IMPACT OF MESHED GRID TOPOLOGIES ON DISTRIBUTION GRID PLANNING AND OPERATION

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ABSTRACT

Due to the high penetration of distributed power generation, many German medium voltage distribution grids are reaching their capacity limits. Meshed grid topology such as "closed loop"- operation and interconnections between grids on the same voltage level can contribute to a reliable operation of the critical infrastructure and reduce costs by avoiding additional conventional grid expansion.

1. INTRODUCTION

Medium voltage networks (MV-networks) are more and more facing problems due to a high penetration of power generation by renewable energy sources (RES) in Germany. Such problems can be violation of voltage limits or thermally overloaded lines. The quantity of situations where these problems occur will increase in the future as a result of the high expansion of distributed generation (especially in subordinated low voltage networks) based on governmental aims of a 80 % renewable energy generation in 2050 [1]. Today typical MV-networks consist of loops operated with an open disconnector [2]. This breaker divides the loop in two lines fed by one busbar. This is mainly for two reasons. At first, this operation mode raises the reliability of the network in case of a fault (switchover to the working line). Secondly, the described topology is easy to understand and to maintain. However, new challenges in energy supply require new operating approaches in order to obtain a cost efficient grid expansion in the context of the turnaround in German energy policy. Hence, the impact of meshed network operation is examined and evaluated in this paper. The work of this paper was derived from results of the project NeToVe, funded by the German Government.

2. SCOPE OF EXAMINATION – NETWORK STRUCTURES

The main goal of this examination is avoiding voltage and/or equipment-load violation caused by high-distributed feed in. Wherever possible new topology structures substitute grid expansion or smart equipment (e.g. variable ration transformers). In order to remain a network structure, which is as simple as possible, a stepwise and consecutive approach is used.

Closed-Loop-Operation (level one)

The first step (level one) is defined as a closed-loop operation of existing disconnectors within a medium-voltage loop (number one in Figure 1). The diminished loop-impedance generally leads to improved voltage stability. No other meshes or additional lines are considered. The closed-loop operation is the basic method in order to avoid forbidden operating states of the networks.

Additional Interconnections within one Network (level two)

Additional interconnections between two loops are applied if the impact of level one on the voltage is not sufficient or to avoid line overloads. This second step is used in addition two level one.

Interconnections between two MV-Networks (level three)

If two neighbouring MV-networks differ in their power supply and demand or if one of these grids´ utilization is significantly less than the other´s a direct coupling of these two networks can be considered (level three). In this paper, the interconnection between two MV-networks does not involve any load flow control. Instead, it is only based on the galvanic connection and the impedance ratio. The level-three topology is applied in addition to the above mentioned steps.

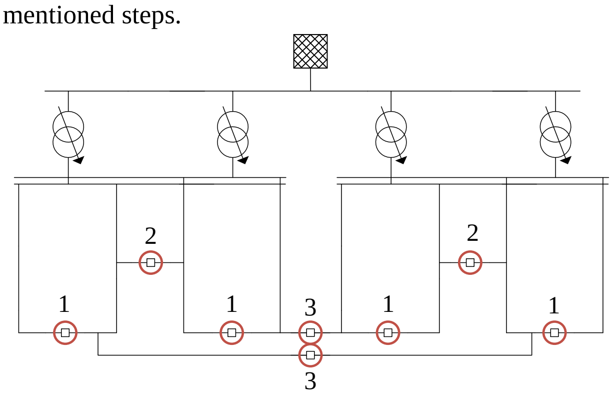

Figure 1: Schematic Overview of examined Network Structures

Applied planning guidelines

In order to evaluate the economic benefits of meshed network structures within distribution grid planning, the planning results are compared to a conventional distribution grid planning in section 4. This means, that in any case of voltage violation or equipment overload new cables or transformers replace or complete existing ones. Since the examination uses real distribution grids, the following commonly used planning guidelines are applied as the MV-voltage restriction and all line capacity restrictions:

$$96\,\% \leq {U_{i,MV}}/{U_{r,MV}} \leq 106\,\% \qquad \textit{Equation 1}$$

$$I_{line}/I_{r,line} \leq 60\,\% \qquad \textit{Equation 2}$$

The node-voltage-guideline is based on the German standard DIN 50160, which allows a deviation of $\pm$ 10 % related to the nominal voltage at any customer node [3]. It means that any node voltage should not exceed voltages higher than the denoted one to guarantee that voltages in the subordinate low-voltage-networks are within its limits. The line capacity guideline ensures, that in case of a failure located somewhere in the loop another feeder can supply power to the customers without critical line overloads and is adopted from [4]. From now on, line overload means a line capacity higher than 60 % related to the maximum thermal current of a cable/overhead line.

3. IMPACT OF MESHED NETWORK TOPOLOGIES ON VOLTAGE STABILITY AND EQUIPMENT LOAD

All results shown in this paper are derived from the examination of a set of two real 20-kV-MV-networks. These two networks are located in the east of Germany with a high penetration of renewable energy sources. Table 1 contains the values of the installed load and infeed in a developed scenario for 2020 compared to a basic scenario (year 2014). The scenario 2020 is a progressive scenario regarding new infeed from RES based on meta-analysis of several studiess.

	basic scenario		scenario 2020	
	grid A	grid B	grid A	grid B
load (MW)	20.8	5.9	20.6	5.9
PV plants (MW)	7.6	17.4	10.6	24.3
Wind (MW)	33	15.7	57.3	35.2

Table 1: Scenario Overview

Grid A/grid B consist of 388/328 nodes and 398/332 lines (mixed cable and overhead lines) and are fed by one substation each with two 50 MVA transformers each. For a proper evaluation of the impact of meshed network structures on the voltage and equipment load, time series-based load-flow calculations (15 min resolution) are executed. By that, one gains both the number of avoided violations and the voltage/equipment load-value of the most critical network state. A short circuit calculation was done for every topology setup. The highest currents did not violate the substation´s short-circuit stability (rated short-time current: 16 kA, measurement peak current: 40 kA). Hence this paper will not focus on further short-circuit analysis in the following.

Level one

Those loops with a violation according to Equation 1 and Equation 2 operate in a closed-loop-state only if this does not cause any additional violation. In grid A seven of nine breakers were switched, in grid B four of eight breakers were switched to close loops. Figure 2 illustrates the voltage node results of a time-series-based calculation executed afterwards.

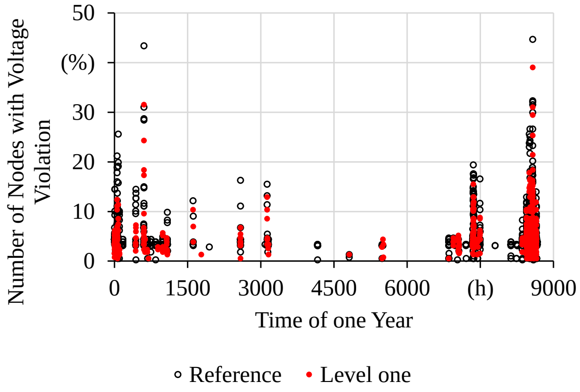

Figure 2: Relative Number of Voltage Violations - Grid A

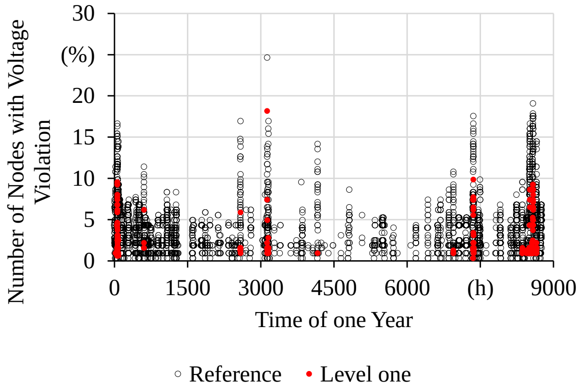

Figure 3: Relative Number of Voltage Violations - Grid B

Figure 2 and Figure 3 show the number of network nodes with a voltage violation referred to the number of network nodes in percent over one year. Each one of the bubbles is one point of time. The blue coloured bubbles represent the status quo network topology without any changes. The green bubbles represent the level one topology, which is a closed loop-operation. Especially in grid A, most of the voltage violations occur during winter season. High wind turbine power causes these violations. The level one topology has a significant impact on the number of violations. In grid A, it avoids 46 % of all violations, in grid B, even almost 95 %. However, also the most critical voltage violation is improved, as Figure 4 shows.

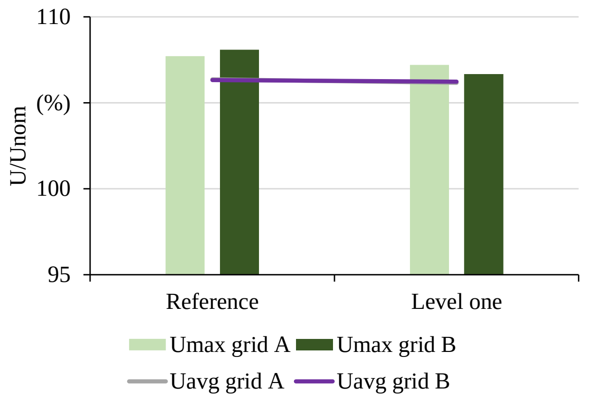

Figure 4: Voltage Violations at most critical Point of Time

The closed-loop operation leads to a voltage reduction of 1.41 % (from U/U_{nom} = 108.08 % to U/U_{nom} = 106.67 %) in grid B at the most critical node at the most critical point of time. The voltage reduction in grid A amounts to 0.5 % (from U/U_{nom} = 107.71 % to U/U_{nom} = 107.21 %). In Figure 4 the two lines describe the average voltage for times with violations. It is trivial, that the closed loops tend level node voltages which results in almost the same average voltage values of the reference case and the level one topology. Figure 5 and Figure 6 image the corresponding number of line overloads over one year for both grids and again compare the level one topology to the reference network structure. Each bubble represents one point of time.

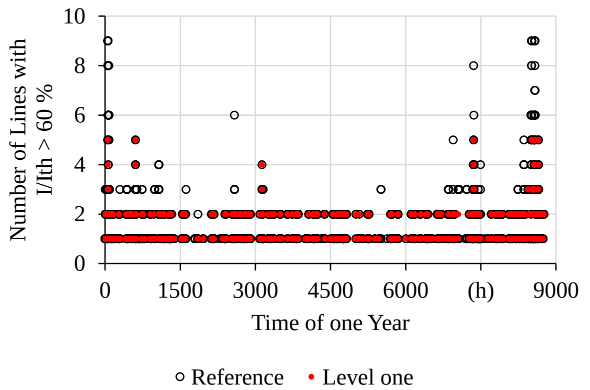

Figure 5: Number of Lines with I/Ith > 60 % - Grid A

One can see a clear pattern in Figure 5. In the scenario 2020, there is one or two line(s) with an overload almost during the entire year. These two lines belong to one loop and are connected directly to the outgoing feeder of the substation. Hence, a closed-loop operation cannot reduce the load significantly.

There are a lot more line capacity violations in grid B (Figure 6) than in grid A. Here, closed-loop operation also avoids most of the occurring line overloads (88 %).

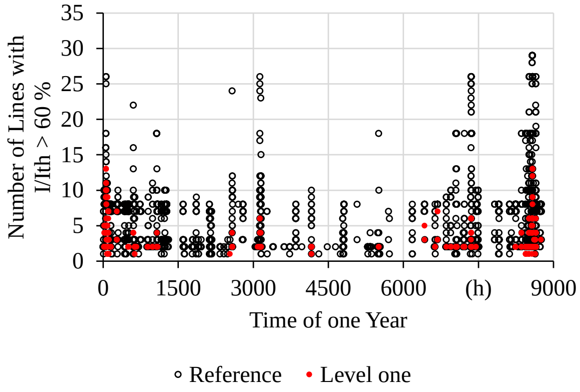

Figure 6: Number of Lines with I/Ith > 60 % - grid B

Level two/Level three

Figure 7 and Figure 8 present the effect of interconnections on voltage violation and overloads between two loops (level two) and the coupling of two MV-networks (level three) together for both grids.

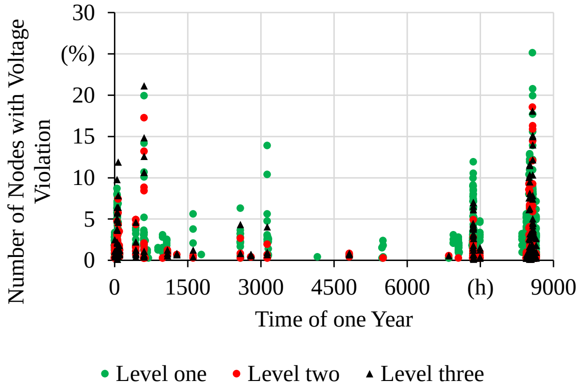

Figure 7: Relative Number of Voltage Violations - Grid A and B

The results of level two and level three topology are compared to level one results. The use of new interconnections between different loops and the coupling of MV-networks reduce the voltage violations additionally. However, a demand for further grid expansion remains.

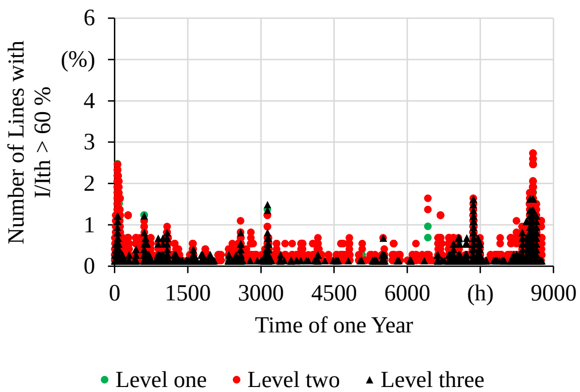

Figure 8: Number of Lines with I/Ith > 60 % - grid A and B

The violation of line overloads cannot be reduced by level two and/or level three topology any further. Even the opposite is the case. Now there are more violations than in level one situation, which nevertheless are less critical (Figure 9).

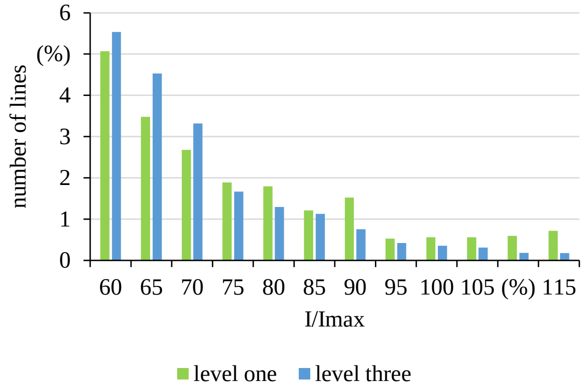

Figure 9: percentage intervals of line capacities

Each bar in Figure 9 represents the relative number of overloaded lines over the entire year within the denoted percentage interval. Applying level three topology, there are more violations in the first three, less critical intervals.

4. COST EVALUATION

Within the project NeToVe, a scenario up to 2050 was developed based on the three projected years 2020, 2030 and 2050. All necessary investments for additional equipment (e.g. cables) to avoid violations of voltage/load limits take place in these years. Operating costs as well as recovery values at the end of the time period are considered. For this evaluation, all cost assumptions are taken from [4]. The final result of the cost evaluation is the net present value of all expected costs within the time period. Figure 10 shows the costs for all topology-levels and compares them to the costs of the conventional grid expansion as described in the section *"Applied planning guidelines"*. In order to compare the costs of all planning variants, Figure 10 illustrates the costs for both grids in one bar.

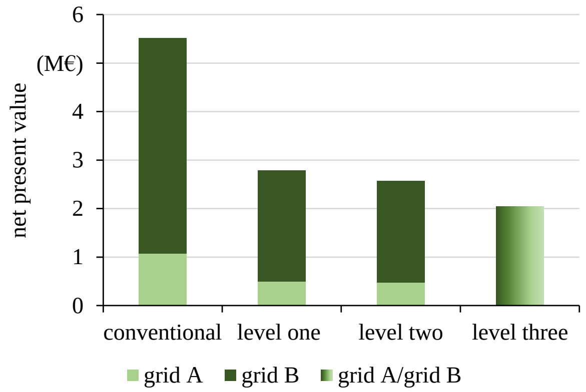

Figure 10: Cost Evaluation of Meshed Network Topologies

With respect to the coupling of the two grids in level three topology, there is no cost separation between grid A and grid B in the last bar. As Figure 2 and Figure 3 let presume, the level one planning variant reduces the expansion costs significantly by almost 50 % as Figure 10 shows. The main reason for that closed loops prevent from most of the violations because of levelled load flow. By closing the loop, the equalized load flow in the loop is sufficient to heal these violations. Although there is an increase of line overloads in level two especially, the expansion costs decrease by another three percent. As shown in Figure 9, especially the lower values of line overloads explain this result. The additional coupling of the two networks leads to an all in all cost-reduction of 63 % related to a conventional grid expansion planning.

5. IMPACT OF MEDIUM-VOLTAGE-NETWORK-INTERCONNECTIONS ON OVERLAID HIGH-VOLTAGE-NETWORK

According to a relief of high-voltage-network (HV-network) equipment load is possible when coupling the two grids A and B on the MV-side. This is supposed to be especially for a significant infeed from RES in MV-networks. Figure 11 shows the results of a simulation for different infeed/load situations in the MV-networks. Each bubble in the Figure 11is the line capacity relief of the HV-network. The simulation was executed with an exemplary network structure as shown in Figure 1.

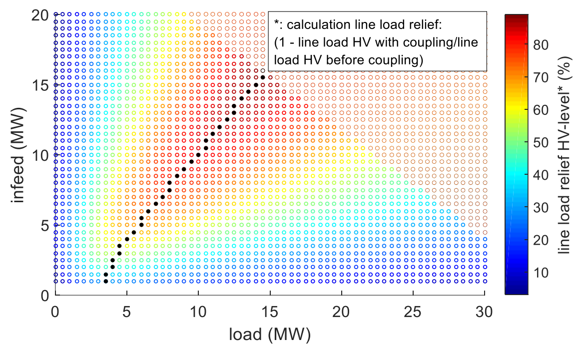

Figure 11: Simulation of Line Capacity Relief of HV-Level for various Infeed/Load-Situations

The brown coloured triangle illustrates invalid states since the load flow surpasses the capacity limit of MV-coupling line. It is obvious, that the MV-coupling (level-three topology) gains the highest effect if the power demand in one network is close to the amount of infeed in the corresponding network (red bubbles). By analogy, there is almost no influence on the HV-level if the amount of power demand and supply differs significantly. The results of the two real MV-grids and their overlaying HV-network confirm the effects of the simulation.

As the values of RES infeed and power demand show in Table 1, power demand of grid A and power supply grid B does not equal (based on the residual loads). Consequently, the coupling has little impact on the HV-equipment load (Table 2).

	reference topology	level three topology	load relief (%)
HV line capacity (%)	46.5	47	-0.5
Transformer load HV/MV (%)	57.6	58.1	-0.5

Table 2: HV-Equipment Relief gained by Level-three Topology

For the considered set of real networks in this paper, the coupling of MV-networks means even a little increase of both line and transformer capacity. The diminished MV-network impedance resulting in diminished power transmission losses cause this effect.

6. SUMMARY AND OUTLOOK

The goal of this paper was to quantify the impact of meshed grid topologies on distribution grid planning and operation. Therefore, different kinds of meshed network structures were introduced and analysed based on a set of two real MV-networks and the corresponding 110-kV-HV-network. The cost evaluation compared the expansion costs of a conventional planning to the planning with respect to the different meshed network topologies.
Summarized, the main results based on the analysed networks are:

- A closed-loop operation (level one topology) has the highest effect on the voltage stability. Especially in case of slightly exceeding voltage and equipment capacity limits, this operation level solves most of the occurring problems (about 70 % of all voltage violations occurring in the reference case could be avoided on average).
- Additional interconnections within one network (level two topology) and the coupling of two MV-networks on the MV-side also have a positive impact on voltage stability. However, since the load flow commutates on further lines, a conflicting violation of line capacity restrictions may occur. This should be considered within the grid expansion planning.
- The overall cost reduction of the meshed topology planning compared to a conventional grid expansion planning amounts about 60 %.
- The effect of a level three topology on the overlaid HV-network will be little if the amount of power demand and power supply of the coupled MV-networks differ significantly. However, in this case the coupling can still contribute to voltage stability.

It is obvious, that a change of the network topology causes an adjustment of the protection system and in the case of highly meshed networks even additional protection devices and new protection system concepts. This comes along with additional costs, which have to be added to the determined expansion costs in this paper. The development of an appropriate protection system for meshed network topologies is also part of the project NeToVe. First results show, that there is an effective way to protect highly meshed networks (especially those operated with a closed-loop) without compensating the cost reduction completely.
A development of an appropriate protection approach as well as detailed analysis of the short-circuit currents need to be taken into account in further research.

ACKNOWLEDGEMENT

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