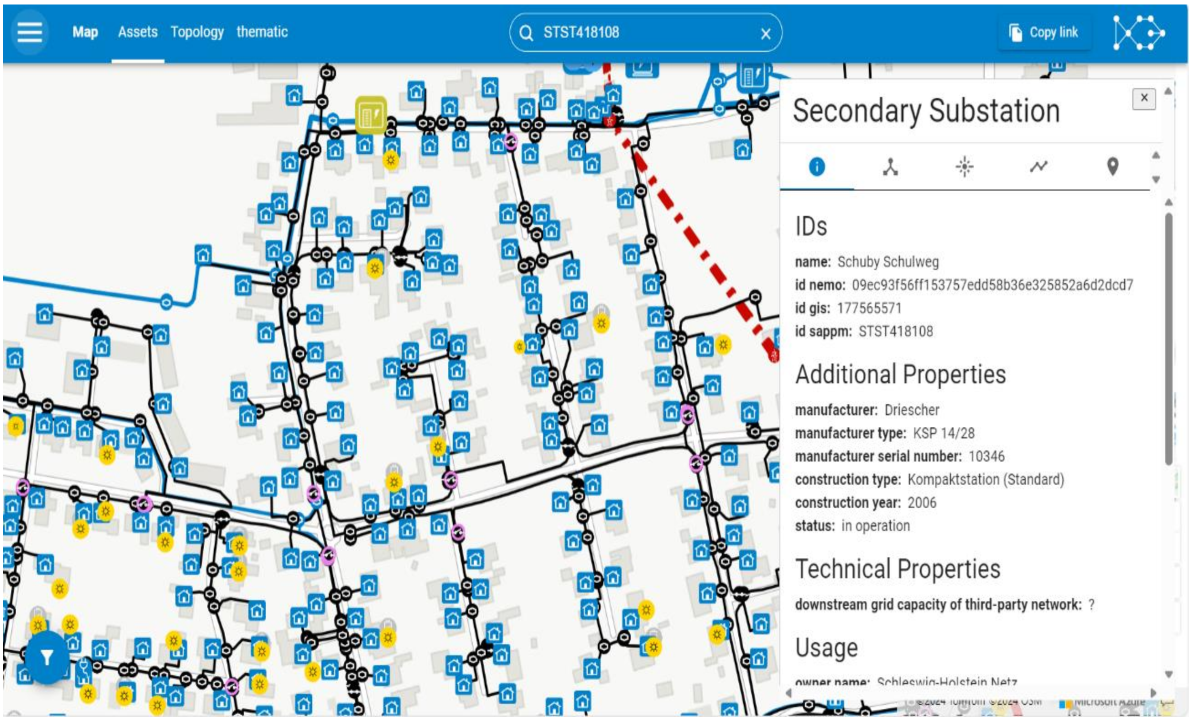


Figure 4-1: LV network with high population density

4.1.2 Model validation on medium population density area

All the inputs required to validate the Python based algorithm for medium population density area are given below in the table 4-2 with a sketch of that particular LV network.

Table 4-2: Specifications of LV network elements

Element Name	Technical Specifications	Value	Quantity
Transformer (STST410635)	Two-winding transformer	20kV/0.4KV	1
Household Fuses	Fuses	25A to 100 A	54
Cabinet Fuses	Fuses	60A to 160A	30
RE Generators	Solar PV Rooftop	9.6Wp to 50kWp	14
Test Loads	Household Load	1kW	54
Lines	LV Distribution Lines	0.4kV	130

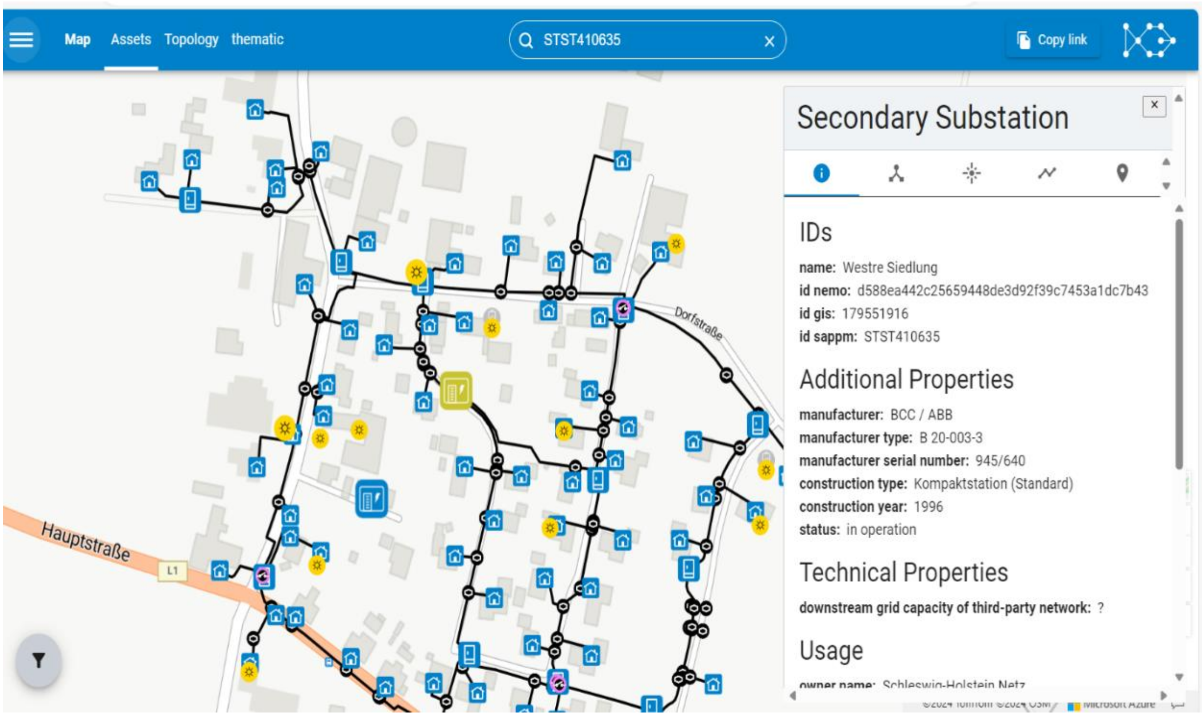


Figure 4-2: LV network with medium population density

4.1.3 Model validation on low population density area

All the inputs required to validate the Python based algorithm for low population density area are given below in the table 4-3 with a sketch of that particular LV network.

Table 4-3 Specifications of LV network elements

Element Name	Technical Specifications	Value	Quantity
Transformer (STST410272)	Two-winding transformer	20kV/0.4kV	1
Household Fuses	Fuses	25A to 63A	32
Cabinet Fuses	Fuses	63 A to 200A	27
RE Generators	Solar PV Rooftop	7.7 kWp to 30kWp	5
Test Loads	Household Load	1kW	32
Lines	LV Distribution Lines	0.4kV	86

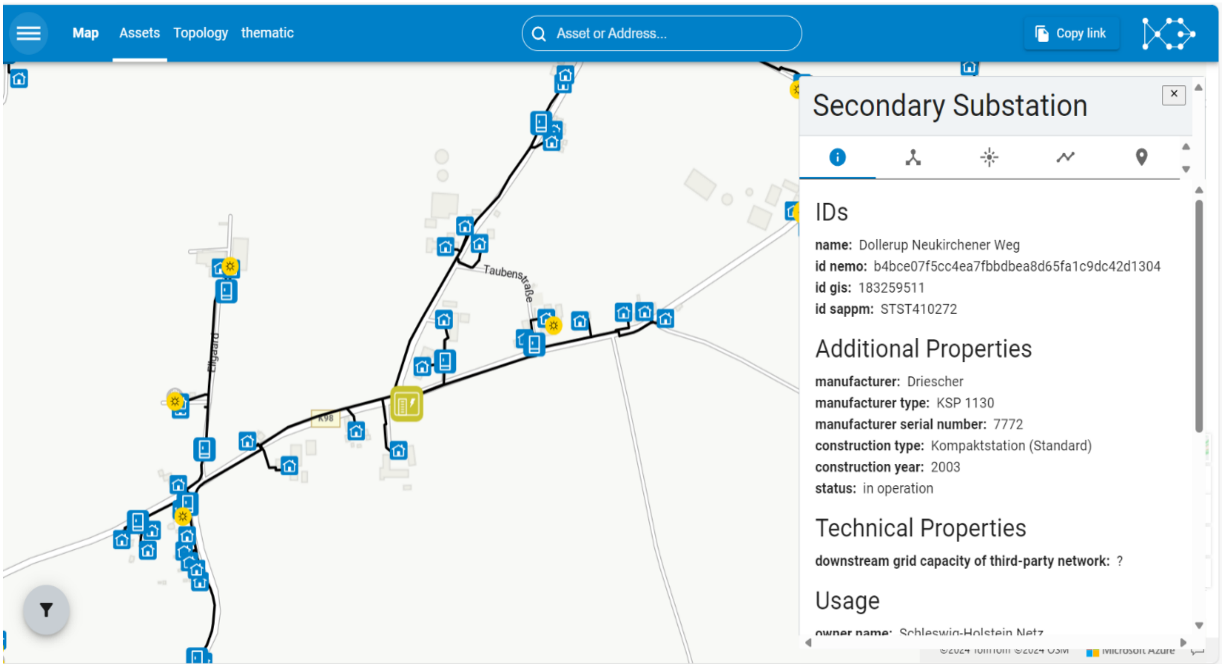


Figure 4-3: LV network with low population density

4.2 Power Fuse Selectivity Analysis

Based on the model development during this research, these results for power fuses (households and cabinets) are obtained for selectivity analysis of power fuses. The results were obtained based on the fundamental equations of single-phase short circuit current analysis and as per the grid regulations of SH Netz. Each fuse has its unique Element ID which helps to evaluate the ratio of nominal current and short circuit current. Some of the factors such as short circuit power, ratio (R/X) at fault location, the magnitude of voltage, the temperature at the end of SC (degree Celsius), and short circuit method (VDE 0102/2016 - IEC 909/2016) (Comission I. E., 2016).

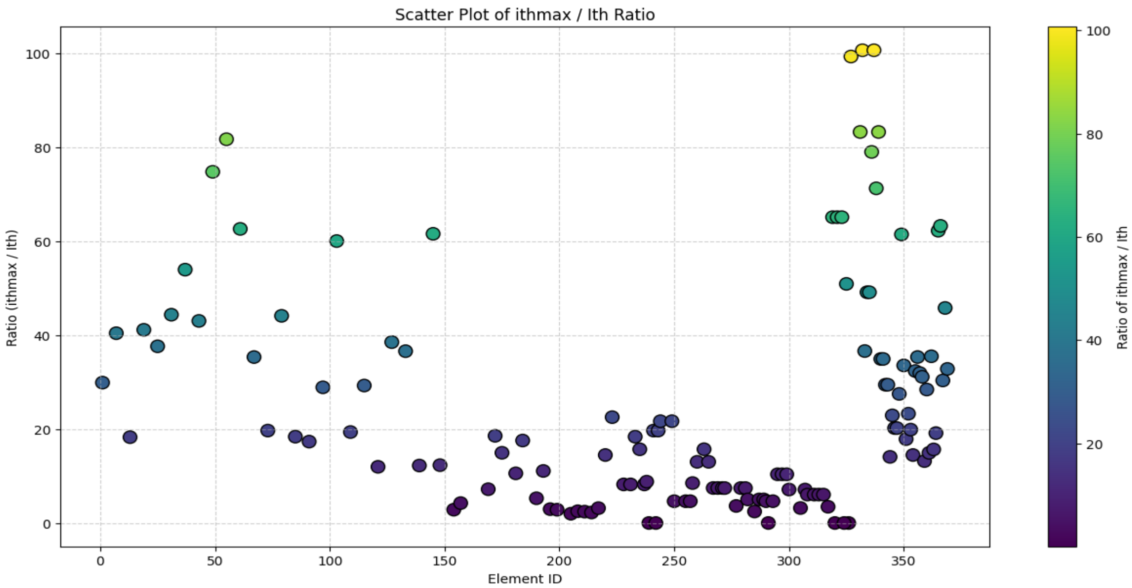


Figure 4-4: Power fuse selectivity in high population density area

As we can observe in the above figure there’s a high density of power fuses which have the ratio of Ithmax and Ith (short circuit current and rated current) close to zero. This shows as per the grid regulations these power fuses at households or cabinets need to be replaced in the LV network. These fuses can be identified using their respective Element ID from the element table from the SQLite database.

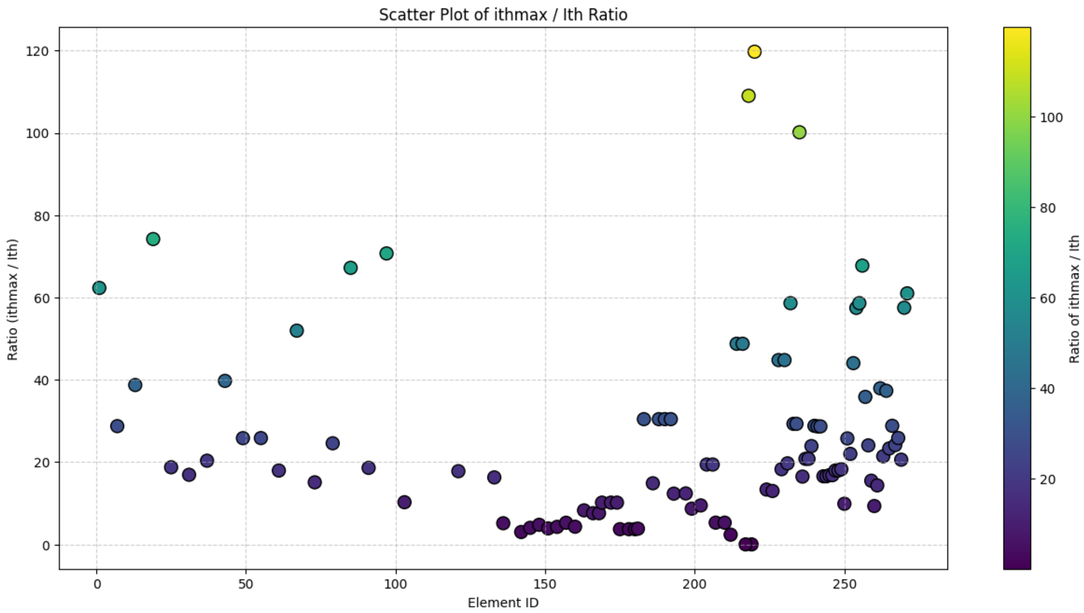


Figure 4-5: Power fuse selectivity in medium population density area

Some of the fuses seem to be having high transient short circuit current that's why the ratio between the short circuit current value and nominal current is much higher than expected. It has been identified that some of these fuses are oversized based on their actual power or current capacity. In the case of a medium population density LV network, there are few fuses that don't adhere to the grid regulations and have a ratio value lesser than 2.5 (which is mentioned above in the standard principles guidelines)

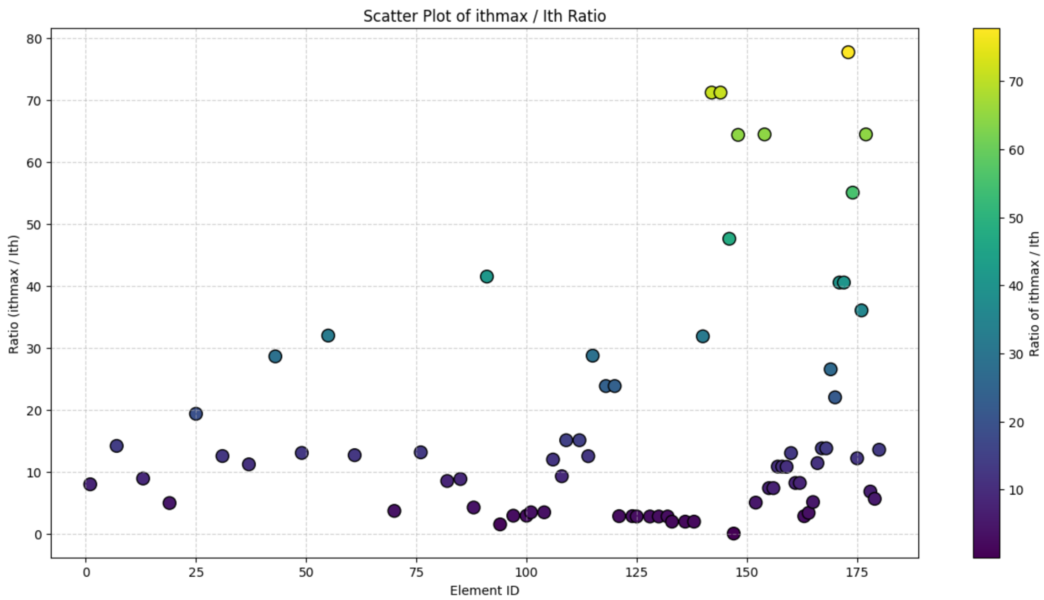


Figure 4-6: Power fuse selectivity in low population density area

Further, in the case of low-population-density areas where fewer loads are connected to the LV network. Only a handful of the power fuses in households and cabinets need to be replaced by higher-capacity fuses. This system arrangement also requires the upgradations of LV lines as well. Therefore, there will be significant costs which will be associated with the upgradation of the LV network. Also, some of these fuses which are connected to cabinets need to be replaced due to high priorities because, in case of any fault, this could lead to further power interruptions or grid outages in that particular area. Further, this research tries to perform a network graph analysis using the node input and short circuit node results using latitude and longitude.

4.3 Network Graph Analysis using Node Results

At the beginning of the process, an LV network needs to be visualized and initialized with network graph analysis (NetworkX library in Python). The NetworkX library allows to be mapping of networks with various topologies. First, each node ID of all the elements in the network needs to be extracted from the database.

Next using the Kamada-Kawai layout helps particularly for the distribution network visualization. It aims to position nodes in a way that minimizes the overall energy of the system, resulting in a more visually appealing and interpretable layout. First, the Kamada-Kawai algorithm calculates the right positions of the nodes using the latitude and longitude input values. Then creating a conditioning scenario and identifying relationships between these nodes, a graph network can be customized and established.

The nodes will be connected according to the rule of the LV network joint. It starts with a network feeder mapped in green color which is connected to the primary side of the secondary transformer (20kV/0.4kV). Further, the secondary side of the transformer is connected to the nearest cabinet box. Further, these cabinets fuses (marked in orange) are connected to the household load (marked in purple color). Every fuse in the network is connected using 0.4kV lines.

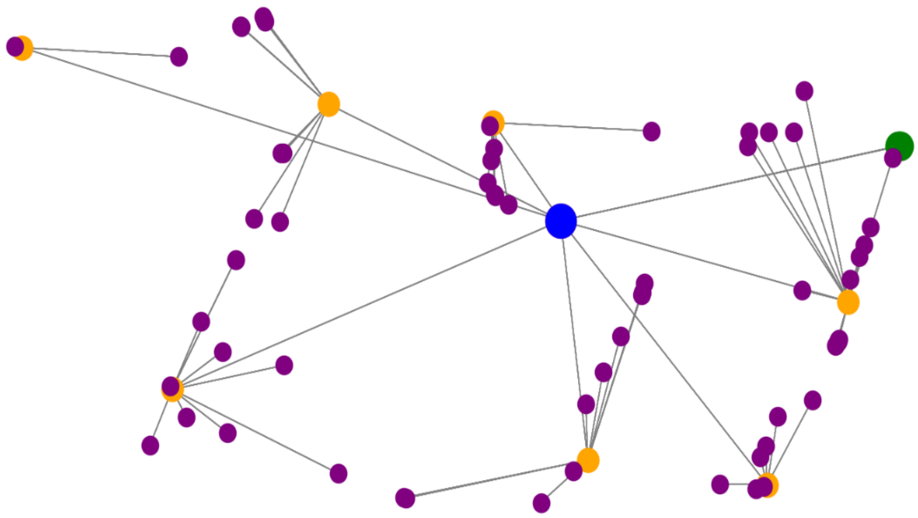


Figure 4-7: Graph Analysis using Python Programming

However, the program tries to find the shortest or most efficient path between two nodes, such as from a transformer to a load. Yet the model isn't fully capable of pulling all the network node data, identifying each element individually, and visualizing a network graph. However further development in the model could perform more efficient graph analysis and identify the shortest path, which can optimize the routing of electrical power and minimize losses.

Also, in case of an event of network failure or fault condition, the model could support to increase in the resilience of the LV network and ensure efficient routing, while minimizing the downtime and maintaining the power supply in critical load areas such as hospitals or offices. Moreover, detailed network graph analysis needs to be carried out using the LV network datasets but that essentially requires expertise in handling big data and the use of machine learning/artificial intelligence techniques.

5 Conclusion

At the beginning of this master thesis, it was identified that there are certain challenges when it comes to the integration of low-carbon technologies such as solar, heat pumps, and electric vehicles. Henceforth the electricity grid must be well prepared for seamless integration of any new technologies. The research has identified that challenges such as voltage fluctuations, fault management, and grid outages happen due to the reason of unpredictability of unpredictable load and generation.

This study underlines the importance of power fuses in low-voltage networks for maintaining the stability and safety of the whole system. Moreover, after performing dimensioning and selectivity analysis, the study addresses major aspects of grid resilience and fault protection. On top of that the framework and control logic built provide single-phase short circuit current analysis and evaluate the performance of power fuses in various scenarios while ensuring that the fuses (households and cabinets) function correctly. This reduces the risk of any electrical equipment damage during the fault condition, or power outage and tries solving other operational challenges.

The key highlight of this master thesis is the development and implementation of a Python-based algorithm for analyzing and optimizing fuse performance in LV networks. This algorithm helps to identify the underperforming fuses that may require urgent replacement as well as automates the analysis process for three different cases. The analysis revealed that several fuses do not comply with grid regulations, exhibiting a ratio value of less than or close to 2.5. Notably, in high population density areas, a higher number of fuses require replacement compared to those in medium and low population density regions. Moreover, these fuses which are close to the minimum required ratio must be replaced, and the connection types need to be upgraded as per the grid codes (mentioned in Table 1-1 and 1-2). This discrepancy underscores the need for targeted interventions to ensure compliance and enhance the reliability of the network across different population densities. The result section highlights the importance of taking specific actions to ensure that the network reliability and meets the required standards, especially in areas with varying population densities.

This research also provides an analysis of various European LV grids and provides valuable insights into the differences in grid topology, fault types, and cost impacts across different regions. This information is critical for the distribution system operator (DSO) in various countries to compare and plan their future network.

In addition to the analysis of dimensioning of fuses, this study also shed some light on digital tools, such as network graph analysis, in enhancing the visibility and controllability of LV networks. Also, the Kamada-Kawai method allows for the visualization of various topologies and identifies the shortest path between two node points (or elements) in the LV network. It finally lays out a groundwork for the future development of machine learning models to improve network analysis and fault detection.

Future Tasks

The areas of study mentioned below require further attention after the completion of this research

- Expansion of the model from one LV network at a time to simulate multiple networks
- Further expansion of research on advance protection and fault detection by conducting simulations of fault scenarios, robust network architecture, and contingency planning
- Conducting a detailed cost-benefit analysis of potential grid outages in distribution networks
- Future approach of network graph analysis to optimize real-time network efficiency, resilience, and predictive fault detection

References

Amprion. (2016). *Minimum Technical Requirements*. Retrieved from Minimum Technical Requirements: https://www.amprion.net/Market/Grid-Customer/Grid-Connection/Minimum-Technical-Requirements.html

Benoît de METZ-NOBLAT, F. D. (2005, Sept). *Calculation of short-circuit currents*. Retrieved from Calculation of short-circuit currents: https://www.studiecd.dk/cahiers_techniques/Calculation_of_short_circuit_currents.pdf

BMWK. (2020). *Expansion of the electricity grid* . Energiewende. Retrieved from German Federal Ministry for Economic Affairs and Climate: https://www.bmwk.de/Redaktion/EN/Artikel/Energy/electricity-grids-of-the-future-01.html

Christian Growitsch, R. M. (2013 , April). *Institute of Energy Economics at the University of Cologne (EWI)* . Retrieved from Institute of Energy Economics at the University of Cologne (EWI) : https://www.ewi.uni-koeln.de/cms/wp-content/uploads/2015/12/EWI_WP_13-07-Costs-of-Power-Interruptions-in-Germany.pdf

Codrey. (2020). *Electrical Fuse*. Retrieved from Electrical Fuse: https://www.codrey.com/electrical/electrical-fuse/

Comission, I. E. (2016). *Short-circuit currents in three-phase a.c. systems*. Retrieved from Short-circuit currents in three-phase a.c. systems: https://webstore.iec.ch/en/publication/24100

Comission, I. E. (2024). *IEC 60269-1*. Retrieved from IEC 60269-1: https://webstore.iec.ch/en/publication/66096

Dittmann, M. (2020, Jan). *When the electrical installation is getting on in years*. Retrieved from When the electrical installation is getting on in years: https://www.bauen.de/a/wenn-die-elektroinstallation-in-die-jahre-kommt/

Elisabeth Wendlinger, A. W. (2023, 07 19). *Series of articles on the characterisation of low-voltage grids: Low-voltage grids in Germany*. Retrieved from FFE: https://www.ffe.de/en/publications/series-of-articles-on-the-characterisation-of-low-voltage-grids-low-voltage-grids-in-germany/

EnWG. (2013). *Gesetz über die Elektrizitäts*. Retrieved from https://www.gesetze-im-internet.de/enwg_2005/__13.html

Erneuerbare-Energien-Gesetz . (2023). Retrieved from Erneuerbare-Energien-Gesetz : https://www.gesetze-im-internet.de/eeg_2014/BJNR106610014.html

FNN, V. (2021). *Erzeugungsanlagen am Niederspannungsnetz*. Retrieved from Erzeugungsanlagen am Niederspannungsnetz: https://www.vde.com/de/fnn/themen/tar/tar-niederspannung/erzeugungsanlagen-am-niederspannungsnetz-vde-ar-n-4105-2018

GmbH, S. N. (2022). *NEMO*. Retrieved from NEMO.

Henryk Markiewicz, A. K. (2004). *Standard EN 50160 – Voltage Characteristics of Public Distribution Systems*. Retrieved from Standard EN 50160 – Voltage Characteristics of Public Distribution Systems: https://powerquality.blog/2021/07/22/standard-en-50160-voltage-characteristics-of-public-distribution-systems/

Matin Meskin, A. D. (2020). *Impact of distributed generation on the protection systems of distribution networks: analysis and remedies – review paper*. Retrieved from The Institution of Engineering and Technology: https://ietresearch.onlinelibrary.wiley.com/doi/10.1049/iet-gtd.2019.1652

Messstellenbetriebsgesetz (MsbG). (2023). Retrieved from Messstellenbetriebsgesetz (MsbG):

https://www.bundesnetzagentur.de/DE/Beschlusskammern/BK08/BK8_09_MsbG/BK8_MsbG.html

Mohamed Numair, A. A.-V. (2023). *Fault Detection and Localisation in LV Distribution Networks Using a Smart Meter Data-Driven Digital Twin*. Retrieved from Fault Detection and Localisation in LV Distribution Networks Using a Smart Meter Data-Driven Digital Twin: https://www.mdpi.com/1996-1073/16/23/7850

Netz, S. (2020, Nov). *Low Voltage Grid Connection*.

Netz, S. (2022). *Planungsgrundsätze Strom*. Retrieved from Planungsgrundsätze Strom.

Nicholas Etherden, M. H. (2014). Overload and overvoltage in low-voltage and medium-voltage networks due to renewable energy – some illustrative case studies. *ELSEVIER*. ELSEVIER.

Niederspannungsanschlussverordnung. (2006). Retrieved from Niederspannungsanschlussverordnung: https://www.gesetze-im-internet.de/nav/NAV.pdf

P. Stefanidou-Voziki, B. R. (2022, Aug). *A review of fault location and classification methods in distribution grids*. Retrieved from A review of fault location and classification methods in distribution grids: https://www.sciencedirect.com/science/article/pii/S0378779622002577?via%3Dihub

PHBB. (2009). *Deckel Hausanschlußkasten*. Retrieved from Deckel Hausanschlußkasten: https://www.diesteckdose.net/viewtopic.php?t=7035

Ruf, H. (2018, Jan). *Science Direct*. Retrieved from ELSEVIER: https://www.sciencedirect.com/science/article/pii/S0038092X17309520

Rui Guo, S. M. (2023, March). *A review of European low-voltage distribution networks*. Retrieved from A review of European low-voltage distribution networks: https://www.sciencedirect.com/science/article/pii/S1364032122009376

SIEMENS. (2020). *PSS SINCAL*. Retrieved from PSS SINCAL: https://www.siemens.com/de/de/produkte/energie/grid-software/planning/pss-software/pss-sincal.html

SINCAL, P. (2022, April). *Release Information – PSS®SINCAL Platform 18.5*. Retrieved from Release Information – PSS®SINCAL Platform 18.5: https://sincal.s3.amazonaws.com/18.5/ReleaseNotes-Eng.pdf

Strom, N. P. (2019). *Grid Development Plan 2030* . Netzentwicklungs Plan Strom.

Wikimedia. (2012, September). *Sicher* . Retrieved from Sicher.

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