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Development of a New Modelling Concept for Power Flow Calculations across Voltage Levels

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Abstract: In the context of the energy transition, the share of new loads such as charging infrastructure for electromobility and electric heat pumps as well as feed-ins such as photovoltaic systems will steadily increase. This results in an increased degree of complexity for strategic network planning. In particular, the power flow analyses for the dimensioning of transformers and lines per network level currently still require different methods for the correct dimensioning of these equipment. They need to be carried out in separate data sets. For the dimensioning of the equipment simultaneity factors are predominantly used for realistic load assumptions in strategic network planning. These simultaneity factors and resulting load assumptions are determined from the planning perspective of the transformers and from the planning perspective of the lines per network level to be able to dimension the corresponding equipment. This results in different power flow results for the analysis and evaluation of different network levels in particular. This contribution presents a new concept for network modelling in which the simultaneity of the different planning perspectives of the different network levels results from a single power flow calculation in a coherent data set.

Keywords: distribution networks; load flow calculation; low-voltage; medium-voltage; new modelling approach; strategic network planning

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1. Introduction

The energy transition aims to achieve the climate targets of the 2015 Paris Agreement [1]. For this purpose, possible transformation pathways for reducing greenhouse gas emissions are mentioned, for example, in [2]. In particular, the electrification of various sectors is progressing steadily [3]. This poses new challenges for distribution system operators. They have to integrate new loads into the distribution networks, such as charging infrastructure for electromobility or electric heat pumps [4]. They need to use appropriate software for calculating electrical networks to check whether the networks are already designed for the new supply tasks or network expansion measures will be necessary. An essential part of this review is the power flow (PF) analysis. In most cases, this is carried out separately for each voltage level (high-voltage (HV), medium-voltage (MV), low-voltage (LV)). This results in separate data sets and network models, each with its respective assumptions. As an alternative to assumptions for each network level, their results can be transferred to the overlying or underlying network models.

The importance of cross-voltage considerations is already emphasized in various publications such as [5,6]. Therefore, a new concept (concept 2) will be developed in this contribution, with which all network levels are modelled in one data set and only one PF is necessary. This PF simulates all modelled network levels with the correct simultaneity factors (SFs). In this context, network levels are understood to mean the voltage levels and the substation levels in the electrical power supply network.

1.1. Literature Review and Novelty

There are already several publications dealing with PF analyses in a combined MV and LV network model [7–18]. Most of these publications carry out a PF considering only conventional loads [5,7–13]. The same power value is applied to each equipment and each network level. Therefore, no SFs are considered. First publications deal with cross-voltage planning and simulation, taking into account distributed energy resources (DERs), such as wind turbines and photovoltaic systems [6,14,15]. Regardless of the network level, fixed power values for conventional loads and fixed feed-in values for DER are used in there for all network levels. Only [16–18] are regarding new loads such as charging infrastructure for electromobility or electric heat pumps in the cross-voltage analysis and planning. In [17], two operating points are calculated, each with a PF simulation over different network levels. There is no information if SFs or compensations between the different network levels are used. Refs. [16,18] perform a time-series calculation for one day based on power time-series to carry out cross-voltage level planning. None of the publications mentioned use or take into account different SFs for the dimensioning of the different equipment in the different network levels. This paper aims to close this lack in modelling with a new modelling concept considering SFs in order to be able to calculate several network levels. The PF simulates the different network levels in such a way that dimensioning with simultaneous consideration of transformers and lines across several network levels is possible. There are also approaches such as [16,18] with time-series calculations in which no SFs are required, and therefore no differentiation of the power values per network level is necessary. However, these require a very large amount of computing power and duration. The results of time-series calculations are largely dependent on the quality, quantity, and combination of the stored time-series.

1.2. Structure and Objective

Section 2 deals with the topic of strategic network planning. First, the basics are described and the previous modelling concept (concept 1) is explained. This is followed by a detailed description of why a new modelling concept offers advantages. Section 3 presents this new modelling concept (concept 2) in detail. Starting with the basic concept, it then explains how the network data sets must be structured and how they are modelled. The application and results are presented in Section 4. In addition to a description of the network data set used, the modelling of concept 1 and concept 2 is carried out to subsequently compare evaluations of the voltage values and the equipment loading of both concepts. In Section 5, the new concept 2 is extensively discussed, evaluated, and compared with the previous concept 1. Section 6 ends with a conclusion.

2. Strategic Network Planning

In strategic network planning, it must be ensured that networks can fulfill their future supply tasks in such a way that the relevant technical constraints or corresponding standards are complied with. On the one hand, this includes the standard DIN EN 50160 [19], which defines that the agreed supply voltage V_n may only have a maximum deviation of $\Delta V_\mathrm{max}/V_\mathrm{n} = \pm 10\%$. In addition, the standards [20,21] for transformers and the standard [22] for power lines regulate the maximum loading under which environmental conditions apply to these equipment. The analyses of the voltage values or voltage value deviations are always carried out with the value V/V_n. V is the measured voltage value at the node and V_n is the nominal voltage of the network level (MV level: V_n = 10 kV; LV level: V_n = 0.4 kV). The analyses of the line loadings or loading deviations are always carried out with the value I/I_th. I represents the measured loading and I_th the maximum permissible thermal limit. The analyses of the transformer loadings or loading deviations are always carried out with the value S/S_r. S represents the measured load and S_r the installed power rating.

2.1. Basic Operational Planning Steps

In order to comply with the technical regulations in the long term, strategic network planning must be carried out to map the new supply tasks before they occur in reality. For this purpose, scenarios for the development of new loads (charging infrastructure for electric vehicles and electric heat pumps) and DER will be regionalized into the networks. These are distributed within the networks and modelled in a network calculation software. For this purpose, appropriate power assumptions for new loads must be made. For conventional loads, there are already existing standards from which planning values can be taken in the case of [23]. It should be noted that a distinction must be made between power values for the dimensioning of the transformers and the dimensioning of the lines due to the different simultaneities. All loads are supplied from a transformer but not from the same lines. The lines only supply a part of the loads. Therefore, different numbers of loads must be taken into account when determining the SF for the transformer and line dimensioning. This leads to different SFs and different power values. This is explained in more detail in Section 2.2.

2.2. Previous Modelling Concept

The dimensioning of an electrical network is classically and cost-effectively carried out in such a way that strategic network planning ensures that the operating equipment are sufficiently designed for the intended normal operation.

This is generally ensured by simulating extreme operating points, which represent the limits for network operation. The dimensioning of the equipment for the relevant extreme operating points enables the intended operation. This means that the operating points between the extreme operating points do not have to be specifically taken into account and the network can be operated. Classically, the operating points peak load and peak feed-in are investigated. The peak load situation represents a point in time in which maximum power consumption takes place in the absence of feed-in from DER. The peak feed-in situation represents the maximum feed-in by DER with minimum power consumption from conventional loads. It is assumed that the new loads at this operating point do not draw any power from the network. In individual cases, this approach can lead to under- and over-dimensioning of networks. Therefore, the formation of relevant operating points continues to be subject of researches.

To correctly model the operating points peak load and peak feed-in, simultaneities of the different loads and DER must be taken into account. For this purpose, different SFs are used for each technology. The SF is defined as the ratio of the maximum simultaneous consumption power to the sum of the maximum individual consumption power [24].

The previous modelling concept (concept 1) requires a separate consideration of the simultaneities for the dimensioning of transformers and lines. For each separate analysis, a fixed voltage value is specified at the network feed-in, which is defined by the fixed distribution of the voltage band. Figure 1 illustrates this basic differentiation of the SF using an example LV network. From the planning perspective of the transformer, all loads in the respective network must be included in the calculation of the SF. From the planning perspective of the lines, only those loads that are located in the respective feeder are relevant. Therefore, different SFs have to be applied, which results in different power assumptions. Otherwise, the use of SF from the planning perspective of the lines for the planning perspective of the transformers leads to an over-dimensioning of the transformers since fewer loads result in higher power assumption values based on SFs [25]. In the example of the use of the SF from the perspective of the transformers for the planning perspective of the lines, this leads to an under-dimensioning of the lines. This can be further extended to the other voltage levels. The SFs from the planning perspective of the LV line lead to strong over-dimensioning of the MV lines. On the contrary, SFs from the planning perspective of the MV lines lead to under-dimensioning of the LV lines. It is therefore important to apply the correct SF based on the number of technologies supplied for each planning perspective. Applying the same SF across several network levels leads to incorrect dimensioning of the equipment and wrong investments.

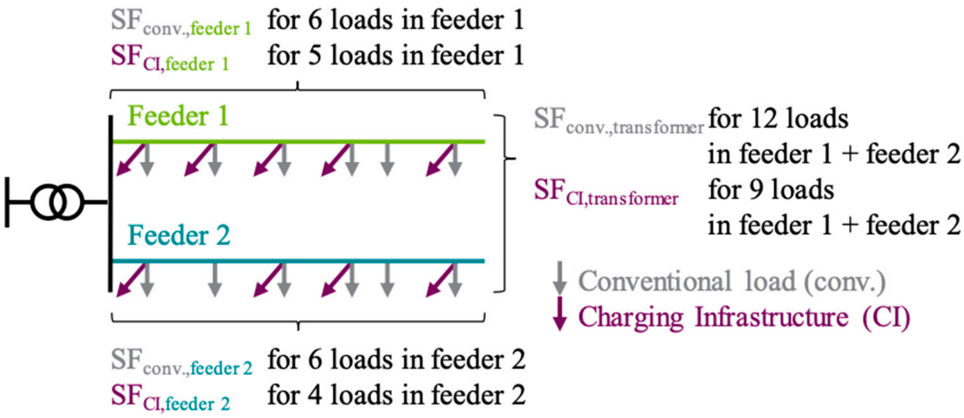

Figure 1. Planning perspectives considering the respective simultaneity factors (SFs).

In most cases, only the planning perspective for the dimensioning of the lines is modelled in detail within the network calculation software. The transformers are only mapped as network feed-ins, otherwise they may be overloaded by the modelling from the planning perspective of the lines. The transformers can be simulated in the network calculation software as well. The SF must refer to the perspective of the transformer. This network level separate modelling concept is possible for all network levels. Using the example of the planning of an MV network with the modelled underlying LV networks, many separate network data sets are therefore necessary. An MV network with ten underlying LV networks is modelled through eleven individual network data sets. One data set is required for the dimensioning of the MV lines and ten data sets for the dimensioning of the lines of the different LV networks.

Within the MV data set, the LV networks are then simulated as equivalent loads per technology. In this case, the power assumptions per equivalent load (representing the underlying LV network) correspond to those values that have to be used for the dimensioning of the MV lines and not for the dimensioning of the LV lines. The power assumptions within a modelled LV data set are modelled for the dimensioning of the LV lines. Thus, the LV loads are modelled differently in the context of the dimensioning for MV and LV lines. Therefore, no coherent MV and LV data set can be modelled so far.

To be able to dimension the corresponding equipment at the MV and LV levels, different PF analyses (planning perspectives) for the evaluation of the MV and LV networks (concept 1) result in analogy to the example mentioned:

- HV/MV transformers;
- MV lines;
- MV/LV transformers;
- LV lines.

Therefore, four separate data sets are modelled. The basic structure is shown in Figure 2.

The following network elements are modelled from the planning perspective of the HV/MV transformer:

- Network feed-in on the high voltage side of the HV/MV transformer;
- HV/MV transformer;
- MV lines per MV feeder;
- MV/LV transformers;
- LV equivalent loads per LV network on the low voltage sides of the MV/LV transformers (without modelling of the LV lines) taking into account the SF from the HV/MV transformer perspective.

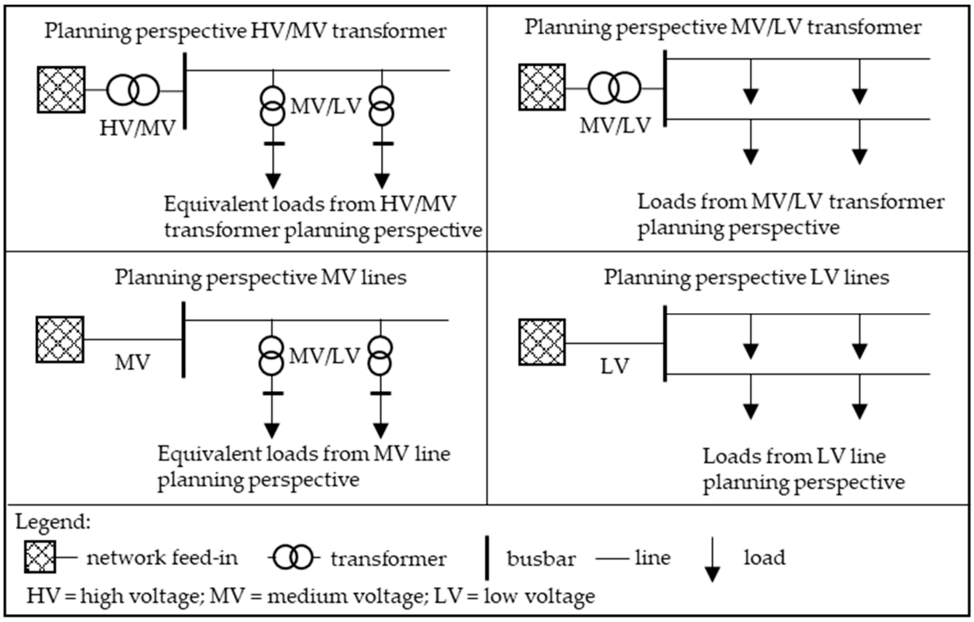

Figure 2. Presentation of the modelling concepts for each planning perspective (concept 1).

The following network elements are modelled from the planning perspective of the MV lines:

- Network feed-in at the MV busbar without modelling the HV/MV transformer;
- MV lines per MV feeder;
- MV/LV transformers;
- LV equivalent loads per LV network on the low voltage sides of the MV/LV transformers (without modelling of the LV lines) taking into account the SF from the MV line perspective.

The following network elements are modelled from the planning perspective of the MV/LV transformer:

- Network feed-in on the high voltage side of the MV/LV transformer;
- MV/LV transformer;
- LV lines per LV feeder;
- LV loads per house connection, taking into account the SF from the MV/LV transformer perspective to the house connection node.

The following network elements are modelled from the planning perspective of the LV lines:

- Network feed-in at the LV busbar without modelling the MV/LV transformer;
- LV lines per LV feeder;
- LV loads per house connection, taking into account the SF from the LV line perspective to the house connection node.

2.3. Need for a New Modelling Concept

The separate way of modelling the planning perspectives is very time-consuming and requires a large amount of time in data preparation and processing. For this reason, and for reasons of the ongoing digitalization of relevant network data, it is useful to prepare a coherent network data set considering SFs, which can be used across voltage levels and from which ideally the dimensioning of all equipment can be derived directly. In summary, there are the following advantages:

- Preparation of only one network data set;
- File reduction by eliminating the spread of information across multiple data sets;

- Calculation results are consolidated and no longer need to be compiled and analyzed separately;
- Cross-voltage level considerations are simplified with regard to result interpretations and presentations;
- Network data modelling is simplified and reduced, e.g., by restricting import information from new loads to one file where many separate files were previously necessary;
- Effects due to technologies used in, e.g., the MV level (voltage regulation at the HV/MV substation) are immediately evident in all underlying LV networks or upside down (load management in the LV level with repercussions on the MV level);
- Voltage band distribution at MV and LV levels is no longer necessary, as both levels are modelled, and therefore only the specification according to DIN EN 50160 [19] has to be observed;
- Avoidance of network feed-ins to map the higher network level, and thus more accurate modelling of the overlying and underlying networks is possible

In the following Section 3, a new concept (concept 2) for network modelling is presented, with which all planning perspectives result from a single PF analysis and no fixed voltage band distribution between the MV and LV levels has to be made. In addition, fixed voltage values no longer have to be specified by network feed-ins for each planning perspective, or voltage values no longer have to be transferred from network data sets of the higher network levels. The new concept is not limited to the MV and LV networks, but can be applied to all network levels or connected network levels.

3. New Modelling Concept

3.1. Structure of the Data Sets

For the application of concept 2, a holistic modelling of the considered network is carried out. This means that all considered network levels are modelled without equivalent loads which represent real networks. It is possible to map all network levels or all connected parts of the network levels for the application of concept 2. Information of all underlying networks must be available for the correct application. The holistic modelling is necessary to consider all relevant effects of all network levels. In particular, the effects of one network level on the other network levels can be mapped through the holistic modelling. In the following, a complete MV network with all underlying LV networks is modelled as an example. This means that the HV/MV substation must be modelled by the corresponding HV/MV transformers as well as the network feed-in as an overlying network level (HV level) and busbars as nodes at the low voltage sides. All MV lines must be modelled with the correct topology interconnection. The MV/LV transformers are modelled with busbars as nodes on the low voltage side. In the case of the loads connected directly at MV level, the load is modelled at the nodes of the low voltage side of the MV/LV transformers. All underlying LV networks of the MV/LV transformers must be modelled with correct topology interconnection. The loads of the houses have to be modelled at the respective LV house connection nodes. An example is shown in Figure 3.

The following network elements are modelled for a cross-voltage analysis of the new concept (concept 2):

- Network feed-in on the high voltage side of the HV/MV transformers;
- HV/MV transformers;
- MV lines;
- MV/LV transformers;
- MV loads taking into account the SF from the MV/LV transformer perspective on the low voltage sides of the MV/LV transformers;
- LV lines;
- LV loads taking into account the SF from the LV line perspective at the house connection nodes.

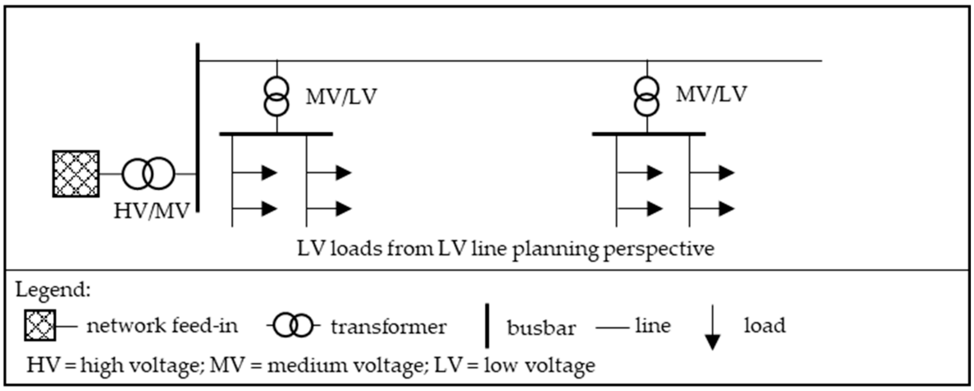

Figure 3. Presentation of the basic data structure of the new modelling concept (concept 2).

3.2. Concept

The new modelling concept is based on network feed-ins at each network level. These compensate for the difference in power values between the planning perspectives and are referred in the following as compensation feed-ins (CFs). With the use of CFs, it is possible to calculate voltage values and equipment loadings of all planning perspectives with one PF analysis. As a result, only one network data set is required instead of, for example, four separate network models for LV networks with an overlying MV network. The further explanations are always related to the operating point peak load and the simulated MV network. However, concept 2 can also be applied analogously to the other network levels and to the operating point peak feed-in with a feed-in of DER.

In the network calculation software, the CFs are defined as network feed-ins with the power flow type "*P* and *Q*" (*P* corresponds to the active power and *Q* to the reactive power). The CFs are modelled on the high voltage and low voltage sides of the transformers. They are used to reduce the power by feed-in of active power and reactive power at the respective node. This reduction is necessary due to the higher number of considered loads for the SF determination. Through the higher load number, there are lower power assumptions per load at the higher network level. It should be noted that the CFs are not used to compensate for the load-dependent line and transformer losses, as these change with each network expansion measure.

Figure 4 shows the modelling of the CFs described in Section 3.1 and illustrated in Figure 3 using an example network. The modelling will be expanded to include the necessary network elements of the new concept (concept 2). The CFs are shown in blue in Figure 4 and compensate for the power difference between the total load in each planning perspective.

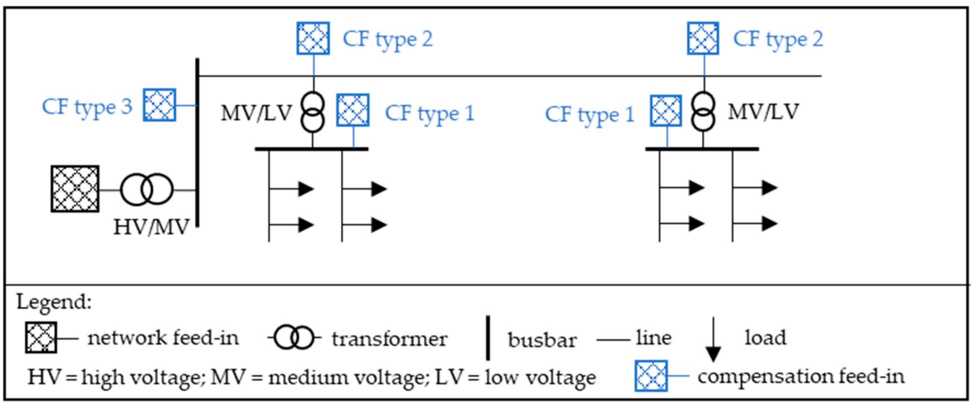

Figure 4. Exemplary illustration of concept 2 with compensation feed-ins.

In the joint simulation of MV and LV networks, three different types of CFs (CF type 1, CF type 2, and CF type 3) are used, which are described below and must be modelled accordingly. If further network levels are mapped in the network model, additional CFs are necessary. In general, CFs must always be modelled and calculated at the nodes on the high voltage and low voltage sides of the transformers, as there is always a change in planning perspectives.

1. CF type 1 is used for the power compensation between the LV line planning perspective and the MV/LV transformer planning perspective to avoid over-dimensioning of the respective MV/LV transformers. The power values in the respective LV feeder remain unaffected by this. The modelling of the CF type is carried out at the low voltage side of each MV/LV transformer.
2. CF type 2 is used for the power compensation between the MV/LV transformer planning perspective and the MV line planning perspective. It is modelled on each high voltage side of the MV/LV transformers. Without this CF, the sum of power per MV feeder is too large, since only the number of loads and DER per MV/LV transformer are taken into account in the SF calculation and not the sum of all loads and DER per MV feeder.
3. CF type 3 is used for the power compensation between the MV line planning perspective and the HV/MV transformer planning perspective to avoid over-dimensioning of the respective HV/MV transformers. The modelling of the CF type is carried out at the low voltage side of each HV/MV transformer.

The corresponding calculations of the active and reactive power per CF type can be found in Equations (1)–(6) and are valid for both operating points. The equations can be transferred to the other network levels. In the first step, the output of the underlying network level is calculated by subtracting the sum of the output of all DER from the sum of the output of all loads. This is also carried out for the overlying network level. Finally, the two calculated power totals of the two network levels are subtracted from each other.

For all loads/DER on the low voltage side of the MV/LV transformer:

$$P_{\mathrm{CF}_1} = \left(\sum P_{\mathrm{load}_{\mathrm{LV\ line}}} - \sum P_{\mathrm{generation}_{\mathrm{LV\ line}}}\right) - \left(\sum P_{\mathrm{load}_{\mathrm{MV/LV\ transformer}}} - \sum P_{\mathrm{generation}_{\mathrm{MV/LV\ transformer}}}\right) \tag{1}$$

$$Q_{\mathrm{CF}_1} = \left(\sum Q_{\mathrm{load}_{\mathrm{LV\ line}}} - \sum Q_{\mathrm{generation}_{\mathrm{LV\ line}}}\right) - \left(\sum Q_{\mathrm{load}_{\mathrm{MV/LV\ transformer}}} - \sum Q_{\mathrm{generation}_{\mathrm{MV/LV\ transformer}}}\right) \tag{2}$$

For all loads/DER on the high voltage side in the MV feeder:

$$P_{\mathrm{CF}_2} = \left(\sum P_{\mathrm{load}_{\mathrm{MV/LV\ transformer}}} - \sum P_{\mathrm{generation}_{\mathrm{MV/LV\ transformer}}}\right) - \left(\sum P_{\mathrm{load}_{\mathrm{MV\ line}}} - \sum P_{\mathrm{generation}_{\mathrm{MV\ line}}}\right) \tag{3}$$

$$Q_{\mathrm{CF}_2} = \left(\sum Q_{\mathrm{load}_{\mathrm{MV/LV\ transformer}}} - \sum Q_{\mathrm{generation}_{\mathrm{MV/LV\ transformer}}}\right) - \left(\sum Q_{\mathrm{load}_{\mathrm{MV\ line}}} - \sum Q_{\mathrm{generation}_{\mathrm{MV\ line}}}\right) \tag{4}$$

For all loads/DER on the low voltage side of the HV/MV transformer:

$$P_{\mathrm{CF}_3} = \left(\sum P_{\mathrm{load}_{\mathrm{MV\ line}}} - \sum P_{\mathrm{generation}_{\mathrm{MV\ line}}}\right) - \left(\sum P_{\mathrm{load}_{\mathrm{HV/MV\ transformer}}} - \sum P_{\mathrm{generation}_{\mathrm{HV/MV\ transformer}}}\right) \tag{5}$$

$$Q_{\mathrm{CF}_3} = \left(\sum Q_{\mathrm{load}_{\mathrm{MV\ line}}} - \sum Q_{\mathrm{generation}_{\mathrm{MV\ line}}}\right) - \left(\sum Q_{\mathrm{load}_{\mathrm{HV/MV\ transformer}}} - \sum Q_{\mathrm{generation}_{\mathrm{HV/MV\ transformer}}}\right) \tag{6}$$

The power values of the conventional loads as well as the new loads and DER are modelled in the network model as a basis, considering the SF from the LV line perspective. In addition, in the case of CF type 2 and CF type 3, the loads and DER connected in the MV level must be taken into account with SF. The power values of the CFs are then determined using Equations (1)–(6) from the power values and SFs of the respective two planning perspectives. These power differences are modelled as CFs to correct the loads and DER to the correct power value for the dimensioning of the overlying planning perspective. As a result, both transformer and line loadings can be simulated with one PF analysis. Further PF analyses in separate data sets are no longer necessary. All voltage drops across the transformers are simulated directly with the load from the respective transformer planning perspective; therefore, no separate specifications of voltage values from the voltage band distribution between the MV and LV levels have to be defined. The resulting voltage values at the busbars are used to simulate the lines with the corresponding power values from the planning perspective of the lines. This new concept 2 can be applied in a single network model across all voltage levels.

3.3. Modelling Example

The modelling is explained and calculated using the example network from Figure 4. The result is illustrated in Figure 5.

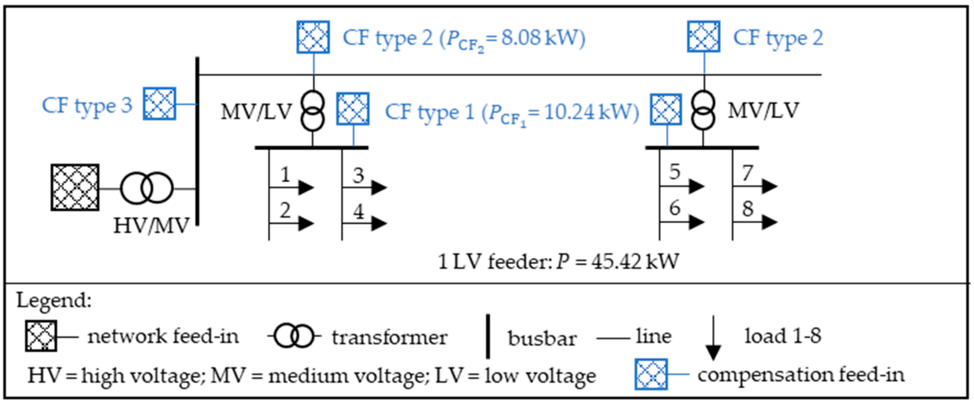

Figure 5. Application of concept 2 with compensation feed-ins on an example network.

In the first step, the SFs and the resulting power values for the charging infrastructure and heat pumps are determined. This is carried out for the four planning perspectives described in Section 2.2 (HV/MV transformers, MV lines, MV/LV transformers, LV lines). This results in the power values shown in Table 1. To simplify the example, each load consists of a constant conventional load with $P_{\text{conventional}}$ = 5 kW as well as a charging point with a $P_{\text{charging point}}$ = 11 kW and an electric heat pump with $P_{\text{heat pump}}$ = 9 kW. In this example, the power factor cos(φ) is set to cos(φ) = 1 for all loads. The SFs are then calculated from the number of charging points and heat pumps for each planning perspective. For this simplified example, it should be noted that there is no difference in the performance of the loads between the planning perspective of the HV/MV transformers and the planning perspective of the MV lines, because in the example shown only one MV feeder is connected to the HV/MV transformer, and thus the number of conventional loads, charging points, and heat pumps does not change between these two planning perspectives.

Table 1. Resulting power values for the example network in Figure 5 (bold formatting represents the respective power value for each planning perspective).

Viewing Area	Number of Loads	P in kW from Planning Perspective LV Lines	P in kW from Planning Perspective MV/LV Transformers	P in kW from Planning Perspective MV Lines	P in kW from Planning Perspective HV/MV Transformer
1 load	1	**22.71**	**20.15**	**19.14**	**19.14**
1 LV feeder	2	**45.42**	40.30	38.28	38.28
1 MV/LV transformer	4	90.84	**80.60**	76.56	76.56
1 MV feeder	8	181.68	161.20	**153.12**	153.12
1 HV/MV transformer	8	181.68	161.20	153.12	**153.12**

The corresponding active powers P_{CF_1}, P_{CF_2}, and P_{CF_3} of the CFs can be determined with Equations (1), (3), and (5). Due to the chosen power factor cos(φ) = 1, the corresponding reactive powers Q_{CF_1}, Q_{CF_2}, and Q_{CF_3} are zero in the following example:

$$P_{CF_1} = (4{\cdot}22.71\ \text{kW} - 0\ \text{kW}) - (4{\cdot}20.15\ \text{kW} - 0\ \text{kW}) = 10.24\ \text{kW}$$

$$P_{CF_2} = (8{\cdot}20.15\ \text{kW} - 0\ \text{kW}) - (8{\cdot}19.14\ \text{kW} - 0\ \text{kW}) = 08.08\ \text{kW}$$

$$P_{CF_3} = (8{\cdot}19.14\ \text{kW} - 0\ \text{kW}) - (8{\cdot}19.14\ \text{kW} - 0\ \text{kW}) = 00.00\ \text{kW}$$

Thus, at the nodes of the low voltage side of the MV/LV transformers, CF with P_{CF_1} = 10.24 kW and Q_{CF_1} = 0 kW must be modelled. These CFs correct the difference between the power values through the SF of the LV line perspective and the MV/LV transformer perspective. To compensate for the power values from the MV/LV transformer perspective to the MV line perspective, CF with P_{CF_2} = 8.08 kW and Q_{CF_2} = 0 kW must be modelled at the nodes of the high voltage side of the MV/LV transformers. As only one MV feeder is modelled in the MV network shown in Figure 4, there is no difference between the power values of the MV line perspective and the HV/MV transformer perspective. Thus, there is potentially no need to model the CF. In the modelling in this example, however, it is modelled with a power of P_{CF_3} = 0 kW and Q_{CF_3} = 0 kW at the node of the low voltage side of the HV/MV transformer for reasons of completeness.

4. Application and Results

In this section, the network data set for the application is presented, which consists of an MV network with all underlying LV networks. This network data set will then be used for modelling the previous concept 1 (additionally differentiated into subvariants 1a and 1b, see Sections 4.2 and 4.4) and for the new concept 2 (see Sections 4.3 and 4.4). Based on these models, the individual results are presented (Sections 4.2.1, 4.2.2 and 4.3) and then both concepts (Sections 4.5 and 4.6) are compared and evaluated. The comparison and evaluation are carried out separately for each planning perspective from concept 1 and the corresponding network level in concept 2. The operating point on which these analyses are based is the peak load situation for an urban network area. The network area will be conventionally replanned, and the results will be evaluated accordingly in Section 4.7. For power flow calculation, the Newton-Rhaphsonian method is used in the network calculation software *PSS®SINCAL* (Sincal 19.0 version).

4.1. Data Set

The MV network supplies a total of 53 underlying LV networks. The HV/MV substation of the MV network consists of two operating HV/MV transformers (T1 and T2). Table 2 shows the essential network structure parameters.

Table 2. Network structure parameters of the complete network data set.

Parameter	Value	Unit
Power rating of the HV/MV transformers	31.5	MVA
MV line length	56.4	km
MV feeders	14	pieces
Distribution stations	53	pieces
Customer stations	26	pieces
LV line length	135	km
House connections	3286	pieces
Metering points	13,893	pieces
Private charging points	5303	pieces
Public charging points	501	pieces
Electric heat pumps	1014	pieces

For the application of the concepts, the Germany-wide developments in the number of electric vehicles and the number of heat pumps from the future scenario EL80 of the dena study "Integrated Energy Transition" [4] are used. These are distributed to the house connections or customer stations of the network area under consideration using a regionalization system [26]. Private charging points with 11 kW and 22 kW installed capacity and public charging points with 11 kW, 22 kW, and 50 kW installed capacity are modelled. For heat pumps, an installed capacity of 9 kW is assumed. The numbers of private and public charging points and electric heat pumps in the investigated network are shown in Table 2.

4.2. Modelling of the Previous Concept (Concept 1)

The modelling of concept 1 (see Section 2.2 or Figure 2) is further divided into concepts 1a and 1b. The analyses in Sections 4.5 and 4.6 will be differentiated in more detail to enable further statements and modelling recommendations.

4.2.1. Concept 1a

Concept 1a is modelled using the fixed voltage band given in Figure 6. From the LV point of view, no reserves from the MV planning are used. The worst-case scenario is depicted, since each LV network is fed with a worst-case voltage value from the MV level.

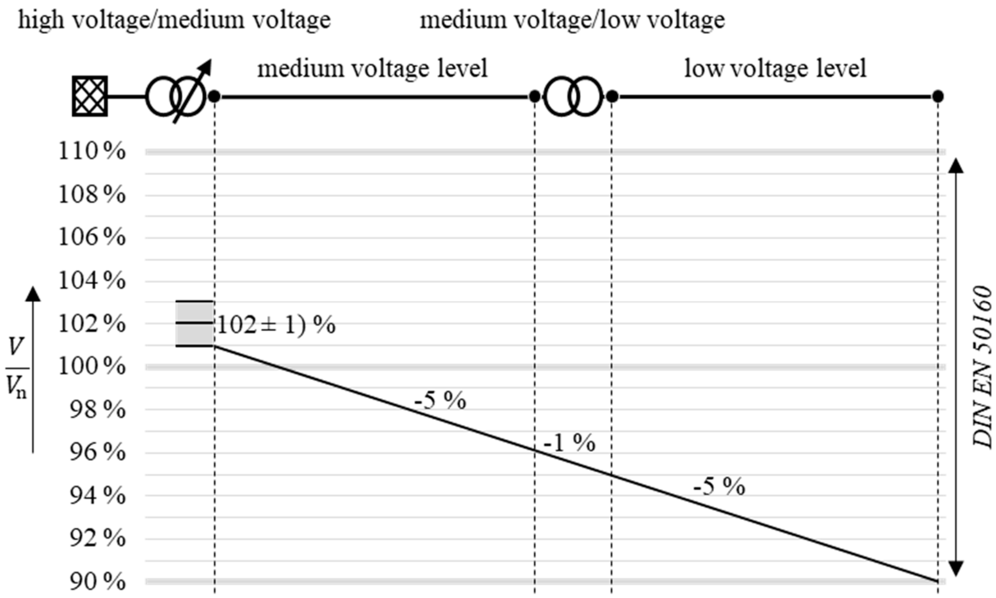

Figure 6. Assumed voltage band distribution for concept 1a in the operation point peak load.

The following voltage value assumptions are taken into account for each planning perspective:

HV/MV transformers:	$V/V_n = 102\%$
MV lines:	$V/V_n = 101\%$
MV/LV transfomers:	$V/V_n = 96\%$
LV lines:	$V/V_n = 95\%$

The PF results in Figures 7–10 are obtained using the fixed voltage band distribution from concept 1a.

The PF results from concept 1a in Figures 7–10 serve as an overview at this point and will be compared and evaluated with the results from concept 2 in Section 4.5.

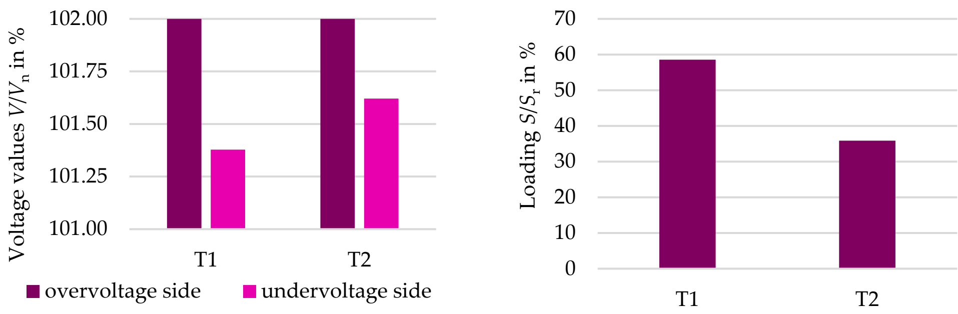

Figure 7. (**Left**): Voltage values of the HV/MV transformer nodes, (**right**): Loadings of the HV/MV transformers; both concept 1a.

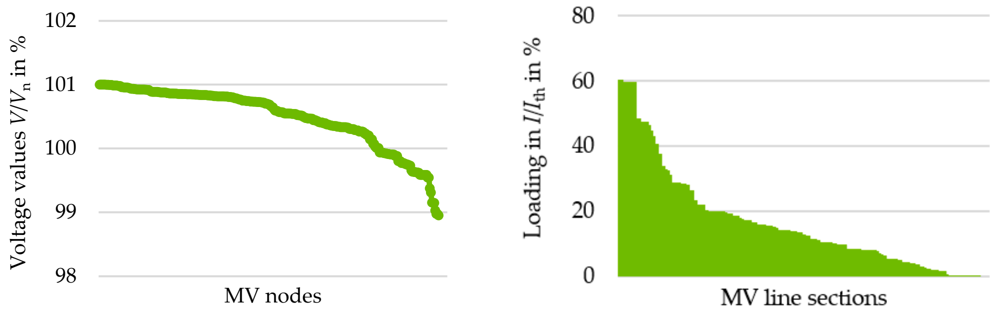

Figure 8. (**Left**): Voltage values of the MV nodes, (**right**): Loadings of the MV line sections; both concept 1a.

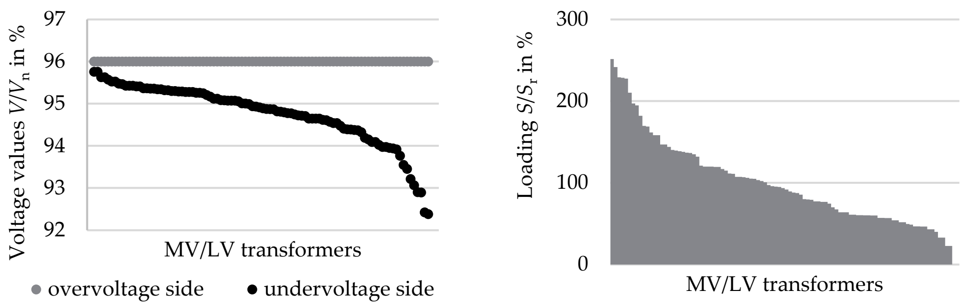

Figure 9. (**Left**): Voltage values of the MV/LV transformer nodes, (**right**): Loadings of the MV/LV transformers; both concept 1a.

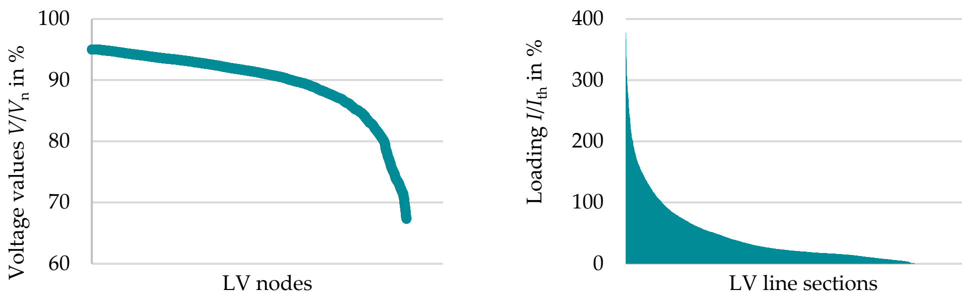

Figure 10. (**Left**): Voltage values of the LV nodes, (**right**): Loadings of the LV line sections; both concept 1a.

4.2.2. Concept 1b

Concept 1b is not modelled with the fixed voltage band specified in Figure 6. Instead, the variable voltage values from the cross-voltage level concept 2 are taken over in advance and modelled in the four separate planning perspectives; therefore, the same reserves from the overlying network levels as in concept 2 are used in the four planning perspectives in concept 1b.

The following voltage value assumptions are taken into account for each planning perspective from concept 2:

HV/MV transformers:	V/V_n = 102%
MV lines:	Respective voltage values of the low voltage sides of the HV/MV transformers from the planning perspective of the HV/MV transformers
MV/LV transfomers:	Respective voltage values of the high voltage sides of the MV/LV transformers from the planning perspective of the MV lines
LV lines:	Respective voltage values of the low voltage sides of the MV/LV transformers from the planning perspective of the MV/LV transformers

The PF results in Figures 11–14 are obtained from the simulation for each planning perspective with the respective voltage values adopted from concept 2 for the network feed-ins of concept 1b.

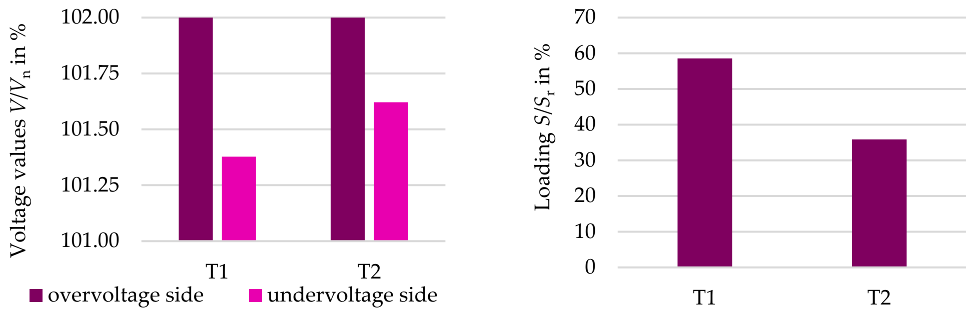

Figure 11. (**Left**): Voltage values of the HV/MV transformer nodes, (**right**): Loadings of the HV/MV transformers; both concept 1b.

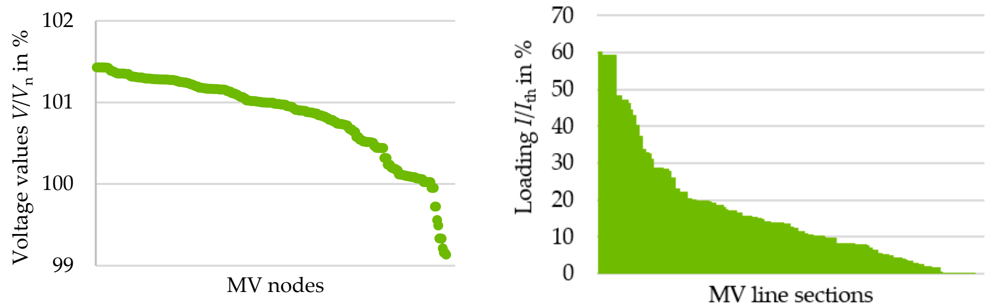

Figure 12. (**Left**): Voltage values of the MV nodes, (**right**): Loadings of the MV line sections; both concept 1b.

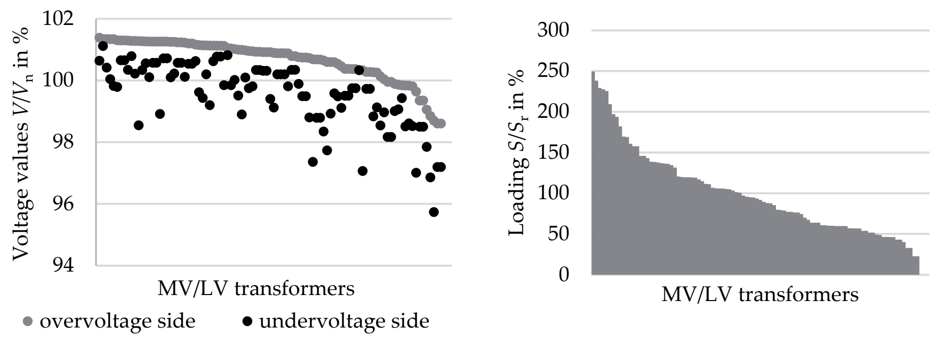

Figure 13. (**Left**): Voltage values of the MV/LV transformer nodes, (**right**): Loadings of the MV/LV transformers; both concept 1b.

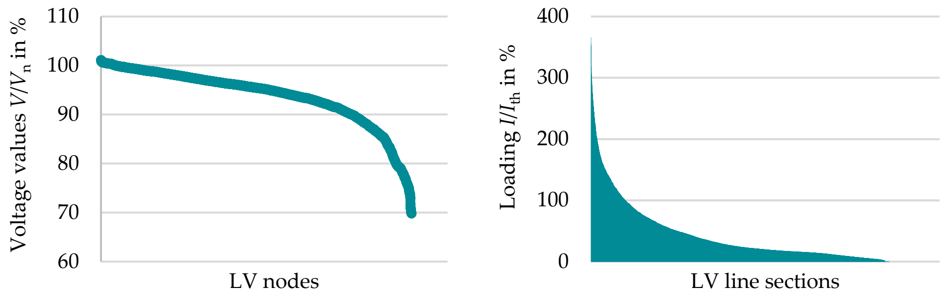

Figure 14. (**Left**): Voltage values of the LV nodes, (**right**): Loadings of the LV line sections; both concept 1b.

The PF results from concept 1b in Figures 11–14 serve as an overview at this point and will be compared and evaluated with the results from concept 2 in Section 4.6.

4.3. Modelling of the New Concept (Concept 2)

The network data set (MV and LV levels) in concept 2 is modelled with the basic structure in Figure 3. This is extended according to Figure 4 by calculating the CFs from the SFs of the different planning perspectives and modelling them as CF type 1, CF type 2, and CF type 3. As already in concept 1a and concept 1b, network feed-ins with voltage values of V/V_n = 102% on the high voltage side of the HV/MV transformers are modelled to represent the overlying HV network level.

The PF results in Figures 15–18 are obtained from the simulation of the entire MV and LV networks using concept 2.

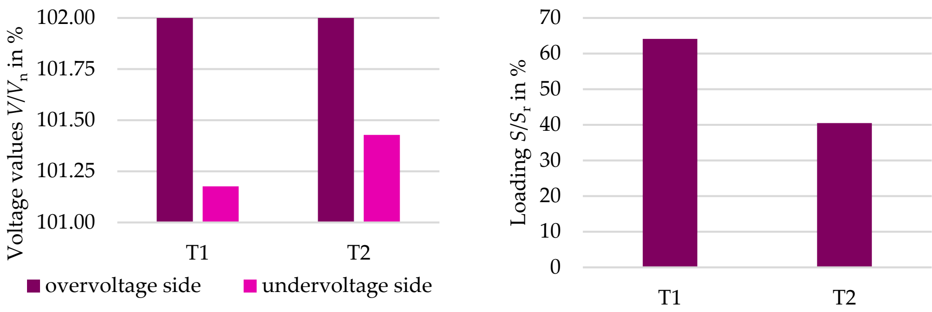

Figure 15. (**Left**): Voltage values of the HV/MV transformer nodes, (**right**): Loadings of the HV/MV transformers; both concept 2.

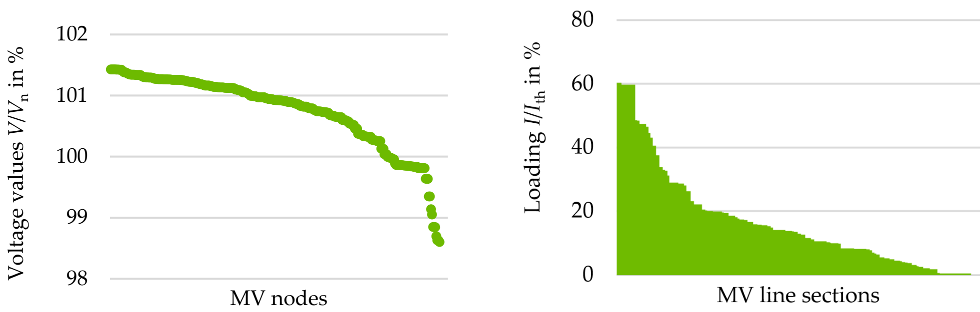

Figure 16. (**Left**): Voltage values of the MV nodes, (**right**): Loadings of the MV line sections; both concept 2.

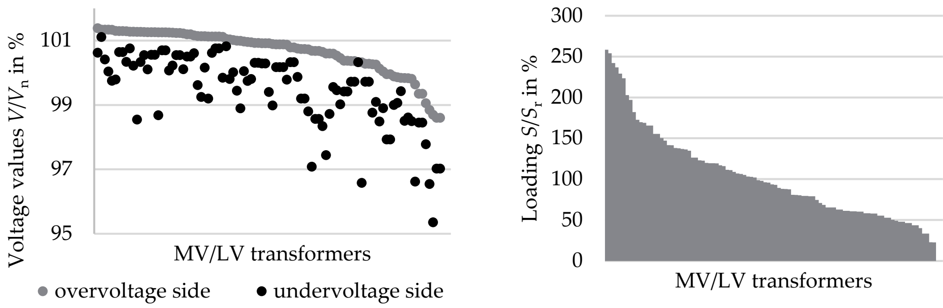

Figure 17. (**Left**): Voltage values of the MV/LV transformer nodes, (**right**): Loadings of the MV/LV transformers; both concept 2.

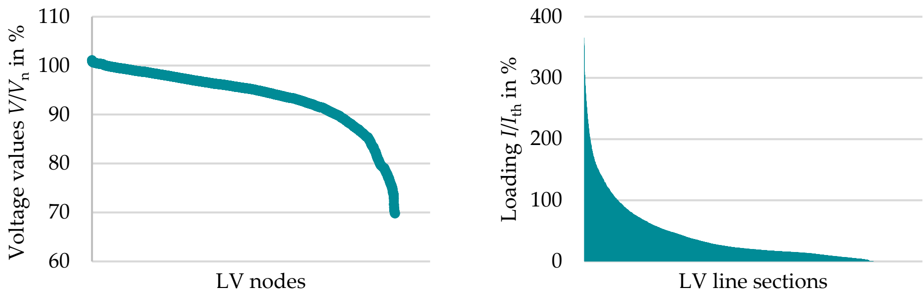

Figure 18. (**Left**): Voltage values of the LV nodes, (**right**): Loadings of the LV line sections; both concept 2.

The PF results from concept 2 in Figures 15–18 serve as an overview at this point and will be compared and evaluated with the results from concept 1a in Section 4.5 and the results from concept 1b in Section 4.6.

4.4. Overview of the Concepts for the Analyses

Figure 19 summarizes and compares the concepts. The different planning perspectives of the equipment are framed in color (purple: HV/MV transformers, green: MV lines, gray: MV/LV transformers, blue: LV lines). Concepts 1a and 1b are the existing concepts from Section 2.2 and concept 2 is the new concept from Section 3. In concept 1a, all four planning perspectives are modelled separately, and each is given a fixed voltage value assumption for the network feed-in. These result from the voltage band distribution in Figure 6. In concept 1b, as well as concept 1a, the planning perspectives are modelled separately. Instead of a fixed specification of the voltage values at the network feed-ins, the specific voltage values of the nodes from concept 2 are used in concept 1b. This has the advantage that the differences between the two concepts 1b and 2 can be investigated without the influence of the different fixed voltage value assumptions (worst-case). Concept 2 represents the complete modelling of the MV and LV network data set. A fixed specification of the voltage values is only set at the node on the high voltage side of the HV/MV transformers. The planning perspectives from concept 1 are compared with the corresponding network levels from concept 2.

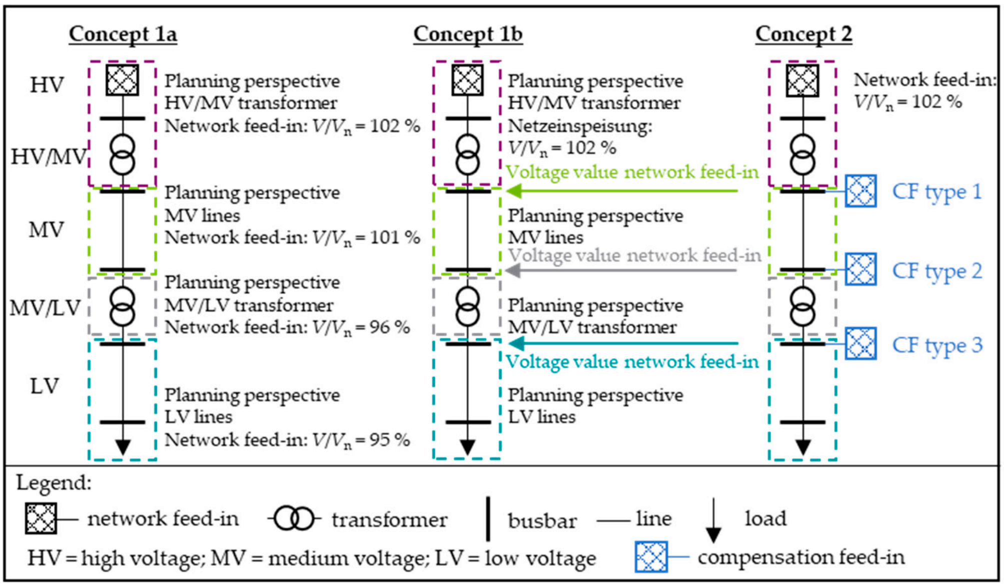

Figure 19. Comparison of the examined concepts 1a, 1b and 2.

4.5. Analysis and Comparison of Concept 2 with Concept 1a

In the following, the PF results from Sections 4.2.1 and 4.3 are analyzed and compared in detail for the aspects of voltage band, equipment loading, and network losses. All data of deviations are always set in relation to concept 1a. They are therefore calculated by subtracting the corresponding values of concept 1a from concept 2.

4.5.1. Voltage Band

HV/MV Transformers

The respective voltage drops over the HV/MV transformers are shown in Figure 20. When comparing the voltage values between concept 2 and concept 1a, it is noticeable that the voltage drops in concept 2 are 37% (T1) and 50% (T2) higher. This is due to differences in power flow within the network. In contrast to concept 1a, in concept 2 the LV lines are modelled so that additional line losses result from the complete network modelling. In addition, concept 2 results in higher losses in the planning perspectives of the MV lines and MV/LV transformers due to modelling since the equipment is loaded from their respective planning perspective, and thus the maximum network losses of all network levels occur at the same time.

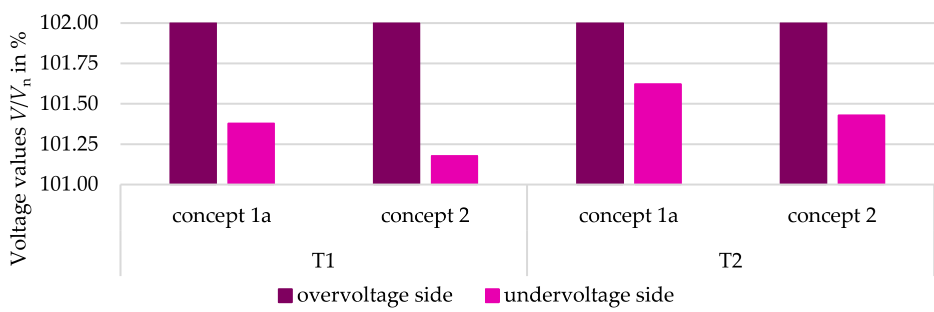

Figure 20. Voltage values of the HV/MV transformer nodes in concept 2 and concept 1a.

When the results are compared to the assigned voltage drop of $\Delta V/V_n = 1\%$ from Figure 6, the assigned voltage band is not fully needed. T1 has a voltage drop of $\Delta V/V_n = 0.82\%$, and thus $\Delta V/V_n = 0.18\%$ of the voltage band remains as a reserve in concept 2. Similarly, a voltage drop of $\Delta V/V_n = 0.57\%$ takes place over T2; therefore, $\Delta V/V_n = 0.43\%$ of the voltage band is still available as a reserve in concept 2.

MV Nodes

Figure 21 shows the voltage drops in the MV network as a deviation between concept 2 and concept 1a.

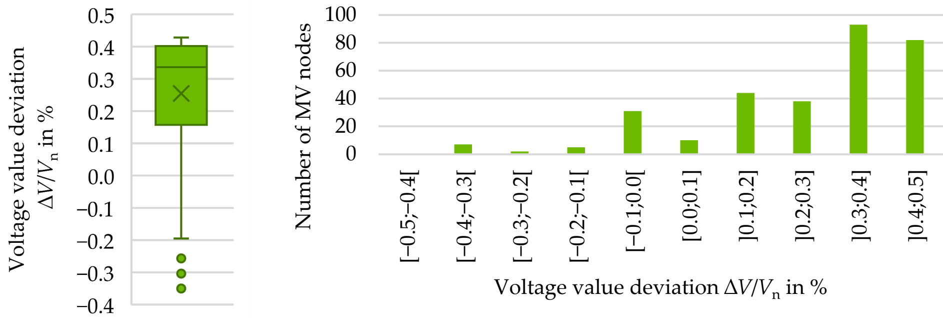

Figure 21. Voltage value deviations of the MV nodes between concept 2 and concept 1a (Inverted square brackets exclude the number from the specified range).

The box plot on the left—as well as all other box plots—basically describes the respective maximum with the upper antenna and the respective minimum with the lower antenna (without outliers). The "X" represents the arithmetic average. The lower part of the box is the lower quartile (Q1), the upper part of the box is the upper quartile (Q3), and the dividing line between them represents the median (Q2). The dots beyond the antennas mark outliers whose data values are 1.5 times higher (positive values) or smaller (negative values) than the distance between Q1 and Q3.

The average deviation of the voltage drops between concept 2 and concept 1a is $\Delta V/V_n$ = 0.25% and the median is $\Delta V/V_n$ = 0.34% (Figure 21 left). In addition, more than 80% of the deviations are higher than zero (Figure 21 right). This means that the voltage values in concept 2 are higher than in concept 1a. This is due to the fact that the assumed and fixed voltage drop $\Delta V/V_n$ = 1% of the HV/MV transformers from concept 1a is not fully required in concept 2. In concept 2, T1 $\Delta V/V_n$ = 0.18% and T2 $\Delta V/V_n$ = 0.43% of the voltage drop of $\Delta V/V_n$ = 1% defined in concept 1a remain unused. Assuming that this is the only factor influencing the voltage value deviations of the MV nodes, the voltage value deviations (depending on which HV/MV transformer the feeder is connected to) should be $\Delta V/V_n$ = 0.18% or $\Delta V/V_n$ = 0.43%, respectively. However, this does not correspond to the voltage value deviations shown. These range from $\Delta V/V_n$ = −0.35% to $\Delta V/V_n$ = 0.43% (Figure 21). Therefore, there must be other factors influencing the deviation of the voltage values.

In addition to the voltage value deviations due to the voltage drop across the HV/MV transformers, the remaining part of the voltage value deviations can be attributed to the different power flows over the MV/LV transformers. The differences are partly the result from different network losses. Concept 2 considers the LV line losses from the LV line perspective and the MV/LV transformer losses from the MV/LV transformer perspective. In concept 1a, the LV line losses cannot be considered due to the lack of modelling of the LV lines. The MV/LV transformer losses in concept 1a can only be considered with the SF from the MV line perspective which is an underestimation. Thus, the deviating voltage values result from the voltage band of the HV/MV transformers that is not fully used and the different equipment losses of the MV/LV transformers and the LV lines in the compared concepts.

Figure 22 shows the deviations of the voltage drop between concept 2 and concept 1a as a function of the MV node voltage values. The left diagram shows the deviations in relation to the voltage values from concept 2 and the right diagram in relation to the voltage values from concept 1a.

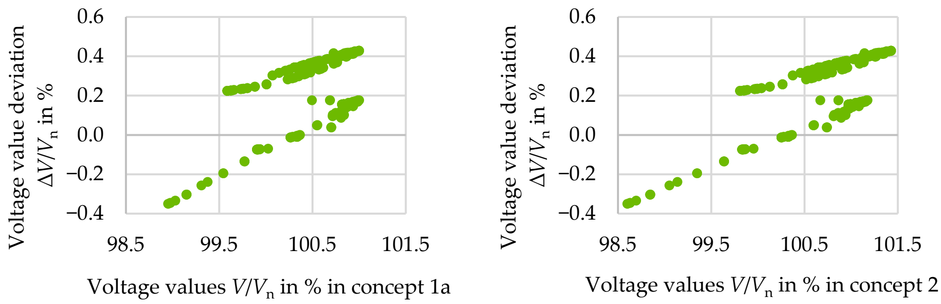

Figure 22. Voltage value deviations of the MV nodes between concept 2 and concept 1a as functions of the node voltage values.

The same statements can be drawn from both diagrams; therefore, only the right diagram will be discussed in the following. An upper and lower data range can be seen in Figure 22. The combination of the power flow results and the topology of the MV network shows that the upper data range belongs to nodes supplied from T2 and the lower data range belongs to nodes supplied from T1. In the upper data range of the diagram on the right (abscissa: voltage values from concept 1a), the voltage values are between V/V_n = 101% (voltage value of the network feed-in in concept 1a) and approx. V/V_n = 99.5% and the deviations drop from $\Delta V/V_n$ = 0.43% (unused voltage drop over T2) to $\Delta V/V_n$ = 0.24%. The decreasing positive voltage value deviations can be explained by the fact that the MV node voltage values in concept 2 fall more sharply due to the higher network losses already mentioned (lack of LV line modelling and MV/LV transformer loading). Thus, the deviation along the feeder becomes smaller. In the lower data range of the diagram on the right (abscissa: voltage values from concept 1a) the voltage values are between V/V_n = 101% (voltage value of the network feed-in in concept 1a) and approx. V/V_n = 99% and the deviations change from $\Delta V/V_n$ = 0.18% (unused voltage drop over T1) to $\Delta V/V_n$ = −0.35%. As in the upper data range, the change in the deviations along the voltage values can be explained by the stronger voltage drop in concept 2 along the feeder due to higher network losses. A negative deviation means that concept 2 has lower voltage values than concept 1a. Thus, the stronger voltage drops in concept 2 affected the deviations up to negative values.

MV/LV Transformers

Figure 23 shows the resulting deviations of the voltage drops at the MV/LV transformers between concept 2 and concept 1a. The average deviation of the voltage drop is $\Delta V/V_n$ = −0.01% and the median is $\Delta V/V_n$ = −0.02% (both left diagram). Concept 2 achieves a lower voltage drop (negative deviation) at the MV/LV transformers for 75% of MV/LV transformers. In about 67% of MV/LV transformers, there is a deviation between $\Delta V/V_n$ = −0.1% and $\Delta V/V_n$ = 0.0%. In the diagram on the right (Figure 23), it can also be seen that there are differences in voltage drop when the MV/LV transformers are differentiated in customer transformers (CTs) and distribution transformers (DTs). In the case of CT, there are only lower voltage drops in concept 2 (negative deviations). The deviations of the voltage drops at the DT show that a large part of it is negative. However, there are also some MV/LV transformers with positive deviations of the voltage drop, and thus higher voltage drops in concept 2.

The differences of the voltage drops can be explained by the different loadings of the MV/LV transformers as well as the higher voltage values on the high voltage side of the MV/LV transformers in concept 2. Figure 24 shows that there is a correlation between the deviation of the transformer loading and the deviation of the voltage drop. In concept 2, higher loadings on the MV/LV transformers lead to higher voltage drops. The higher loadings of the MV/LV transformers are due to the consideration of the line losses of the LV lines from their respective planning perspective.

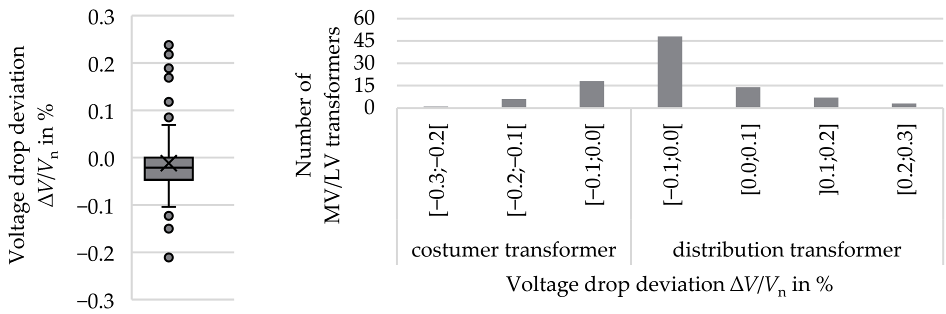

Figure 23. Voltage drop deviations of the MV/LV transformers between concept 2 and concept 1a. (Inverted square brackets exclude the number from the specified range).

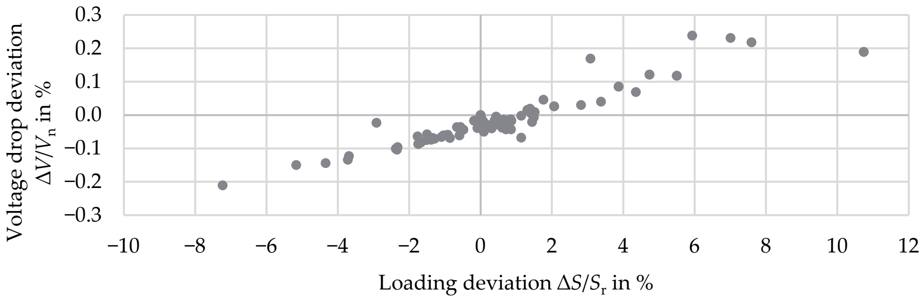

Figure 24. Voltage drop deviations of the MV/LV transformers between concept 2 and concept 1a as a function of the loading deviations of the MV/LV transformers.

Figure 25 also shows that most MV/LV transformers have significantly higher voltage values in concept 2. This is because the MV lines do not require the full assigned voltage band as shown in Figure 6. The voltage value deviations at the nodes on the high voltage and low voltage sides of the MV/LV transformers are predominantly between $\Delta V/V_n$ = 4% and $\Delta V/V_n$ = 6%. These higher voltage values result in lower loadings, and thus lower voltage drops at the MV/LV transformers in concept 2.

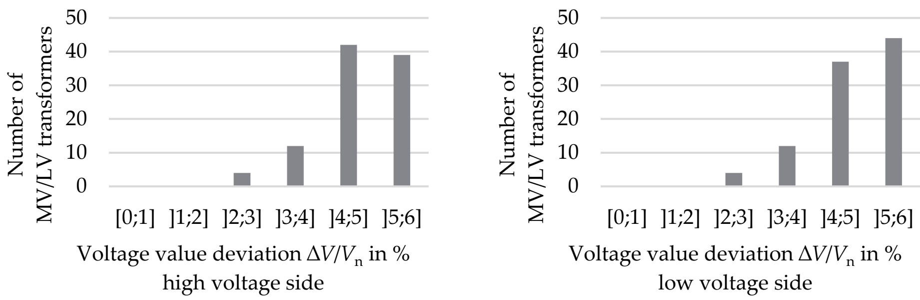

Figure 25. (**Left**): Distribution of the voltage value deviations on the high voltage sides of the MV/LV transformers between concept 2 and concept 1a, (**right**): Distribution of the voltage value deviations on the low voltage sides of the MV/LV transformers between concept 2 and concept 1a (Inverted square brackets exclude the number from the specified range).

Thus, when investigating the voltage drops at the MV/LV transformers, two effects can be detected that have opposite influences. The higher voltage values in concept 2 result in lower voltage drops. The higher power flows at the MV/LV transformers due to the LV line losses of the LV lines loaded from their respective planning perspective cause higher voltage drops. The CTs have only lower voltage drops, which is caused by the lower loadings from the higher voltage values. The DTs partly have higher loadings, and thus higher voltage drops due to the higher LV line losses. If the voltage drops are lower in concept 2 (negative deviation), the effect of the higher voltage values is more significant than the additional LV line losses. Therefore, DTs can have negative and positive deviations, depending on which effect has a higher impact.

LV Nodes

Figure 26 analyzes and evaluates the voltage values of the LV nodes between concept 2 and concept 1a. The voltage value deviations in the LV networks have an average value of $\Delta V/V_n$ = 4.1% and a median of $\Delta V/V_n$ = 4.5%. They are significantly higher in concept 2 than in concept 1a. This is caused by the voltage band distribution that is not fully needed in the higher network levels.

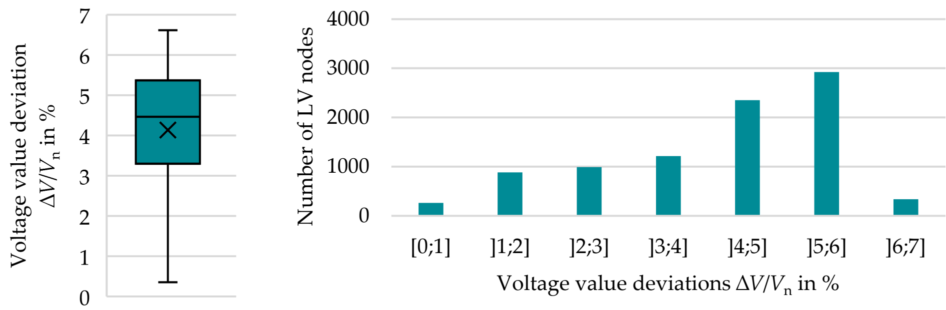

Figure 26. Voltage value deviations of the LV nodes between concept 2 and concept 1a (Inverted square brackets exclude the number from the specified range).

If the deviations shown in Figure 26 are related to the voltage values, the diagrams in Figure 27 result in the following (left: related to the voltage values in concept 2, right: related to the voltage values in concept 1a). The various recognizable horizontally contiguous data ranges represent the different LV networks. The deviations of the voltage values become higher the lower the voltage values become. The increasing voltage value deviations can be explained by the voltage value difference. Due to the higher voltage values with an average value of $\Delta V/V_n$ = 4.1%, the LV line sections are less loaded and this results in a lower voltage drop along the LV lines. Consequently, the further away the LV nodes are from the MV/LV transformers, the higher the voltage value deviations between concept 2 and concept 1a.

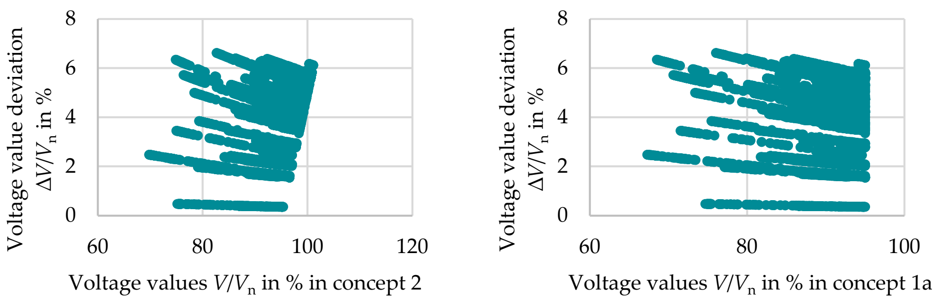

Figure 27. Voltage value deviations of the LV nodes between concept 2 and concept 1a as functions of the node voltage values.

4.5.2. Equipment Loading

In addition to the voltage value analyses in Section 4.5.1, analyses of the respective equipment loadings are also necessary. These are evaluated in the following section.

HV/MV Transformers

Figure 28 shows that the loading of T1 in concept 2 with $\Delta S/S_r$ = 5.7% and of T2 with $\Delta S/S_r$ = 4.7% is higher than in concept 1a. This is due to the power flows at the HV/MV transformers (Figure 28 right). These are higher in concept 2 because higher network losses of the underlying network levels are taken into account. Again, this is because the LV lines are modelled in concept 2 in difference to concept 1a. As a result, LV line losses occur in concept 2, which are not included in concept 1a. In addition, in concept 2, the loadings of the MV lines and the MV/LV transformers are modelled from their respective planning perspective. This leads to higher loadings and thus to higher network losses in concept 2 than in concept 1a.

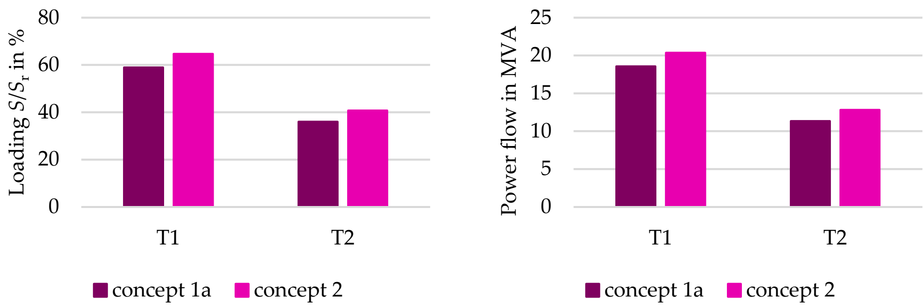

Figure 28. (**Left**): Loadings of the HV/MV transformers in concept 2 and concept 1a, (**right**): Power flows of the HV/MV transformers in concept 2 and concept 1a.

<u>MV Lines</u>

Figure 29 shows the deviations of the loadings of the MV line sections between concept 2 and concept 1a. The average deviation of the loadings is $\Delta I/I_{\text{th}}$ = 2.17% and the median is $\Delta I/I_{\text{th}}$ = 1.05%. Almost all MV line loadings are higher in concept 2 than in concept 1a. The exception is a single line, consisting of eight line sections, which only supplies a single large MV load. Due to the higher voltage values (see Figure 21), the line loadings of these sections are lower ($\Delta I/I_{\text{th}} = -0.051\%$).

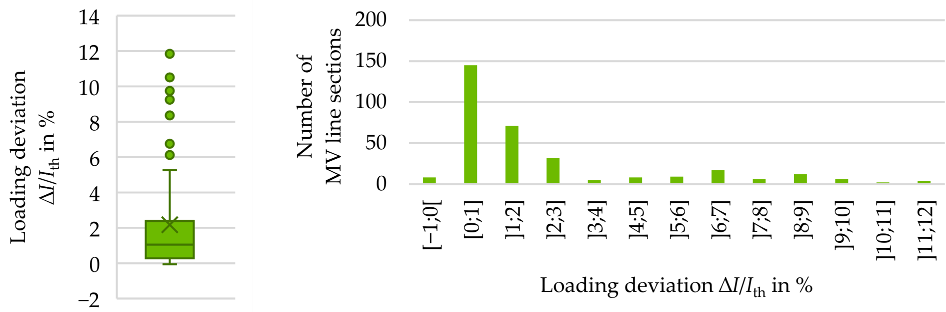

Figure 29. Loading deviations of the MV line sections between concept 2 and concept 1a (Inverted square brackets exclude the number from the specified range).

The higher MV line loadings can partly be explained through the additional modelling of the LV lines in concept 2. These are not modelled in the data set for the evaluation of the MV lines in concept 1a, and thus do not cause any LV line losses in concept 1a. In addition, the MV/LV transformer losses in concept 2 are higher because the MV/LV transformers are loaded from their respective planning perspective. The higher the MV line loading, the higher the deviation. This is because more LV networks are supplied through MV lines with higher loading, and thus more additional LV line losses are taken into account in concept 2. This can be seen in Figure 30, which shows the deviations as a function of the MV line loading. The network losses resulting from the higher MV/LV transformer loadings and the LV line modelling can be seen in the percentage differences of the load over the MV/LV transformers between concept 2 and concept 1a in Figure 31.

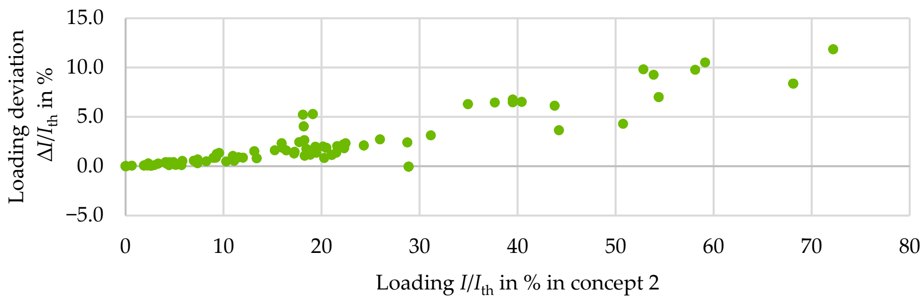

Figure 30. Loading deviations of the MV line sections between concept 2 and concept 1a as a function of the line loadings.

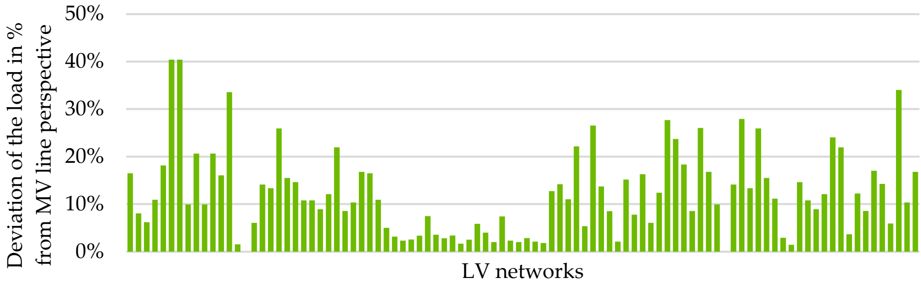

Figure 31. Percentage deviations of the load of the LV networks from the MV line planning perspective (load incl. LV line losses and MV/LV transformer losses from MV line planning perspective) between concept 2 and concept 1a.

MV/LV Transformers

Figure 32 shows the resulting loading deviations of the MV/LV transformers between concept 2 and concept 1a. The average deviation of the loadings is $\Delta S/S_{\mathrm{r}}$ = 2.37% and the median is $\Delta S/S_{\mathrm{r}}$ = 1.08%. Around two-thirds of all loading values have a positive deviation. This means that the loading is higher in concept 2. Again, this is primarily due to the additional LV line losses in concept 2 because the LV lines are loaded from their respective planning perspective. The MV/LV transformers therefore have to supply the LV line losses from the LV line perspective. This is countered by the higher voltage values (Figure 25) on the high voltage side of the MV/LV transformers in concept 2. As a result, the MV/LV transformer loadings are potentially lower. These two effects work in opposite directions and result in most deviations being small. The right-hand diagram in Figure 32 shows that the deviations of CT are only negative. Thus, the voltage drops are smaller in concept 2. This is due to the higher voltage values at the MV/LV transformer nodes on the high voltage side, as there are no LV line losses at CT. In the case of DT, most of the loadings on the MV/LV transformers are higher due to the additional LV line losses.

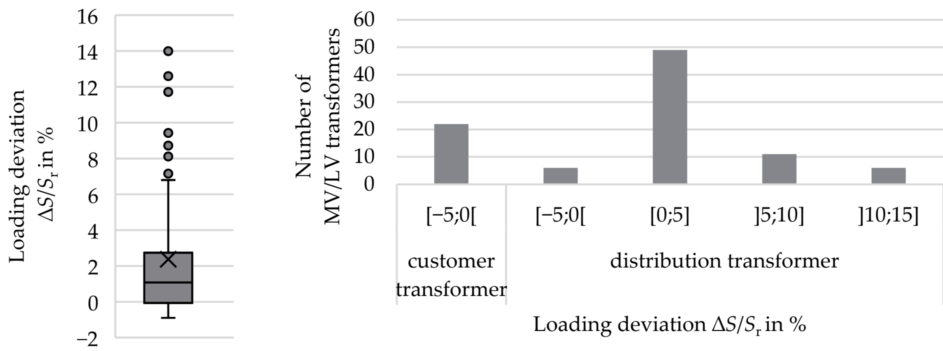

Figure 32. Loading deviations of the MV/LV transformers between concept 2 and concept 1a. (Inverted square brackets exclude the number from the specified range).

Based on the findings from the previous Figure 32, Figure 33 shows the deviations of the loading of the MV/LV transformers as a function of the deviations of the LV line losses in the LV networks. As the deviation of the LV line losses increases, the deviation of the MV/LV transformer loadings also increases.

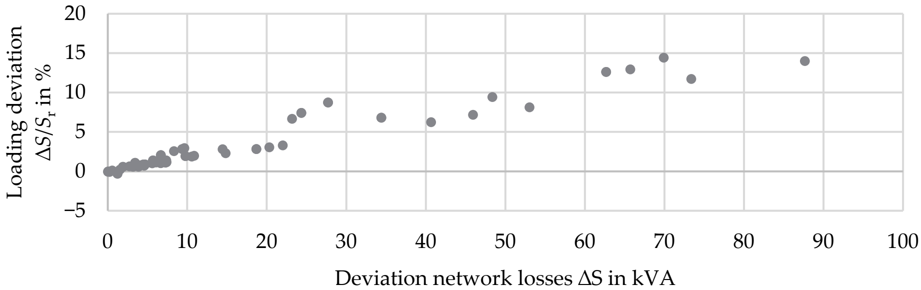

Figure 33. Loading deviations of the MV/LV transformers between concept 2 and concept 1a (only distribution transformers) as a function of the deviations of the network losses (apparent power in kVA).

<u>LV Lines</u>

Figure 34 shows the deviations of the loading of the LV line sections between concept 2 and concept 1a. The average deviation of the loadings is $\Delta I/I_{\text{th}}$ = −1.73% and the median is $\Delta I/I_{\text{th}}$ = −0.88%. The line loadings of all LV line sections are lower in concept 2 than in the LV line perspective of concept 1a (negative deviation). This is due to the deviation of the voltage values (see Figure 26). Due to the higher average voltage values of $\Delta V/V_{\text{n}}$ = 4.1%, the line loadings in concept 2 are lower at the same electric current. The LV line sections with a deviation of $\Delta I/I_{\text{th}}$ = 0% are unloaded and represent lines at the end of a feeder without loads.

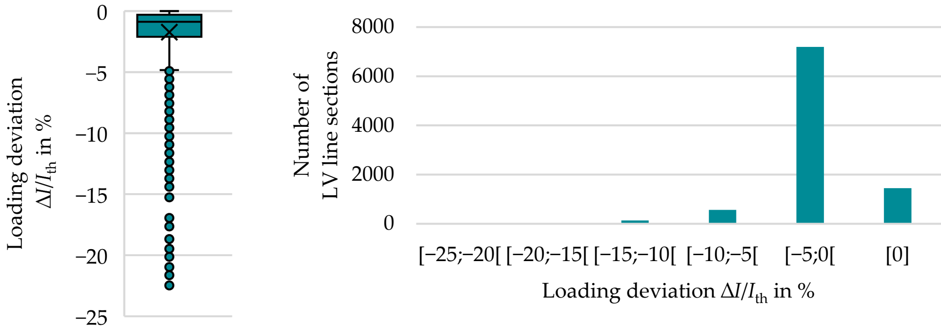

Figure 34. Loading deviations of the LV line sections between concept 2 and concept 1a (Inverted square brackets exclude the number from the specified range).

As a further analysis, the diagrams in Figure 35 show that the deviations of the line loadings depend on the values of the LV line loadings and the deviation of the voltage values. The higher the voltage values are in concept 2 (higher voltage value deviation), the lower are the line loadings, and thus the higher the negative line deviations. It can also be seen that the negative deviations of the line loadings increase the higher the line loadings become.

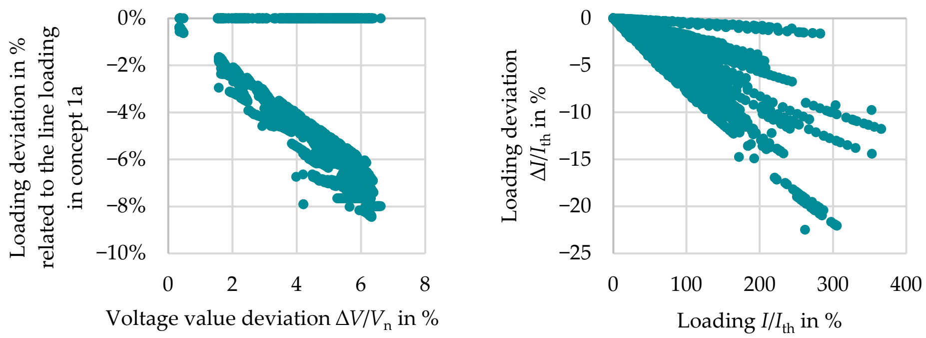

Figure 35. (**Left**): Percentage loading deviations of the absolute loadings of the LV line sections between concept 2 and concept 1a as a function of the voltage value deviations of the starting nodes of the LV lines between concept 2 and concept 1a, (**right**): Loading deviations of the LV line sections between concept 2 and concept 1a as a function of the LV line loadings.

4.5.3. Network Losses

In this section, the network losses and the losses of the individual types of equipment in the respective concept are analyzed to be able to compare their influence with each other. Figure 36 therefore shows the network losses incurred for each concept and planning perspective. Large differences between the two concepts result from the unmodelled network level in concept 1a and the loading of all equipment from the same planning perspective in concept 1a. In concept 2, the loadings of the equipment and thus the network losses are determined at all network levels from their respective planning perspective. Thus, there is a slight overestimation of the network losses in concept 2, because the network losses occur in such a way that a maximum loading of the equipment at all network levels occurs at the same time. The CFs compensate only for the load difference of the SFs, but not the load-dependent network losses, as these cannot be determined in advance. In contrast to this, the network losses in concept 1a are underestimated in some planning perspectives. If one or more underlying network levels are not modelled, the associated network losses of these network levels are missing in the simulation.

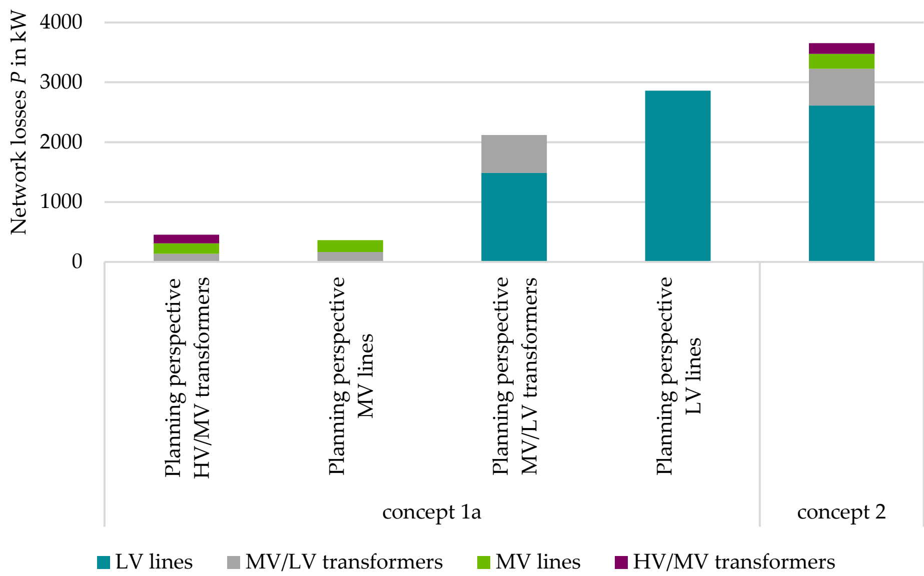

Figure 36. Network losses per planning perspective in concept 2 and concept 1a.

Figure 37 looks at the differences between concept 2 and concept 1a. In the left-hand diagram, deviations between separate equipment types or network elements (e.g., only HV/MV transformers without underlying network levels) are evaluated. In the diagram on the right, all underlying network levels are taken into account (e.g., HV/MV transformer with underlying MV lines, MV/LV transformers, and LV lines). The LV line losses and the MV/LV transformer losses in concept 2 are lower due to the higher voltage values. The MV line losses and HV/MV transformer losses are higher in concept 2. This is due to the overall higher power flow (due to the network losses of the underlying network levels) and the resulting higher loadings of the equipment, which can be seen in the right diagram in Figure 37.

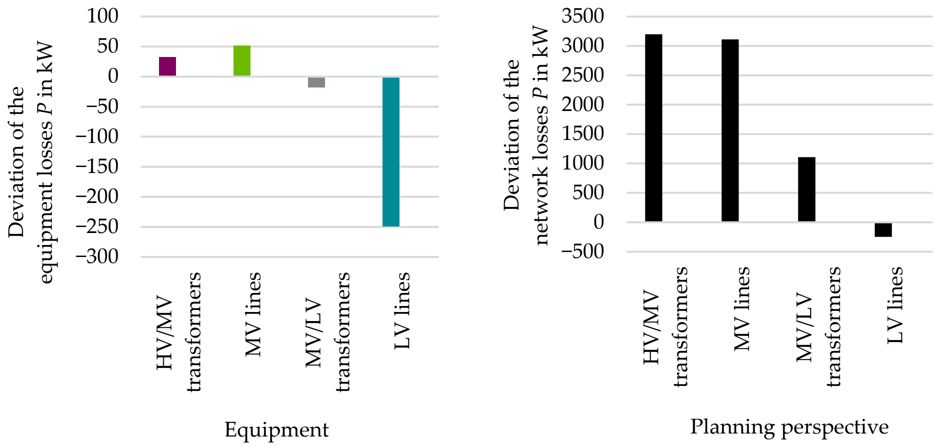

Figure 37. (**Left**): Deviation of the equipment losses of the equipment in the respective network level between concept 2 and concept 1a, (**right**): Deviation of the network losses of equipment in the different planning perspectives of concept 1a between concept 2 and concept 1a.

The lack of modelling of the LV lines in the planning perspective of the HV/MV transformers and the MV lines in concept 1a and the equipment loadings of the underlying network levels from the examined planning perspective lead to the fact that the network losses at the HV/MV transformers and the MV lines are about 3 MW lower in concept 1a than in concept 2. The network losses at the MV/LV transformers are higher in concept 2, because the LV line losses result from the loading of the LV line perspective, and in concept 1a only result from the loading of the MV/LV transformer perspective. As previously described, the network losses of the LV lines are lower due to the higher voltage values in concept 2.

4.5.4. Interim Conclusion

Table 3 summarizes the results of the analyses by listing the parameters examined, the deviations determined and the associated justification. The deviations are caused, on the one hand, by the network losses and, on the other hand, by the voltage band sections that are not fully used in the network levels in concept 2 compared to the fixed voltage band distribution in concept 1a. The modelling of the LV lines as well as the loadings of the underlying network levels from their respective planning perspective lead to higher network losses, and thus to higher voltage drops and higher loadings on the HV/MV transformers in concept 2. Similarly, the modelling of the LV lines and the loading of the underlying network levels from their respective planning perspective lead to higher network losses when comparing the MV lines, which leads to higher loadings of the MV lines in concept 2 and higher voltage drops along the MV lines in concept 2. However, the voltage band of the HV/MV transformers, which is not fully used, counteracts this, and sometimes leads to higher voltage values at the MV nodes in concept 2. In the case of the DT, higher voltage values are present in concept 2 due to the partially unused voltage bands in the overlying network levels. Due to the higher voltage values, there are DTs that have lower voltage drops and lower loadings in concept 2. However, there are also DTs that have higher voltage drops and higher loadings in concept 2. This can be explained by the higher network losses in concept 2 due to the loading of the LV lines by their respective planning perspective. In concept 2, only higher voltage values are applied to the CT due to the partially unused voltage band of the overlying network levels, since there are no underlying LV networks that cause LV network losses. This results in lower voltage drops, lower loadings, and lower network losses of the CT in concept 2. Due to the partially unused voltage band of the overlying network levels, higher voltage values are applied to the LV lines in concept 2, which lead to lower loadings and thus to lower LV network losses.

Table 3. Summary of key findings from the comparison of the evaluations of concept 2 and concept 1a.

Equipment	Parameter	Concept 2	
		Effect	Justification
HV/MV transformers	Voltage values	Lower	Higher voltage drop
	Voltage drop	Higher	Higher network losses
	Loading	Higher	Higher network losses
	Network losses	Higher	Loading of the equipment from their respective planning perspective, additional modelling of LV lines
MV nodes/ MV lines	Voltage values	Higher Lower	Voltage band of the HV/MV transformer network level not fully utilized Higher network losses
	Loading	Higher	Higher network losses
	Network losses	Higher	Loading of the equipment from their respective planning perspective, additional modelling of LV lines
MV/LV transformers (DT)	Voltage values	Higher	Voltage band of the overlying network levels is not fully utilized
	Voltage drop	Higher Lower	Higher network losses Higher voltage values
	Loading	Higher Lower	Higher network losses Higher voltage values
	Network losses	Higher	LV line loading from their respective planning perspective
MV/LV transformers (CT)	Voltage values	Higher	Voltage band of the overlying network levels is not fully utilized
	Voltage drop	Lower	Higher voltage values
	Loading	Lower	Higher voltage values
	Network losses	Lower	Higher voltage values
LV nodes/ LV lines	Voltage values	Higher	Voltage band of the overlying network levels is not fully utilized
	Loading	Lower	Higher voltage values
	Network losses	Lower	Higher voltage values

Concept 2 offers the advantage over concept 1a that all underlying network levels are modelled, and thus network losses from all network levels are considered in the simulation. Therefore, there is no underestimation of the simulated situation as in concept 1a. In addition, the real voltage values are transferred between the network levels so that no fixed voltage band distribution (especially between the MV and LV network levels) is necessary. This means that unused voltage reserves can be utilized in the underlying networks. The disadvantage of concept 2 is the slight overestimation of the network losses. These occur simultaneously in all network levels.

The evaluations show that the deviations of the voltage values and the equipment loadings are influenced by the different voltage values between concept 2 and concept 1a (due to the fixed voltage band distribution). This effect is particularly present in the two lower network levels, where there are large voltage value differences. Therefore, in Section 4.5, the evaluations between concept 1b and concept 2 are carried out.

Concept 1a and concept 1b differ so far as concept 1b does not receive fixed voltage values at the network feed-ins from a voltage band distribution, but uses the voltage values at the corresponding nodes from concept 2. As a result, in all four planning perspectives, the same voltage values are present in both concepts at the nodes of the network feed-ins from concept 1b. Thus, an evaluation can be carried out in Section 4.6 in which the deviations are not influenced by different voltage values at the network feed-ins and a voltage band that is only partially used.

4.6. Analysis and Comparison of Concept 2 with Concept 1b

In this section, the results of Section 4.2.2 (concept 1b) and Section 4.3 (concept 2) are analyzed. Thus, a comparison is made with the same voltage values at the nodes of the network feed-ins of the respective planning perspectives. This is necessary because the fixed distribution of the voltage band in concept 1a leads to different voltage values at the transition nodes of the overlying network levels, and thus influences all results. They are compared in detail for the aspects of voltage band, equipment loadings, and network losses. The focus are the differences of the results in comparison with the analysis in Section 4.5. All data of deviations are always related to concept 1b. They are therefore formed in such a way that the corresponding values of concept 1b are subtracted from concept 2.

4.6.1. Voltage Band

The voltage values and the voltage drops of the HV/MV transformers T1 and T2 are identical to the comparison of concept 1a and concept 2. This is due to the fact that the HV/MV transformer level is the top level considered with the specification of a fixed voltage value (V/V_n = 102%) at the network feed-ins at the HV/MV transformer nodes on the overvoltage side. In the modelling of concept 1a and concept 1b, there are no differences due to the same voltage value of the network feed-in.

The voltage value deviations at the MV nodes between concept 2 and concept 1b and between concept 1b and concept 1a are shown in Figure 38. The average deviation is $\Delta V/V_n = -0.1\%$ and the median is $\Delta V/V_n = -0.06\%$ between concept 2 and concept 1b. All deviations are zero or negative, which means that there is a higher voltage drop in concept 2 than in concept 1b. This is due to the higher network losses of the underlying network levels, which are loaded by their respective planning perspectives. It can be seen that in concept 1b the voltage values are higher than in concept 1a. This is due to the fact that the difference between concept 2 and concept 1a is caused only by the partially used voltage band of the HV/MV transformers. This unused voltage band leads to lower voltage values in concept 1a compared to concept 1b.

Figure 39 shows the deviations of the voltage drop $\Delta V/V_n$ at the MV/LV transformers. There are no or very small deviations of $\Delta V/V_n = \pm 0.001\%$ of the voltage drop at the CT. For the DT, the average deviation is $\Delta V/V_n = 0.09\%$ and the median is $\Delta V/V_n = 0.03\%$. It also shows that all deviations in the DT are higher than or equal to zero. Thus, the voltage drops in concept 2 are higher at the MV/LV transformers than in concept 1b. If the deviations of the voltage drop between concept 1a and concept 1b are compared, they are smaller in concept 1b (negative deviation). This can be explained by the higher voltage values at the MV/LV transformers and LV nodes in concept 1b. These lead to lower equipment loadings and, as a result, to lower network losses. Thus, the voltage drops in concept 1b are lower than in concept 1a due to the higher voltage values and lower network losses.

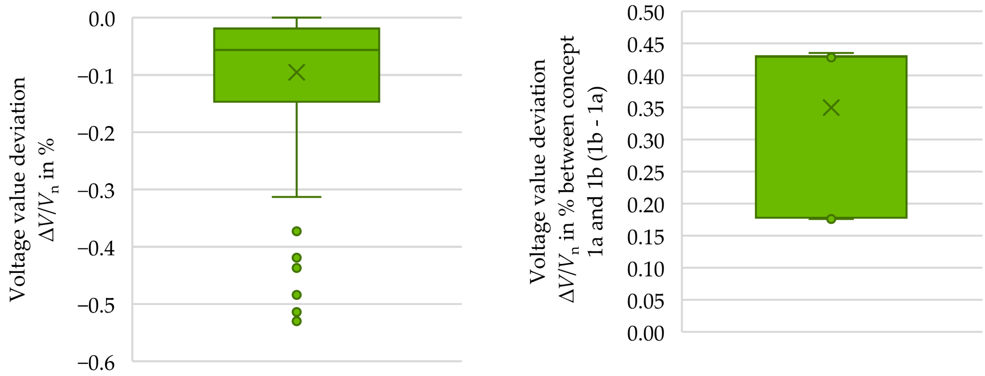

Figure 38. (**Left**): Voltage value deviations of the MV nodes between concept 2 and concept 1b, (**right**): Voltage value deviations of the MV nodes between concept 1b and concept 1a.

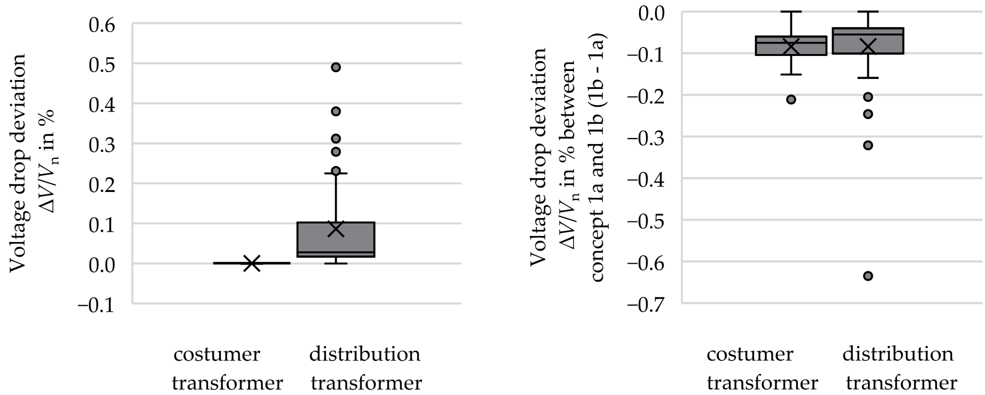

Figure 39. (**Left**): Voltage drop deviations of the MV/LV transformers between concept 2 and concept 1b, (**right**): Voltage drop deviations of the MV/LV transformers between concept 1a and concept 1b.

Figure 40 shows the deviations of the voltage values $\Delta V / V_n$ of the LV nodes. It can be seen that there are no significant differences between the voltage values of the two concepts. The right-hand diagram in Figure 40 shows the voltage value deviations at the LV nodes between concept 1a and concept 1b. It can be seen here that the voltage values are higher in concept 1b, as there is no fixed voltage band distribution as in concept 1a.

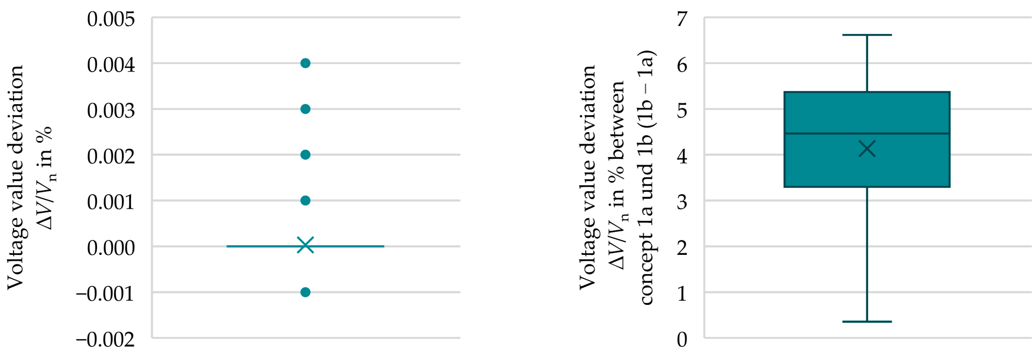

Figure 40. (**Left**): Voltage value deviations of the LV nodes between concept 2 and concept 1b (further decimal places were not output in the network calculation software), (**right**): Voltage value deviations of the LV nodes between concept 1a and concept 1b.

4.6.2. Equipment Loading

The loading deviations of the HV/MV transformers between concept 2 and concept 1b are the same than between concept 2 and concept 1a. This is caused by the same voltage value assumption at the network feed-ins in concept 1a and concept 1b. The loadings of

T1 and T2 are higher in concept 2 due to a higher power flow. The higher network losses from the loadings of the equipment of the underlying network levels from their respective planning perspective as well as the existing modelling of the LV lines in concept 2 cause the higher loadings.

Figure 41 shows on the left the deviation of the line loadings $\Delta I/I_{th}$ between concept 2 and concept 1b and Figure 41 on the right the deviations of the line loadings $\Delta I/I_{th}$ between concept 1b and concept 1a. The average deviation between concept 2 and concept 1b is $\Delta I/I_{th}$ = 2.23% and the median is $\Delta I/I_{th}$ = 1.08%. There are only minor differences between concept 1b and concept 1a. As a result, the deviations between concept 2 and concept 1b are relatively similar to the divergences between concept 2 and concept 1a. The higher loadings in concept 2 are caused by the lack of modelling of the LV lines in concept 1b and the loading of the underlying networks from the considered planning perspective in concept 1b.

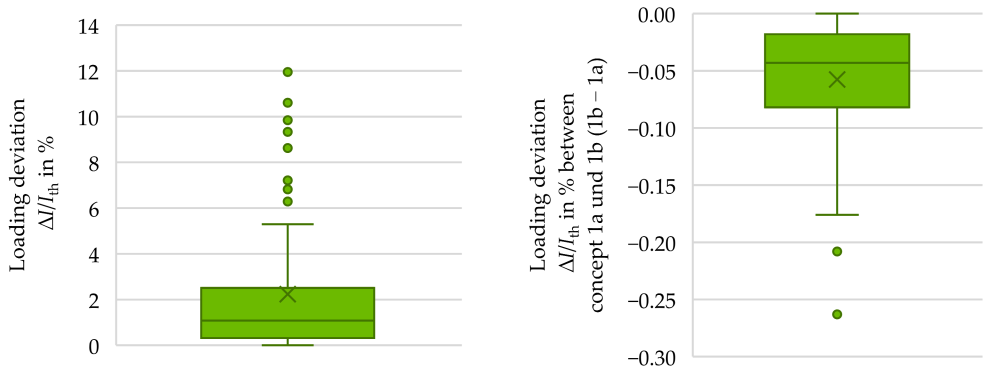

Figure 41. (**Left**): Loading deviations of the MV line sections between concept 2 and concept 1b, (**right**): Loading deviations of the MV line sections between concept 1a and concept 1b.

Figure 42 shows on the left the deviations of the MV/LV transformer loadings between concept 2 and concept 1b. The average deviation of the loadings of the DT is $\Delta S/S_r$ = 3.8% and the median is $\Delta S/S_r$ = 1.6%. The CT analysis shows that there are no deviations between concept 2 and concept 1b. The deviations in the loadings of the MV/LV transformers are caused by the different LV line losses in the two concepts. When comparing concept 1b and concept 1a, it can be seen that the loadings in concept 1b are lower. This is due to the higher voltage values in concept 1b.

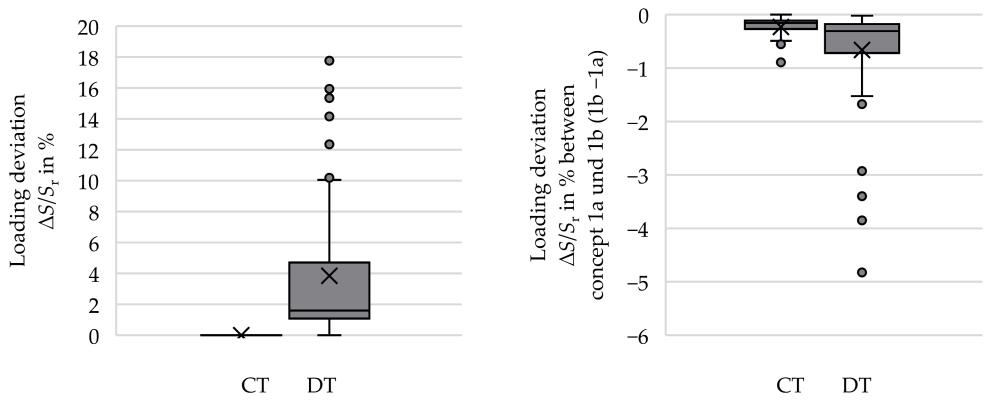

Figure 42. (**Left**): Loading deviations of the MV/LV transformers between concept 2 and concept 1b, (**right**): Loading deviations of the MV/LV transformers between concept 1a and concept 1b.

In Figure 43, it can be seen that there are no significant differences between the loadings of the LV lines between concept 2 and concept 1b. The average value of the deviation of the LV line loadings is $\Delta I/I_{th}$ = −0.0003%. The right-hand diagram in Figure 43 shows the deviations of the loadings between concept 1a and concept 1b. These are caused by the different voltage values at the LV nodes in concept 1a and concept 1b.

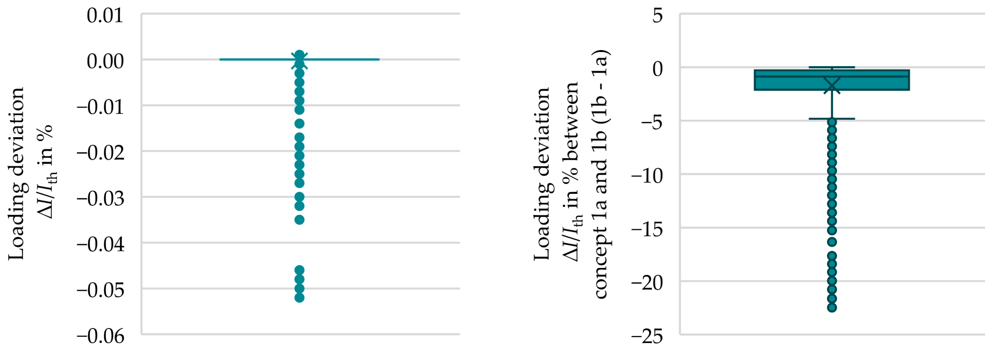

Figure 43. (**Left**): Loading deviations of the LV line sections between concept 2 and concept 1b, (**right**): Loading deviations of the LV line sections between concept 1a and concept 1b.

4.6.3. Network Losses

Figure 44 shows the network losses for each concept and planning perspective. Here, it is clearly recognizable that in concept 2 the network losses of all network levels occur from the respective planning perspective. In concept 1b, lower network losses occur through the lack of modelling of the LV network level in some planning perspective and the loading of all underlying network levels from the considered planning perspective. The higher voltage values and the resulting lower loadings of the equipment lead to lower network losses in concept 1b compared to concept 1a. These higher voltage values have a particular impact on the network losses in the MV/LV and LV network levels.

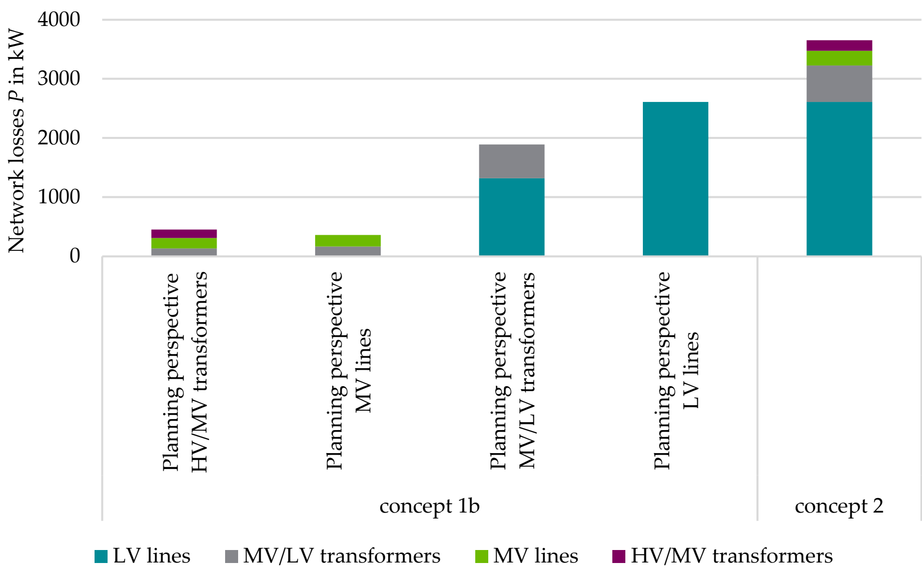

Figure 44. Network losses per planning perspective in concept 2 and concept 1b.

4.6.4. Interim Conclusion

Table 4 summarizes the results of the analyses by listing the parameters examined, the deviations determined, and the associated justification. It turns out that all deviations are caused by the different network losses. Due to the lack of modelling of the LV lines when considering the HV/MV transformers and the MV lines in concept 1b, the LV line losses are missing in the respective PF calculations. In addition, the network losses are higher in concept 2, as all equipment is loaded to the maximum at the same time due to the consideration of the operating point of heavy load, considering the corresponding SF. The underlying network levels in concept 1b are only loaded from the planning perspective of the network level under investigation, which results in lower network losses.

Table 4. Summary of key findings from the comparison of concept 2 and concept 1b.

Equipment	Parameter	Concept 2	
		Effect	Justification
HV/MV transformers	Voltage values	Lower	Higher voltage drop
	Voltage drop	Higher	Higher network losses
	Loading	Higher	Higher network losses
	Network losses	Higher	Loading of the equipment from their respective planning perspective, additional modelling of LV lines
MV nodes/ MV lines	Voltage values	Lower	Higher network losses
	Loading	Higher	Higher network losses
	Network losses	Higher	Loading of the equipment from their respective planning perspective, additional modelling of LV lines
MV/LV transformers (DT)	Voltage values	Lower	Higher voltage drops
	Voltage drop	Higher	Higher network losses
	Loading	Higher	Higher network losses
	Network losses	Higher	LV line loading from their respective planning perspective
MV/LV transformers (CT)	Voltage values	Equal	Equal network losses
	Voltage drop	Equal	Equal network losses
	Loading	Equal	Equal network losses
	Network losses	Equal	No network losses through underlying network levels
LV nodes/ LV lines	Voltage values	Equal	Equal network losses
	Loading	Equal	Equal network losses
	Network losses	Equal	

Concept 2 offers the advantage that all underlying network levels are modelled, and thus network losses from all network levels are considered. Therefore, there is no underestimation of the simulated situation as in concept 1b. In concept 1b, not all underlying network levels are modelled in some planning perspectives, and thus the network losses of the missing network levels are not considered. The disadvantage of concept 2 is the slight overestimation of the network losses. These occur simultaneously in all network levels.

Since a future scenario for the year 2050 is assumed in the investigated MV network with all underlying LV networks, very high loadings on the equipment (up to I/I_{th} = 370%) are present in some cases. Due to these high overloads of the equipment, very high network losses occur at the overloaded equipment. These increasingly lead to significant differences in the power flow results of the concepts. Therefore, in a final step in Section 4.7, the network is replanned and the comparison is then carried out again.

4.7. Analysis of the Overplanned Networks

As shown in Sections 4.4 and 4.5, there are differences between the PF results of concept 2 and concept 1b. These were mainly attributed to the different network losses. In concept 2, these are particularly higher caused by the high loadings of the MV/LV transformers and LV lines from their respective planning perspective. Equations (7) and (8) show the equations for calculating the power losses of lines and transformers. To calculate the line losses P_{L}, the line resistance R_{L} is multiplied by the measured loading I squared. The transformer losses P_{v} are made up of the load-independent iron losses P_0 and the load-dependent copper losses P_{c}.

$$P_{\mathrm{L}} = R_{\mathrm{L}} \cdot I^2 \tag{7}$$

$$P_{\mathrm{v}} = P_0 + \left(\frac{S_{\mathrm{Last}}}{S_{\mathrm{r}}}\right) \cdot P_{\mathrm{c}} \tag{8}$$

For this reason, the network is reinforced for the (n-0) case. This means that the network complies with the voltage value limits of $\Delta V_{\mathrm{max}}/V_{\mathrm{n}}$ = ±10% of DIN EN 50160 [19] at all nodes during permissible operation and the equipment is not loaded above I/I_{th} = 100%. This results in the new LF results shown below.

At this point, it should be noted that the reinforcement is neither cost-optimized nor resource-optimized, but only carried out in such a way that overloads and undervoltages are no longer present. Due to the reinforcement of the network, lines with higher cross-sections and transformers with higher power rating are generally available. This new equipment has lower resistances and higher power ratings than the equipment previously available in the network, which leads to lower network losses.

Furthermore, concept 1b is chosen instead of concept 1a for the reinforcement in order not to be influenced by different voltage values due to the unused voltage band. Thus, all deviations are only caused by the different network losses.

Table 5 summarizes the results of the analyses by listing the parameters examined, the deviations determined, and the associated justification. It turns out that all deviations are caused by the network losses. The lack of modelling of the LV lines when considering the HV/MV transformers and the MV lines in concept 1b(p) as well as the loadings of the underlying network levels based on the examined planning perspective leads to lower network losses in concept 1b(p). Due to the overplanning, the deviations between the two concepts have been reduced. This is due to the fact that the overplanning has reduced the loading of the MV/LV transformers, and thus the losses of the MV/LV transformers. In addition, the overplanning of the LV lines results in lower line resistances, which also leads to lower network losses.

The network losses have been reduced by 42% overall as a result of the overplanning of the network between concept 2(p) and concept 1b(p). The network losses were reduced by 45% in the LV and MV/LV network levels and by 10% in the MV and HV/LV network levels. As a result, the deviations of the voltage drops have been reduced from 37% to 14% for T1 and from 50% to 28% for T2 in contrast to the unplanned network. The deviation of the loading of T1 has been reduced from $\Delta S/S_{\mathrm{r}}$ = 5.7% to $\Delta S/S_{\mathrm{r}}$ = 2.6% and of T2 from $\Delta S/S_{\mathrm{r}}$ = 4.7% to $\Delta S/S_{\mathrm{r}}$ = 2.9%. The deviations of the voltage drops and loadings in the MV network level have been reduced by nearly 50%. The overplanning of the MV/LV transformers reduced the deviation of the voltage drops by an average factor of 3. The largest deviations have been reduced by a factor of up to 6 (largest deviation reduced from $\Delta V/V_{\mathrm{n}}$ = 0.49% to $\Delta V/V_{\mathrm{n}}$ = 0.075%). The average deviation of the loading of the MV/LV transformers is reduced by a factor of 2.5 and the largest deviations are reduced by a factor of up to 4. As in the unplanned network, the deviations in the LV network level are almost non-existent. The maximum deviation of the line loading has been reduced from $\Delta I/I_{\mathrm{th}}$ = −0.052% in the unplanned network to $\Delta I/I_{\mathrm{th}}$ = −0.001% in the planned network.

The maximum deviation of the voltage values has been reduced from $\Delta V/V_\mathrm{n}$ = 0.004% to $\Delta V/V_\mathrm{n}$ = 0.001%.

Table 5. Summary of key findings from the comparison of concept 2(p) and concept 1b(p).

Equipment	Parameter	Concept 2	
		Effect	**Justification**
HV/MV transformers	Voltage values	Lower	Higher voltage drop
	Voltage drop	Higher	Higher network losses
	Loading	Higher	Higher network losses
	Network losses	Higher	Loading of the equipment from their respective planning perspective, additional modelling of LV lines
MV nodes/ MV lines	Voltage values	Lower	Higher network losses
	Loading	Higher	Higher network losses
	Network losses	Higher	Loading of the equipment from their respective planning perspective, additional modelling of LV lines
MV/LV transformers (DT)	Voltage values	Lower	Higher voltage drop
	Voltage drop	Higher	Higher network losses
	Loading	Higher	Higher network losses
	Network losses	Higher	LV line loading from their respective planning perspective
MV/LV transformers (CT)	Voltage values	Equal	Equal network losses
	Voltage drop	Equal	Equal network losses
	Loading	Equal	Equal network losses
	Network losses	Equal	No network losses through underlying network levels
LV nodes/ LV lines	Voltage values	Equal	Equal network losses
	Loading	Equal	Equal network losses
	Network losses	Equal	

Concept 2(p) offers the advantage that all underlying network levels are modelled, and therefore network losses from all network levels are considered. Therefore, there is no underestimation of the network losses in the simulation as in concept 1b(p). In concept 1b(p), not all underlying network levels are modelled in some planning perspectives. The network losses of the missing network levels are therefore not considered. The disadvantage of concept 2(p) is the slight overestimation of the network losses. These occur simultaneously in all network levels. Each network level sees the network losses of all underlying network levels at the same time in the amount of the respective planning perspective.

5. Discussion

5.1. Method Reflection

The developed concept 2 is based on the use of only one data set with one modelled MV network and all underlying LV networks as well as the requirement to apply the SF correctly. Otherwise, incorrect results are obtained in a cross-voltage data set with the application of SF such as in concept 1a and concept 1b. Only one network level is calculated with the correct SF and the other network levels are calculated with the wrong SF which leads to incorrect results.

According to Section 1.1, there are also approaches using time-series calculations that make the application of concept 2 obsolete. If a time-series simulation is carried out with considering the network losses of all network levels, the same data set as in concept 2 is necessary. This means that concept 2 and the time-series simulation have the same data set. In concept 2, only one time step (power flow) has to be simulated, and in a 15-min time-series simulation for one year, 35,040 time steps (power flows) have to be carried out. The time-series simulation then achieves the correct network losses in each time step, which is not possible in concept 2. It must therefore be weighed whether a significantly shorter calculation time justifies a slight overestimation of the network losses. Additionally, if equivalent loads are used instead of real underlying networks (data set of concept 1) in the time-series calculation, the advantage of the correct network losses is lost. Due to the lack of modelling the underlying networks, the network losses of these cannot be considered in the simulation and the same problem as in concept 1 occurs with higher computing power and computing time. It should also be noted that the quality, quantity, and combination of the time-series per load or DER have a high influence on the simulation results of the time-series simulation and that the simulation of one year may not represent the worst-case scenario. Many time-series are only synthetically generated and attempt to reflect user behavior as close as possible This worst-case scenario is represented through the use of SF, which explicitly represent the maximum simultaneous power of the loads and DER: In addition, according to [25], the SFs applied in this paper are based on real mobility data; therefore, the time-series are indirectly taken into account.

Regarding Section 3, it should therefore be noted that it is possible to map SFs with CFs in such a way that all modelled network levels (in the article: an MV network with all underlying LV networks) can be analyzed and evaluated with one PF calculation. The main advantages result from the simple handling of the modelling of new loads, such as private and public charging infrastructure, as well as the correspondingly short calculation time. Especially since a calculation using SFs and operation points analysis according to [24] leads to almost identical results than time-series in the context of load development.

5.2. Influence of the General Conditions

The detailed comparisons within Sections 4.5–4.7 have shown that there are dependencies between the concepts in terms of voltage band, equipment loadings, and network losses. For example, in concept 2, less voltage drops are required by the MV/LV transformers than is assumed in concept 1a. This is an approximate reflection of reality for concept 2 than in the case for concept 1a. However, according to Section 5.3 below, it should be considered that corresponding voltage drops change as, for example, other transformers are modelled. In addition, Section 4.7 shows that the deviations between the concepts are significantly reduced after overplanning. This is relevant because the strategic network planning is the basis for recommended actions and not the pure limit value violations, which tend to show slightly higher deviations between the concepts according to Sections 4.5 and 4.6 than is the case in Section 4.7. Thus, the future scenario used has an influence on the results. The more progressive the scenario and the higher the loadings of the equipment in the network, the higher the relative deviations between the concepts.

5.3. Fuzziness of Network Modelling

All results and PF analyses are based on the selected MV network with all underlying LV networks. Specific aspects that only affect the respective network area, such as cable types and cross-sections, have a significant influence on the PF results. The identified deviations may therefore change if other cable types and cross-sections are in the network area. Furthermore, a uniform selection of transformers (e.g., same short-circuit powers, etc.) from the standard equipment library of the calculation software is used in all network levels to be able to make generalized statements. However, this does not affect the basic findings regarding concept 2.

6. Conclusions

Within the scope of this paper, a new modelling concept (concept 2) is developed to consider SFs within a cross-voltage data set. This was not possible with the previous concept (concept 1) in the context of a consideration of SFs. In concept 1, only one network level with the correct SF can be simulated with one PF calculation. The use of SF from one planning perspective leads to over- or under-dimensioning of the equipment in the other network levels. The new concept 2 enables a simultaneous simulation of different network levels by using CFs to compensate for the load differences through SFs between the different planning perspectives of the network levels. The CFs are modelled at the transitions of the network levels (transformer nodes on the overvoltage and low voltage sides). They feed-in power (at the peak load operating point) to compensate for the power values with the SF of the underlying network level to the power values with the SF of the overlying network level. In comparison with the previous concept 1, the new concept 2 shows that an application is expedient and offers the significant advantage that, on the one hand, only one instead of, for example, four data sets, are modelled and, on the other hand, all network losses are mapped through the cross-voltage data set. In concept 1, not all network levels are modelled in some planning perspectives, which leads to missing network losses in the simulation. At the same time, the existing complexity of new loads (and DER) can be mapped in the context of future supply tasks.

It is also possible to map the effects of expansion measures at all network levels with just one data set. Conventional expansion measures have an influence on the voltage values in the underlying network levels, as they lead to different voltage values there. Thus, for example, an MV line measure has an influence on the voltage values in the underlying LV networks. In addition, the impact of innovative technologies on all network levels can be considered. As an example, the voltage regulation at the HV/MV substation can be considered and evaluated directly for all underlying LV networks. This is interesting because in a network area, LV networks with different supply tasks (e.g., heavy load situation and heavy feed-in situation) may have to be taken into account, which may require different voltage value adjustments. Conversely, the application of load management at the LV level can be analyzed in terms of the effects on the overlying MV network. Thus, the use of the new concept 2 enables a direct evaluation of the expansion measures carried out and the technologies used at all network levels.

Furthermore, a comparison of the PF results showed that there are only minor deviations between the old and new concept for unplanned networks with modelled future scenarios. These deviations become even smaller if the networks under consideration are overplanned, and thus represent the target state. The discrepancies between the two concepts are caused by the different network losses. In the new concept 2, the network losses are slightly overestimated since all network levels are loaded by their respective planning perspective. This means that the simultaneous network losses of all underlying network levels are included in the respective overlying network levels. Conversely, the network losses are underestimated in the previous concept 1 as not all network levels are modelled depending on the data set, and therefore network losses are not taken into account.

In the context of the ongoing energy transition and the necessary expansion of the distribution power networks, the new modelling concept developed for cross-voltage PF calculations with CFs represents a good opportunity to carry out realistic assessments of the networks and to recognize the effects of expansion measures and innovative technologies across all network levels.

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