Tagung Zukünftige Stromnetze | Future Power Grids Conference 2025

Conference Papers

https://doi.org/10.52825/zukunftsnetz.v2i.2587

Published: 11 Jun. 2025

Development of a Cross-Voltage-Level Planning Approach for Automated Strategic Network Planning

Concept and First Results of Application

Christoph Becker[1,*], Tobias Rebentisch[1], Markus Zdrallek[1], Felix Nolteernsting[2], and Paul-Martin Körner[3]

[1]University of Wuppertal, Germany

[2]IAV – Ingenieurgesellschaft Automobil und Verkehr, Germany

[3]Sachsennetze GmbH, Germany

*Correspondence: Christoph Becker, cbecker@uni-wuppertal.de

Abstract. This contribution presents a method for automated strategic network planning for electric distribution networks across voltage levels. Three approaches for cross-voltage-level planning using level-separate network-datasets are presented. Advantages and disadvantages for all approaches are compared. The approach of successive automated strategic network planning starting with the lower voltage level is selected. The contribution then describes the underlying method and its implementation into two existing software solutions. The implementation is then tested by performing strategic network planning for two network areas with medium- and low-voltage networks from a German distribution system operator. The emerging results show that cross-voltage-level planning leads to a significant reduction of reinforcement expenses for both network areas. The contribution concludes that using the presented approach could lead to lower estimated reinforcement expenses in distribution networks, but further analyses on the impact of different constellations are necessary.

Keywords: Automated Network Planning, Strategic Network Planning, Cross-Voltage Network Planning

1. Introduction

The transformation of the German energy system from the concept of electrical power supply by few large-scale power plants to many decentralised regenerative-source power plants combined with the growth of electric heating systems and electric vehicles has high impact on the reinforcement requirement of electrical distribution networks [1]. To address that impact strategic network planning (SNP) is used. It especially considers the development of load and generation over longer periods of time to develop solutions for long-term network reinforcement and expansion [2, pp. 6-7]. The use of automated SNP (ASNP) is increasing. ASNP allows high amounts of SNPs with low demand for personnel [3][4].

This contribution shows the development of an approach for cross-voltage ASNP. The approach is based on two existing tools for ASNP, which allow ASNP for medium-voltage (MV) networks and low-voltage (LV) networks separately. The software for MV-network ASNP is using an ant colony optimisation [3]. The software for LV-network ASNP is based on a genetic algorithm [4]. The method shown in this contribution can be transferred to approaches using different software or algorithms and voltage levels.

1.1 State of research and technology

Separate ASNP for each voltage level has already been considered in research [3][4][5][6]. Some tools are available as commercial solutions [3][6]. For cross-voltage ASNP two different approaches are known. It is possible to either generate one dataset for all relevant voltage levels or to generate datasets for each voltage level separately. Both approaches were already subject of research [7][8][9]. Most solutions to the first approach use time-series based load models to estimate load and generation. They usually lead to high calculation times for load- and generation-behaviour in the network and thus to high optimisation times [9][10]. The second approach with separate datasets requires less calculation time, because power-flow calculations (PF) with fixed operating points (OP) and simultaneity factors are possible and common [10]. An exchange of parameters between the datasets is mandatory to consider boundary conditions of the surrounding voltage levels. This approach was already considered in manual and semi-automated SNP with fixed OPs for each voltage level [6][7][10]. It is not used in ASNP, where SNPs for both voltage-levels are fully automated. The research project this contribution is based on closes this gap by developing a method for cross-voltage ASNP with separate datasets and thus separate PFs for each level, based on fixed OPs.

2. Method

As explained before, the following method uses separate datasets for each voltage level. It is mainly chosen because it allows cross-voltage ASNP even for datasets with different structure and origin for each voltage level. Furthermore, optimisation times are possibly low compared to methods using one dataset for all relevant voltage levels. Both aspects are strong advantages when applying the method to a greater amount of real distribution network models.

The datasets for LV- and MV-networks can have different structures, but have to offer a possibility for mutual allocation. To achieve this, the voltage levels need to be linked by a unique identifier for the high-voltage-side node of each MV/LV-transformer (level-linking node). That node is part of both network-datasets. The MV/LV-transformer is part of the LV-dataset for each network, because transformer loading is mainly influenced by the LV-level (LVL). To allow easier explanation in the upcoming paragraphs LVL refers to the dataset including the MV/LV-transformer and its high-voltage-side node. The MV-network is replaced by an external network in the LV-dataset. A fixed voltage value is set as slack voltage (SV), the level-linking node is used as slack node.

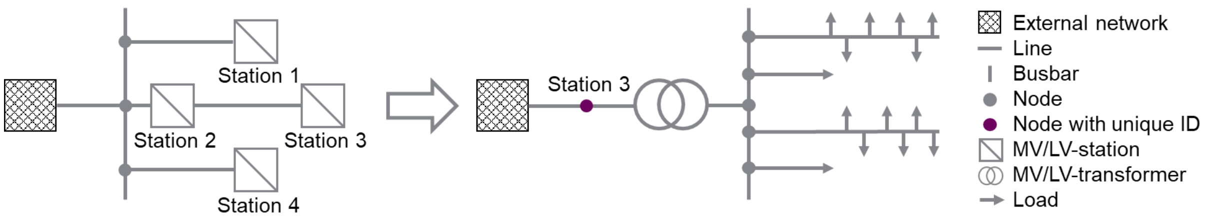

Figure 1. *Division and allocation of MV- and LV-datasets*

2.1 Possible approaches

For cross-voltage ASNP without cross-voltage-level PF three different approaches were identified. For all approaches several parameters are exchanged between the datasets for the different voltage levels to allow cross-voltage ASNP. The number of parameters depends on the boundary conditions and varies between the different approaches. As a minimal basis the resulting loads at each OP are transferred from the LV-dataset to the MV-dataset. From the MV-dataset to the LV-dataset the resulting voltage values for all level-linking nodes are transferred (compare [7]).

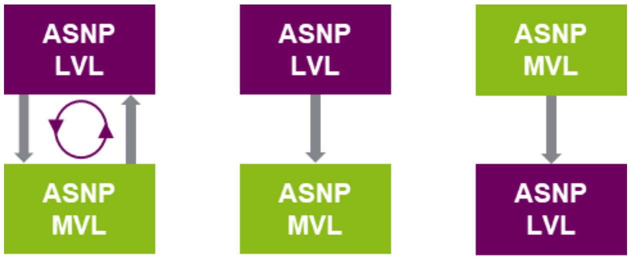

Figure 2. *Different possible approaches for cross-voltage ASNP*

Figure 2 shows the three different identified approaches. The left-hand side shows the approach of multiple alternating ASNP (Approach 1). This example starts with a PF for the LVL (see Figure 3). After transferring network losses to MV-dataset a PF is performed for the MV-level (MVL). An ASNP is processed, followed by another PF. Resulting voltage values for all level-linking nodes are provided for subsequent LV-datasets. PF and ASNP are performed for LVL. The entire process is repeated until ASNPs for both voltage levels are still valid under the conditions of the following PFs.

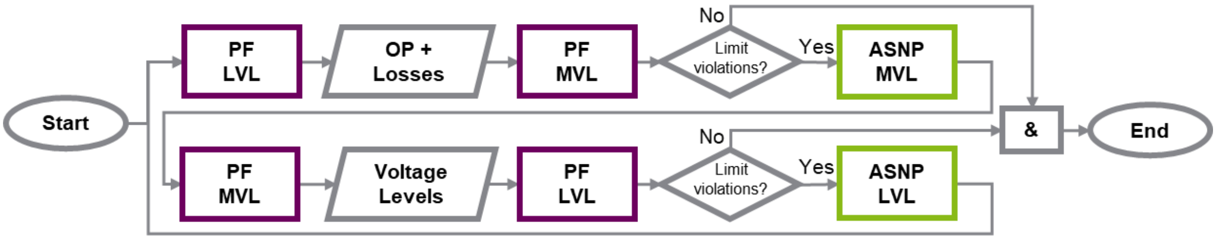

Figure 3. *Process of cross-voltage ASNP according to Approach 1*

In the centre of Figure 2 the approach of successive ASNP, starting with the LVL, is displayed (Approach 2). It starts with a PF for the LVL (see Figure 4). The SV is set to an initial value. This will typically be the value that would be used in separate ASNP. An ASNP is performed afterwards. Parameters are transferred to the MV-dataset. At the end, an ASNP for the MVL is performed. Validity of results from the LV-ASNP under conditions of the MV-ASNP has to be assured.

Figure 4. *Process of cross-voltage ASNP according to Approach 2*

The right-hand side of Figure 2 shows the approach of successive ASNP, starting with the MVL (Approach 3). The process is similar to Approach 2 but begins at the MVL (see Figure 5). The ASNP has to be performed with fixed assumptions regarding network losses of the subsequent voltage level. Then the ASNP of the LVL is performed with parameters from the MVL, especially SVs are derived from the MVL in this approach (compare to [7]).

Figure 5. *Process of cross-voltage ASNP according to Approach 3*

Table 1 shows the advantages and disadvantages of all three approaches. Applicable aspects are marked with “+”, non-applicable aspects are marked with “-“. Calculation effort is rated with “high” or “low”. Exact quantification of the calculation effort is not possible in general, as it depends on PF-strategies and available computing power.

Table 1. *Advantages and disadvantages of the approaches for cross-voltage ASNP*

Aspect	**Approach 1**	**Approach 2**	**Approach 3**
Load and losses from LVL are available for MVL PF	+	+	-
Voltages for slack nodes are available from MVL results	+	-	+
Separate execution in terms of time and place	-	+	+
Calculation effort for PF and ASNP	High	Low	Low

2.2 Selected approach

The positive aspects of the approaches 2 and 3 outweigh those of Approach 1 to the same extent. Especially the high effort for PF and ASNP in Approach 1 makes it difficult to apply it to real networks. Approach 1 is therefore not implemented. In Approach 3, the load values from the LVL can be considered in the MV PF. The losses in the LVL should be estimated or set to 0, but inaccurate estimations lead to deviations in the resulting voltages compared to the actually expected values. In Approach 2, the transferability of the solution found for the LVL to other voltages occurring at the level-linking node must be ensured. For this purpose, the validity of the result of the ASNP must be evaluated for deviating voltages and a corresponding corridor of permissible voltages must be transferred to the MVL. Since transferability can be ensured, Approach 2 is implemented. A corresponding implementation is shown below.

2.2.1 Implementation in the ASNP for the LVL

The first step in the selected approach (Approach 2) is the ASNP for the LVL. A SV per OP is assumed for the slack nodes. The value of the SV has to be set corresponding to the minimum or maximum voltage to be permitted at the level-linking node. A PF is performed using this SV. The PF is used to estimate whether limit violations (line overload, voltage limit violations) occur in the LV-dataset. In case of limit violations an ASNP is performed for the network. The algorithm creates and evaluates different network variants (NV) by mutation and recombination. Unlike described in [4] the algorithm does not optimise for a single cost-optimal NV. Cost-optimal NVs are determined for different SVs instead. This is achieved by evaluating each NV for different SVs and calculating costs of the necessary network reinforcement measures. For this purpose, three options were identified:

1. PF and NV evaluation for different SVs with high resolution
2. Inverse PF
3. Linearisation of node voltages and line loading

The first option requires repeated execution of a large number of PFs and thus leads to a long runtime and high demand for computational power. In the second option, the node with the greatest voltage deviation from the LV-busbar voltage value is determined. This node is defined as new slack node. The initial new SV is set to the limit according to DIN EN 50160 [11]. The external network remains in place, but is not used as slack node anymore. The power-flow direction of all loads and generators is reversed. Voltage at the external network and line utilisation are determined via PF. However, this requires an external network that models a variable source/sink without also serving as a slack node. Such an external network is not available in the network modelling library used [12] or in other common libraries. In the third case, only two PFs are required for two-point-linearisation. As the expected demand for computational power for the third option is low and implementation in the software is possible, the linearisation is implemented. The approach for that linearisation is described in the succeeding part.

In a simple network consisting of one slack node, line, load node and load with constant power, the voltage of the load node basically follows equation 1 [13].

$$\underline{V}_{\text{load node}}{}^{2} - \underline{V}_{\text{slack}} \cdot \underline{V}_{\text{load node}} + \frac{\underline{Z}_{\text{line}} \cdot \underline{S}_{\text{load}}}{3} = 0 \tag{1}$$

$\underline{V}_{\text{load node}}$ can be determined using equation 2. According to [13] one iteration is usually sufficient for acceptable accuracy in LV-networks. Beside that it can be assumed that $\underline{V}_{\text{load node}}{}^{(0)} \approx \underline{V}_{\text{slack}}$.

$$\underline{V}_{\text{load node}}{}^{(1)} = \underline{V}_{\text{slack}} - \frac{\underline{Z}_{\text{line}} \cdot \underline{S}_{\text{load}}}{3 \cdot \underline{V}_{\text{load node}}{}^{(0)}} \approx \underline{V}_{\text{slack}} - \frac{\underline{Z}_{\text{line}} \cdot \underline{S}_{\text{load}}}{3 \cdot \underline{V}_{\text{slack}}} \tag{2}$$

For more complex networks with several serially connected lines and intermediate loads or generators of constant power, there is mutual interference [13]. Since the voltage drop across typical line sections in LV-networks should remain low, it can be assumed that the relationship between $\underline{V}_{\text{slack}}$ and $\underline{V}_{\text{load node}}$ can still be linearised with sufficient accuracy (see [13]). The line utilisation can be determined from the power of the loads/generators and the estimated node voltages by calculating the resulting current over each line.

For OP 1 (high load, no generation) and OP 2 (high generation, low load) a range from 0.92 p.u. – 1.08 p.u. is specified for the SV. This is based on the assumption that a range of 0.9 p.u. – 1.1 p.u. is permanently permissible in accordance to DIN EN 50160 [11]. A voltage drop or elevation of at least 0.02 p.u. should be allowed in each OP. Lower maximum voltage drop or elevation hinders the finding of valid network topologies and thus prolongs runtime, potentially ending without valid variants for narrowest drop or elevation. SV is varied in 0.01-p.u.-steps within the previously discussed range. For every combination of SV for OP 1 and OP 2 limit violations regarding voltage values and line loadings are checked for all NVs. The evaluation is carried out as shown in [4]. The results of each optimisation step are stored in a data structure as shown in Table 2.

Table 2. *Exemplary visualisation of the results for one optimisation step*

NV	**Total costs SV1__SV1**	**…**	**Total costs SV1_SVn**	**…**	**Total costs SVn_SV1**	**…**	**Total costs SV_SVn**
NV1	10,000	…	0	…	8,000	…	5,000
NV2	2,000,000	…	6,000	…	40,000	…	30,000

Valid NVs for each combination of SVs are sorted in ascending order by cost. The cheapest NVs for each combination are used as data basis in the genetic algorithm in the next optimisation step. Additionally, a fixed number of random NVs are selected, too. All NVs, even those not used in the next optimisation step, are stored in a separate data structure. This structure is used to avoid multiple evaluation of NVs already found.

At the end of the optimisation (after a set number of iterations), the results are sorted in ascending order by cost again. The most cost-effective NV for each SV combination is determined. All cost-optimised NVs are compared. Identical NVs that were cost-optimal for several SV combinations are discarded, except for the first occurrence. The remaining NVs are processed for use with the MV-ASNP. First, the node with the lowest (OP 1) or highest voltage (OP 2) in the network is determined for each NV. Then, starting from this node and applying the linearisation described above again, the minimum and maximum voltage per OP, for which the respective NV is still valid, is determined. In addition, network losses and losses at MV/LV-transformer are also determined separately for each OP.

2.2.2 Implementation of the interface between LVL and MVL

Information exchange between the software solutions is realised through a JSON-formatted data structure. Figure 6 shows the basic structure. It is generated as separate file for each LV-network. As several LV-networks are connected to one MV-network (see Figure 1), a unique identifier is specified for the LV-network first. The number and the sum of installed power of all loads and generators in the LV-network are provided aggregated by type. Momentary power for each OP is given, also aggregated by type. For each NV the costs for the expansion measures, power losses (network and transformer) and the permissible voltage band are then provided. The voltage band is defined through the minimum and maximum voltage at the slack node.

JSON-files for all LV-networks are stored by the software for LV-ASNP. The files are transferred manually and parsed by the software for MV-ASNP.

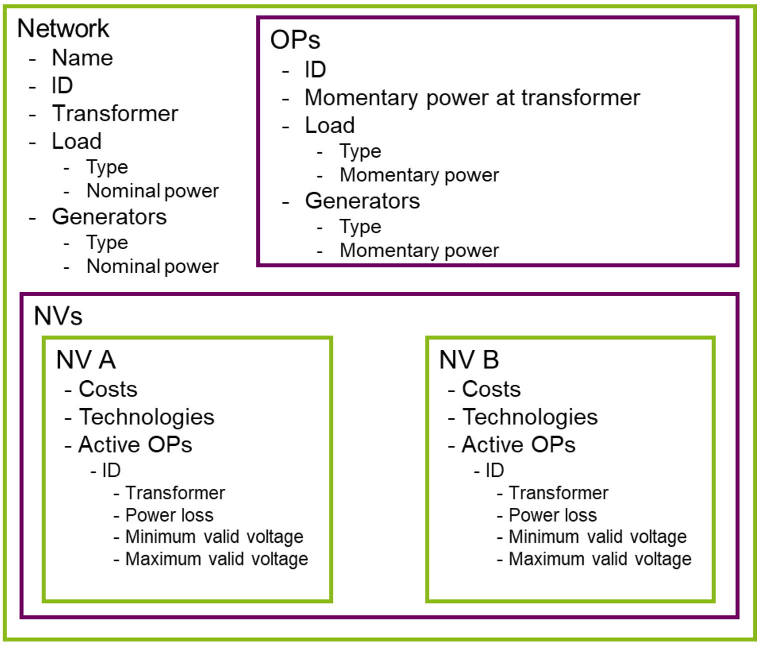

Figure 6. *Basic structure of the transmitted data*

2.2.3 Implementation in the ASNP for the MVL

The standalone ASNP at the MVL seeks the most cost-effective valid network to accomplish the supply task. To achieve this, all stations can be connected to existing or new lines, with the latter incurring additional costs.

Integrating with the upstream LV-ASNP introduces an additional degree of freedom for the MV-ASNP. The algorithm must choose a variant of the LV-network for each station, with each variant specifying the voltage limits to be adhered to at the level-linking node and associated costs. To facilitate this, a new input interface is incorporated into the algorithm, encompassing the previously detailed information for all MV-network stations. Each station has multiple LV-NVs, each with distinct costs and OP-specific voltage limits for the MVL.

The selection of LV-NVs is embedded within the MV-ASNP algorithm. Initially, the existing ant colony optimisation algorithm constructs a graph in each iteration, ensuring stations are connected via MV lines. Subsequently, the most advantageous MV lines are chosen to achieve valid PF results. Initially, the least expensive LV-NVs are selected for all stations. Should voltage limit violations arise in any MV-network section, the algorithm can address them through network expansion or by selecting alternative LV-NVs. Based on the costs, either network expansion or LV-NV replacement is chosen. If neither strategy suffices, a combination of both is employed. When assessing the validity of the PF, substitute circuits for the failure of individual substation feeders are considered (n-1 contingency). The costs and validity of the evaluated network impact the optimization progress in subsequent iterations.

3. Results

The presented approach is applied on two network areas of a German distribution system operator. Network 1 consists of a MV-network partly run on 10 kV (Part 1) and partly on 20 kV (Part 2) with a total of 154 underlying LV-networks. The optimisation is split in two parts according to the nominal voltage of the MV-parts. Network 2 consists of a MV-network run with 10 kV and 143 underlying LV-networks. Nominal voltage of Network 2 will be increased to 20 kV in the future. Characteristics for Network 1 and Network 2 are shown in Table 3.

Table 3. *Characteristics for Network 1 and Network 2*

Network	Type of region	Voltage level	Number of substations with LV-network	Number of customer substations	Length of MV lines
Network 1 P 1	Urban	10 kV	42	6	26 km
Network 1 P 2	Urban	20 kV	112	25	103 km
Network 2	Rural	20 kV	143	35	227 km

The recognised costs for all ASNPs are shown in Table 4. They mainly consist of costs for underground engineering, cables and reinforcement of transformers. Underground engineering costs are not differentiated by the type of surface or voltage level. They are an average value of different types of surfaces from different German distribution system operators. Cable costs and transformer costs are generic, but related to each other in a way that ensures significant impact to the overall costs and realistic level of cost components. This said, costs in this contribution should mainly be understood as a measure for the difference between variants. Cost approaches are mandatory in the implementation as NVs are specifically chosen by lowest costs and thus cannot be left out.

Table 4. *Recognised costs for all ASNP*

Type of costs	Costs
Underground engineering	200 €/m
Cable NAYY 4x150	20 €/m
Cable NAYY 4x240	30 €/m
Cable NA2XS2Y 3x1x240	30 €/m
Transformer 250 kVA	20,000 €
Transformer 400 kVA	25,000 €
Transformer 630 kVA	30,000 €
Transformer 800 kVA	40,000 €
Transformer 1,000 kVA	45,000 €
Replacement of substation	40,000 €

The future scenarios “Technologiemix” and “Fokus PV” for the year 2045 from [1] will be used to estimate load development in both networks. Load development is stored in the datasets for each network and used throughout the ASNP. Voltage values and limits for both OPs are given in Table 5. For separate ASNP all values are used. For cross-voltage ASNP on the MVL only busbar voltage values and on the LVL only voltage limits are applied. For cross-voltage ASNP on the MVL voltage limits are derived from the LV-NVs. For stations without LV-NVs 0.9 p.u. – 1.1 p.u. is set, they are treated as customer stations.

Table 5. *Voltage values and limits for different OP*

Node/area	OP 1 MV	OP 2 MV	OP 1 LV	OP 2 LV
busbar	1.00 p.u.	1.04 p.u.	0.95 p.u.	1.07 p.u.
network max. voltage	1.10 p.u.	1.06 p.u.	1.10 p.u.	1.10 p.u.
network min. voltage	0.96 p.u.	0.90 p.u.	0.90 p.u.	0.90 p.u.

For the MVL the n-1 contingency is considered for both OPs for Network 1. Voltage limits are extended to 0.91 p.u. – 1.1 p.u. for both OPs in separate ASNP. For Network 2 n-1 contingency for OP 1 was checked as described before. For OP 2 check for n-1 contingency was deactivated, because valid solutions for that configuration led to such high efforts for network reinforcement that altering any other configuration had no significant impact to final reinforcement solution. As check for n-1 contingency is not required for OP 2 in German distribution networks with decentralised generators [2, p.15] the results remain valid.

Due to the fact, that both voltage levels are optimised by heuristic algorithms, differences between repeated executions of the ASNP may occur. To limit these differences and increase comparability, LV-NVs are created in one run of LV-ASNP and then used for all further considerations. It is assured, that NV with SV of 0.95 p.u. for OP 1 and 1.07 p.u. for OP 2 is contained in the results for every LV-network. This NV is then used for separate ASNP, while all available NVs are used for cross-voltage ASNP.

3.1 Results for Network 1

First, PF on LVL is carried out to check whether all LV-datasets create valid results. For Part 1 all datasets passed LV PF test, while for Part 2 only 109 datasets passed. For that reason, all ASNPs for Part 2 will only consider NVs for 109 instead of 112 LV-networks. For the remaining three LV-networks the PF did not converge. After that check, separate ASNP was carried out. It is used as a basis for comparison with the cross-voltage ASNP. Table 6 shows the results for both parts of Network 1. All boundary conditions were set as described in the last section.

Table 6. *Costs and line length from separate ASNP for Network 1*

Network	Network 1 P 1	Network 1 P 2
Costs LV	6,209,950 €	14,354,484 €
Length of replaced lines LV	11.873 km	33.847 km
Length of new build lines LV	18.213 km	38.861 km
Costs MV	920,170 €	276,280 €
Length of replaced lines MV	0.581 km	0.003 km
Length of new build lines MV	3.419 km	1.163 km

Next, cross-voltage ASNP is carried out for both parts of Network 1. The results show that the overall costs for both, Part 1 and Part 2, are lower when performing cross-voltage ASNP. Overall costs for Part 1 are only 71.56 % compared to separate ASNP. For Part 2 the difference is even higher, costs from cross-voltage ASNP are only 64.76 % compared to the costs from separate ASNP (see Table 6, Table 7).

Table 7. *Costs and line length from cross-voltage ASNP for Network 1*

Network	**Network 1 P 1**	**Network 1 P 2**
Costs LV	4,443,590 €	8,473,870 €
Length of replaced lines LV	13.182 km	21.948 km
Length of new build lines LV	5.808 km	14.228 km
Costs MV	1,351,520 €	1,000,810 €
Length of replaced lines MV	1.816 km	4.295 km
Length of new build lines MV	5.838 km	1.234 km

Costs for MVL increase in both network parts while costs for LVL decrease (Figure 7). Decreasing LVL costs are caused by the MVL algorithm choosing LV-NVs with higher voltage drop and thus lower reinforcement costs (compare fixed voltage limits for separate ASNP to Table 8). Increasing MVL costs may be caused by the MVL algorithm aiming at minimising the overall costs for a valid combination of MV-NV and LV-NVs. Overall costs can be lower for combinations with higher MVL costs, as savings in LV-network reinforcement from lower MVL voltage drop can outweigh additional MVL costs. The characteristics of the used heuristics can also explain higher costs for MVL, overall cost-optimal solution might not be found. To address the last aspect the MVL optimisation could be repeated several times and overall cost-optimal solutions of every run can be compared, especially regarding MVL costs.

Table 8. *LV variants chosen by MV-algorithm in cross-voltage ASNP without and with OLTC*

Network 1 P 1	**No OLTC**	**OLTC**	**Network 1 P 2**	**No OLTC**	**OLTC**
SV (OP 1)	**Number**	**Num-ber**	**SV (OP 1)**	**Number**	**Num-ber**
V ≥ 0.99 p.u.	4	20	V ≥ 0.99 p.u.	17	42
0.99 p.u. > V ≥ 0.97 p.u.	14	2	0.99 p.u. > V ≥ 0.97 p.u.	25	9
0.97 p.u. > V ≥ 0.95 p.u.	8	6	0.97 p.u. > V ≥ 0.95 p.u.	27	22
V ≤ 0.95 p.u.	16	14	V ≤ 0.95 p.u.	40	36

In an additional run transformers with on-load tap changer (OLTC) are introduced. OLTC are implemented in the MVL and increase the spread of allowed voltage range for all LV-NVs by ± 0.1 p.u.. All LV-NVs are duplicated, one set is then altered by the OLTC model. For example, a LV-NV that allows 0.95 p.u. – 1.05 p.u. at coupling point is altered by OLTC model to allow 0.85 p.u. – 1.15 p.u., but voltage in MVL remains limited according to [11], thus finally increasing voltage range for the variant to 0.9 p.u. – 1.1 p.u.. Costs for the use of an OLTC are set to 6,000 € as addition to costs for transformer exchange. Using OLTC allows use of NVs with even higher voltage drop in LVL, compared to the solution without OLTC (compare Table 8).

Table 9. *Costs and line length from cross-voltage ASNP with OLTC for Network 1*

Network	**Network 1 P 1**	**Network 1 P 2**
Costs LV	3,715,680 €	6,100,850 €
Length of replaced lines LV	8.986 km	16.185 km
Length of new build lines LV	4.501 km	3.640 km
Costs MV	1,264,680 €	1,040,490 €
Length of replaced lines MV	3.717 km	1.048 km
Length of new build lines MV	1.743 km	3.476 km

The use of NVs with higher voltage drop in LVL leads to overall costs of 85.94 % compared to cross-voltage ASNP without OLTC for Part 1 and to overall costs of 75.37 % for Part 2 (see Table 9, Figure 7). 23 substations were equipped with transformers with OLTC in Part 1, 49 in Part 2.

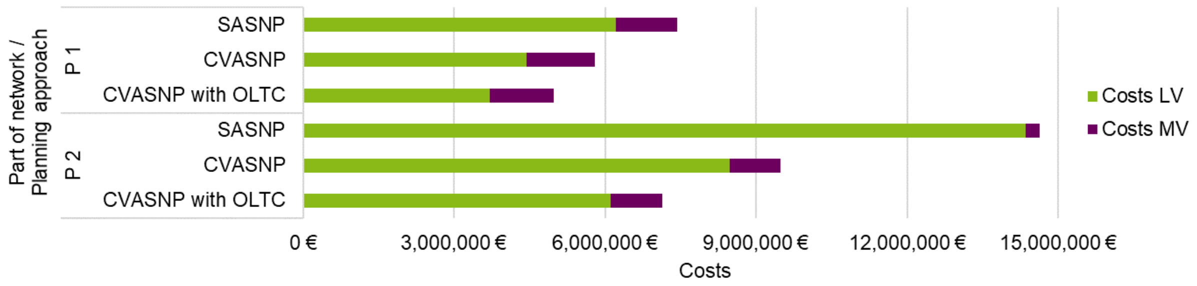

Figure 7. *Comparison of costs between separate ASNP, cross-voltage ASNP without and with OLTC for Network 1*

3.2 Results for Network 2

For Network 2 the nominal voltage is increased from 10 kV to 20 kV in the SNP. Approximately 121.2 km of existing lines have to be discarded because they are not compatible with the new voltage level. Only lines, that are compatible with 20 kV are imported to the MV-dataset. Missing connections from the discarded lines are left open. Separate ASNP for the MVL is run first to find a valid solution for the MV-network with all relevant nodes connected. This solution is then used as a seed (base network topology to start from) for MVL algorithm in cross-voltage ASNP. Running cross-voltage ASNP without a seed led to poor results for MV-topology, because additionally choosing LV-NV increases the solution space in optimisation, so that only few valid solutions for cross-voltage ASNP are found during runtime. Lines planned in separate ASNP remain marked as new lines in cross-voltage ASNP, allowing the MVL algorithm to alter baseline costs by discarding or altering these lines again. This ensures that more cost-efficient solutions can still be found and that the seed is not treated incorrectly as existing network.

Table 10 shows the results for separate ASNP, cross-voltage ASNP and cross-voltage ASNP with OLTC, where both cross-voltage ASNP used the seed from separate ASNP. MVL costs remain nearly constant. Differences may result from separate ASNP not having found the globally cost-optimal solution and from cross-voltage ASNP allowing less restructuring while still not violating voltage limits. The second explanation is supported by the fact that the separate ASNP has taken 22.276 km of MV-lines out of service, while cross-voltage ASNP (without OLTC) has taken 20.826 km out of service. The minimal difference between the actual voltage and the permitted voltage per node (measure for the voltage reserve in MV-network) is very low for both cases (0.05 % for ASNP, 0.01 % for cross-voltage ASNP). This can explain the lower amount of replaced and new build lines (Table 10) at least to a certain extend.

Table 10. *Costs and line length from ASNP for Network 2*

Network	**separate ASNP**	**cross-voltage ASNP**	**cross-voltage ASNP with OLTC**
Costs LV	26,704,540 €	20,883,920 €	7,343,990 €
Length of replaced lines LV	47.140 km	34.796 km	14.801 km
Length of new build lines LV	94.983 km	65.767 km	2.889 km
Costs MV	43,453,720 €	42,843,570 €	43,269,140 €
Length of replaced lines MV	0.558 km	0.217 km	0.518 km
Length of new build lines MV	190.999 km	186.060 km	188.127 km

Costs for LVL and MVL for the different ASNP from Table 10 are displayed in **Figure 8**. With regard to overall and LVL costs Network 2 shows similar behaviour as Network 1, cross-voltage ASNP allows lower overall (90.83 %) and LVL costs (78.20 %) compared to separate ASNP. cross-voltage ASNP with OLTC again allows lower overall (79.42 %) and LVL costs (35.17 %) compared to cross-voltage ASNP without OLTC. Massive cost reduction on LVL can be explained with a few LV-networks, that have high reinforcement needs. Costs in these LV-networks decrease rapidly with higher acceptable voltage drop. The effect is especially high in rural LV-networks. For example, a LV-network used to validate the results has reinforcement costs of 1,043,460 € if SV for OP 1 is 0.95 p.u. and 1.07 p.u. for OP 2 (voltage drop and rise: 0.03 p.u.). The same LV-network has reinforcement costs of only 138,250 € if LV-side voltage at the transformer is 1.05 p.u. for OP 1 and 0.97 p.u. for OP 2 (voltage drop and rise: 0.13 p.u.) and a transformer with OLTC is used.

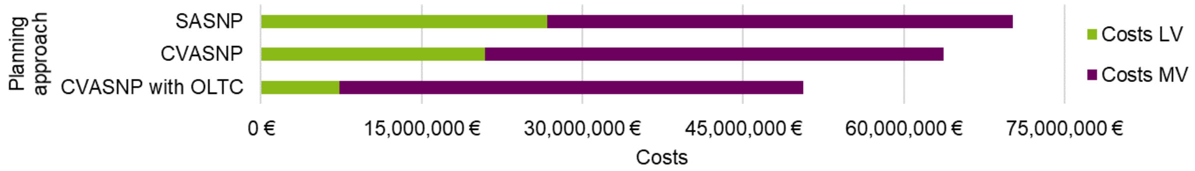

Figure 8. *Comparison of costs between separate ASNP, cross-voltage ASNP without and with OLTC for Network 2*

4. Conclusion

The contribution presents three approaches for cross-voltage ASNP with separate datasets for LVL and MVL. One approach is selected. In that approach cross-voltage ASNP is performed starting with LV-ASNP, then providing parameters for MV-ASNP. It is implemented into software used for separate ASNP before. The boundary conditions for the implementation are described and solutions for arising obstacles are explained, especially rating LV-NVs for different SVs.

The presented approach is then applied to two MV-networks with underlying LV-networks of a German distribution system operator. Results show that cross-voltage ASNP leads to lower overall costs compared to separate ASNP for both network areas. The introduction of transformers with OLTC allows additional cost reduction. The degree of cost reduction differs for the networks, but can be recognised even for Network 2, which has a generally high need for reinforcement on MVL because of a planned change of voltage level. Using the presented approach can generally lead to lower estimated reinforcement expenses in distribution networks. Especially the possibility to allow a higher voltage drop and rise in LVL reduces the reinforcement expenses. LV-NVs for different SVs should always be generated in LV-ASNP or the resulting voltage at the level-linking node from the MVL should be taken into consideration, when using different approaches.

The impact of the heuristic algorithms on the results, while seeming low, cannot be finally estimated using the results presented in this contribution. The application of the approach to more network areas is planned to estimate that impact and the robustness of the approach regarding different network constellations.

Data availability statement

The data used in this contribution is restricted. Network-datasets are based on networks of SachsenNetze GmbH, Dresden, Germany. Datasets and detailed results cannot be provided because they concern critical infrastructure of the German electrical power supply system. Application of the approach on other datasets is planned, the authors are available for further information.

Underlying and related material

This contribution stands on its own, but further information is available in additional publications of the SpaZiel project. More publications especially on additional results and application of geodata in the LV-ASNP are planned.

Author contributions

Christoph Becker: Conceptualisation, Investigation, Data curation, Visualisation, Writing – original draft, Writing – review & editing. Tobias Rebentisch: Data curation, Writing – review & editing. Markus Zdrallek: Funding acquisition, Supervision. Felix Nolteernsting: Data curation, Writing – original draft paragraph 2.2.3, Writing – review & editing. Paul-Martin Körner: Data curation – network datasets

Competing interests

The authors declare the following competing interests: Software for automated medium-voltage network planning is developed by IAV GmbH, software and medium-voltage automated network planning are offered as a service. Cross-voltage automated network planning might be offered as a service in the future.

Funding

The research project this contribution is based on is supported by the German Federal Ministry for Economic Affairs and Climate Action within the framework of the 7th Energy Research Programme under the funding reference number 03EI6087A.

References

[1] G. Luderer, C. Kost and D. Sörgel (Ed.), “Deutschland auf dem Weg zur Klimaneutralität 2045 – Szenarien und Pfade im Modellvergleich (Ariadne-Report)”, 2021
[2] J. Jäger, C. Romeis and E. Petrossian, Duale Netzplanung, 1st ed. Wiesbaden, Germany: Springer Vieweg, 2016
[3] L. Tesch, L. Ruck and M. Schollmeyer, “Multi Criteria Optimisation in Automated Medium Voltage Network Planning”, Proceedings of the CIRED 2021 Conference, vol. 2021, no. 6, pp. 2655-2659, 2021, doi: https://doi.org/10.1049/icp.2021.1473
[4] T. Riedlinger, B.B. Wierzba, M. Zdrallek, L. Lohrberg and D. Wolter, “Integration of Renewal Planning Results in an Automated Strategic Power Grid Planning”, Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MEDPOWER), vol. 2022, no. 1, pp. 13-18, 2022, doi: https://doi.org/10.1049/icp.2022.3296
[5] A. Scheidler, L. Thurner and M. Braun, “Heuristic optimisation for automated distribution system planning in network integration studies”, IET Renewable Power Generation, vol. 12, no. 5, pp. 530-538, Apr. 2018, doi: https://doi.org/10.1049/iet-rpg.2017.0394

[6] D. Mende, “Operationalisierte Zielnetzplanung”, Fraunhofer IEE, https://www.iee.fraunhofer.de/de/anwendungsfelder/energienetze/zielnetzplanung.html (01/08/2025)
[7] R. Bolgaryn, A. Scheidler and M. Braun, “Combined Planning of Medium and Low Voltage Grids”, Proceedings of the 13th IEEE Milan PowerTech, vol. 2019, no. 1, pp. 1-6, 2019, doi: https://doi.org/10.1109/ptc.2019.8810603
[8] A. Valencia, R. Hincapie and R. Gallego, “Integrated Planning of MV/LV Distribution Systems with DG Using Single Solution-Based Metaheuristics with a Novel Neighborhood Search Method Based on the Zbus Matrix”, Journal of Electrical and Computer Engineering, vol. 2022, no. 1, 2022, doi: https://doi.org/10.1155/2022/2617125
[9] D. Rupolo, J. Roberto Sanches Mantovani and B. Rodrigues Pereira Jr., “Medium- and Low-voltage Planning of Electric Power Distribution Systems with Distributed Generation, Energy Storage Sources, and Electric Vehicles”, Proceedings of the 13th IEEE Milan PowerTech, vol. 2019, no. 1, pp. 1-5, 2019, doi: https://doi.org/10.1109/ptc.2019.8810573
[10] T. Riedlinger, P. Wintzek and M. Zdrallek, “Development of a New Modelling Concept for Power Flow Calculations across Voltage Levels”, Electricity, vol. 2024, no. 5, p. 175, 2024, doi: https://doi.org/10.3390/electricity5020010
[11] German Institute for Standardisation (Ed.), DIN EN 50160: Voltage characteristics of electricity supplied by public electricity networks, Berlin, Germany: Beuth Verlag, Nov. 2020
[12] L. Thurner, A. Scheidler, F. Schaefer, J.-H. Menke, J. Dollichon and F. Meier, “pandapower - an Open Source Python Tool for Convenient Modeling, Analysis and Optimization of Electric Power Systems”, IEEE Transactions on Power Systems, vol. 33, no. 6, pp. 6510-6521, Apr. 2018, doi: https://doi.org/10.1109/tpwrs.2018.2829021
[13] K. F. Schaefer, “3.8.4 Berechnung in Mittel- und Niederspannungsnetzen” in Netzberechnung, 2nd ed., Wiesbaden, Germany: Springer Vieweg, 2023, pp.308-312, doi: https://doi.org/10.1007/978-3-658-40877-0