# PHOTOVOLTAIC-SYSTEM HOSTING CAPACITY OF LOW VOLTAGE DISTRIBUTION NETWORKS

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## 1. Introduction

In the recent years, there is a strong increase of photovoltaic (PV) systems which are installed in Germany. Most of the PV-systems are connected to the low voltage distribution network. Today a voltage rise up to 3% (FNN2011) of the nominal voltage is allowed by generators connected to the low voltage grid. Staying within the allowed voltage band is one of the major issues. In low voltage grids compared to higher voltage levels we have relatively small short circuit impedance at the connection point, and a relatively large resistive fraction of the network impedance. So often the upper voltage limit is reached even if the thermal capacity of the distribution lines would allow the connection of many more systems.

In Degner et al.(2010) we have shown for one network the possibilities to suppress the voltage rise from active power feed-in by using reactive power directly delivered by the inverters. In the following first we will analyse the effect of the network parameters on the voltage rise and then calculate the maximum apparent connection power assuming a maximum allowable voltage change in the network of +/-3%. The potential of reactive power to reduce voltage rise and therefore to increase the PV-system hosting capacity is shown. Finally we quantify the potential of controllable medium voltage (MV) / low voltage (LV) transformers with variable ratio to increase the connectable power.

## 2. Effect of network parameters on voltage rise

The voltage rise caused by active power feed-in strongly depends on the network characteristic parameters, in particular to mention are the short circuit power and the network impedance angle at the connection point of the PV system, as well as the impedance of the LV/MV-transformer. Especially if the voltage control by reactive power is considered the network impedance angle $\psi_{kV}$ is important. The relative voltage rise $\Delta u_{aV}$ at the connection point V can be calculated by:

$$\Delta u_{aV} = \frac{S_{A\max} \cdot \cos\left(\Psi_{kV} + \varphi\right)}{S_{kV}} \qquad \text{(eq.1)}$$

With $S_{Amax}$ the apparent power at the connection point and φ the phase angle between current and voltage of the PV system. The equation is also given in the VDEW(2001) and in Braun(2009).

### *2.1. Typical network data at the network connection point*

Fig. 1 shows network short circuit power and network impedance angle at the low voltage bus bar of the MV/LV substation for different transformer types and MV network data. It can be seen that the LV-network short circuit power mainly depends on the parameters of the MV/LV transformer, namely the rated power of the transformer and the short circuit voltage $u_k$. The network impedance angle varies between 63° and 80°.

Fig. 2 shows how the network short circuit power and the network impedance angle change according to the distance from the substation. This diagram was also made for other transformer types (not shown here). For short distances (< 100-200m) the network short circuit power and the impedance angle are mainly depending on the transformer parameters, while for longer distances the properties of the cable type are dominating.

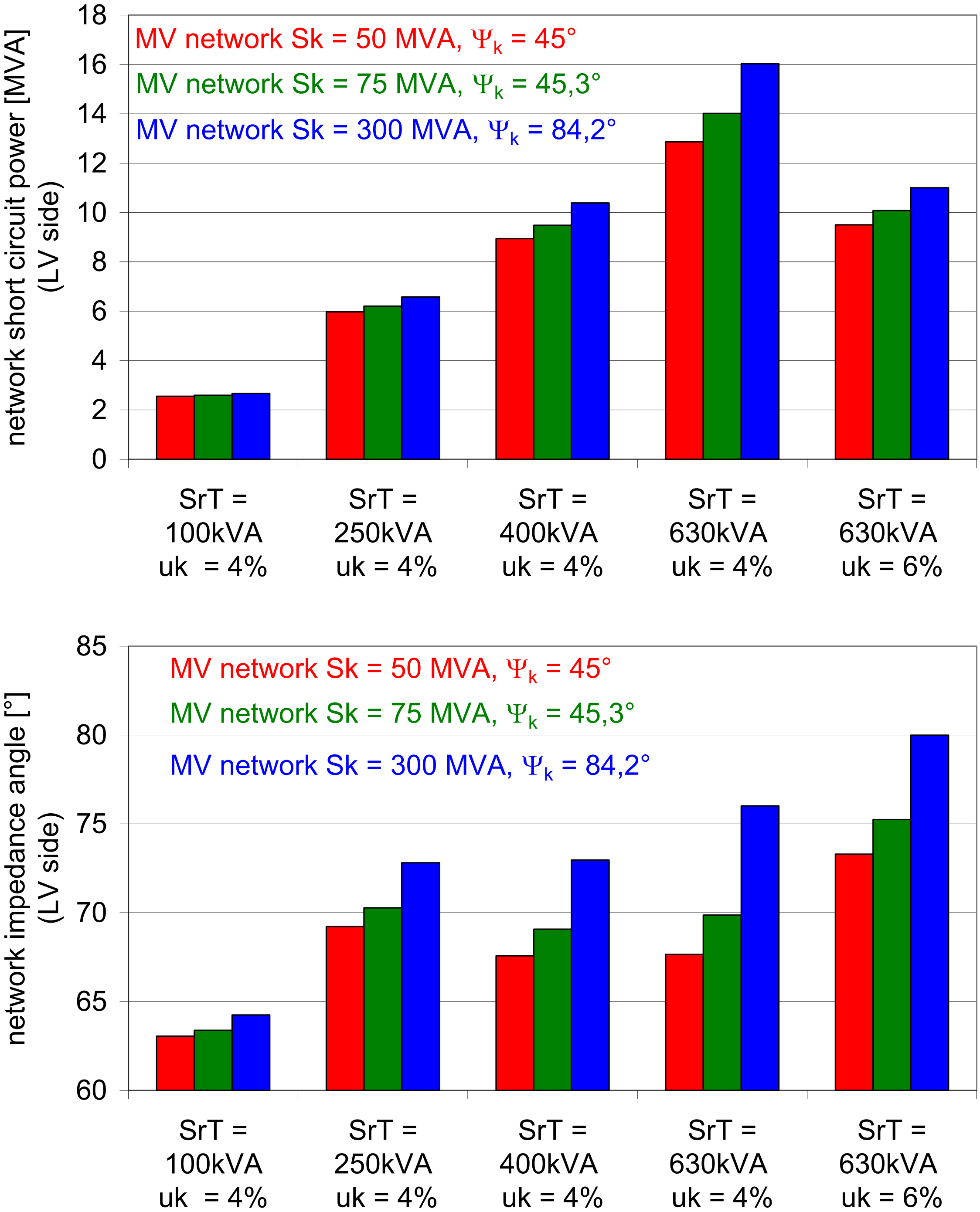


**Fig. 1: Network short circuit power (top) and network impedance angle (bottom) at the low voltage bus bar of the MV/LV transformer for different transformer types**

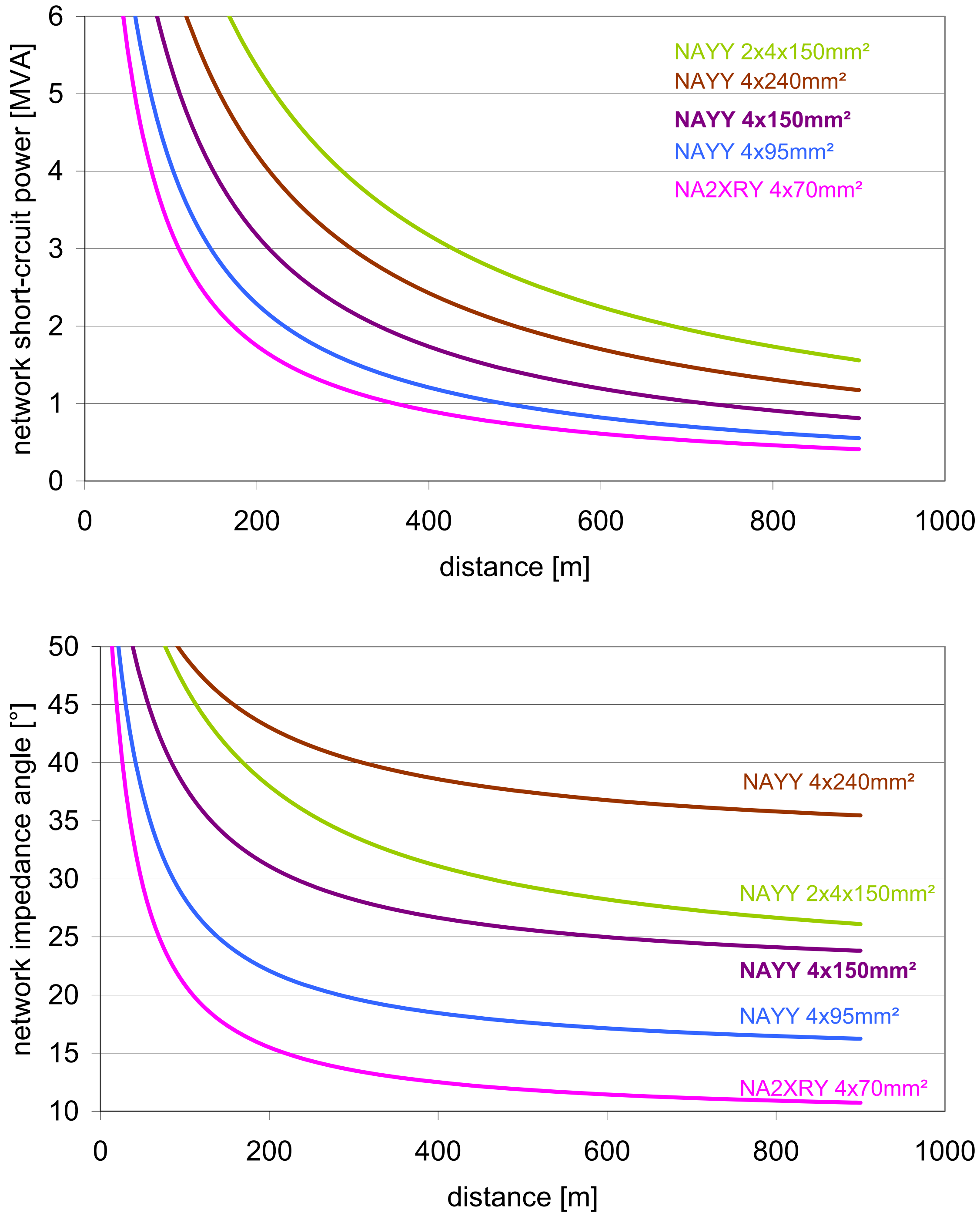


**Fig. 2: Network short circuit power (top) and network impedance angle (bottom) as a function of the distance to the low voltage bus bar at the transformer for different types of cables. These values are for a substation with a MV/LV transformer of $S_{rT}$ = 630 kVA and $u_k$ = 4% with connection to a MV network with $S_k$ = 75 MVA and $\psi_k$ = 45.3°.**

### 3. Maximum permissible connection power

What is the maximum apparent PV power, which can be connected to the LV network? To answer this question we have investigated different cases in one simple network. For this investigation we used the criteria of the German FNN requirements for generators connected to LV networks (FNN2011).

Fig. 3 shows the investigated network data and the analysed cases: Case A refers to a single feeder, single PV system, Case B to a single feeder configuration, with 5 PV systems equally connected along the feeder, and Case C to a radial network with 4 feeders, each hosting 5 PV systems. For each case different feeder lengths have been studied and the rated power of the PV systems is assumed to be equal for all PV systems.

The apparent power of the PV systems was increased stepwise until the voltage change compared to the zero load case exceeds the 3% limit. The power system calculation tool used for the calculations was PowerFactory from DIgSILENT GmbH.

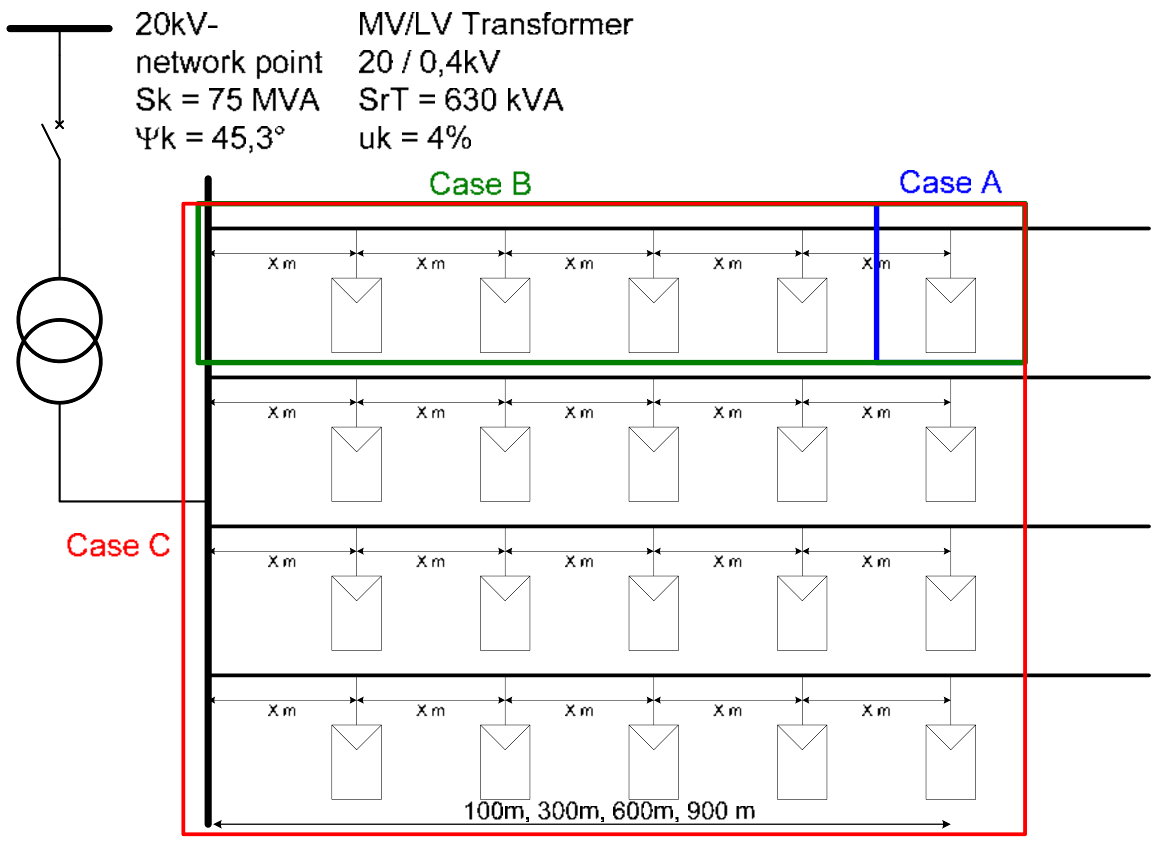


**Fig. 3: Network topology and analysed cases.**

As a result Fig. 4 shows the maximum permissible connection power as percentage of the short circuit power at the end of the feeder and as function of the network impedance angle. As a conclusion of this, Case A shows, that in this kind of scenario different transformers or network cables have nearly no effect. For this case the answer of the question for “the maximum permissible connection power” is very well given by the network parameters of the network connection point ($S_k$, $\psi_k$).

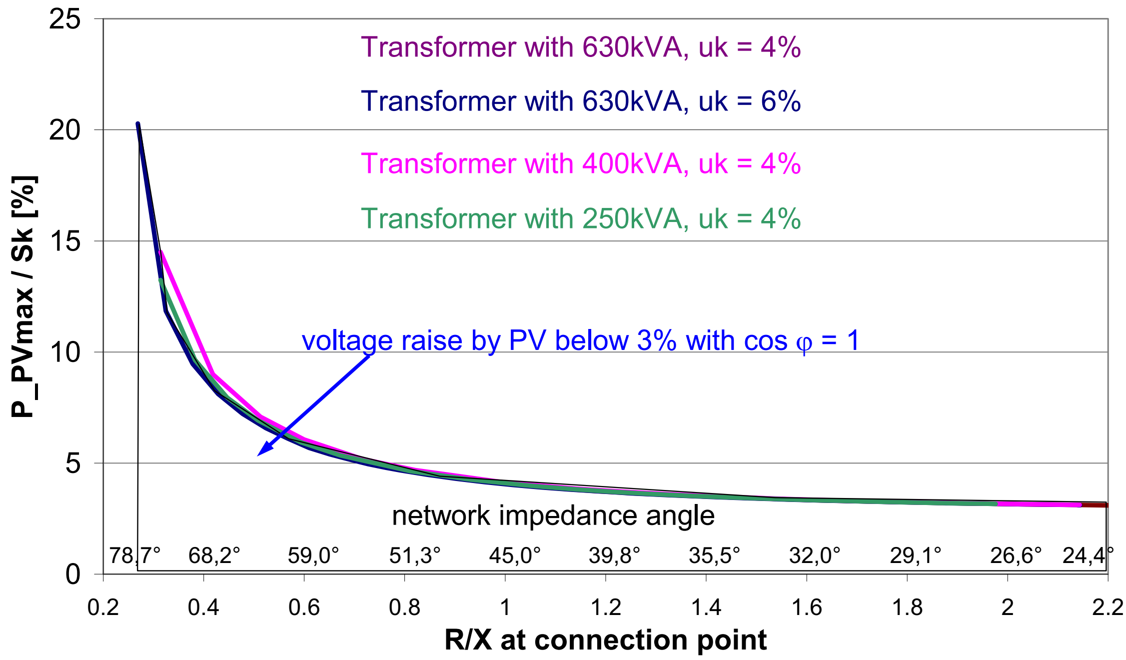


**Fig. 4: Results of Case A for different transformer types.**

For the single feeder with 5 PV-systems (Case B) this conclusion also applies very good, if the network parameters $S_k$ and $\psi_k$ at the end of the feeder are taken as reference values. In the multi feeder case (Case C) the variation due to different cables and transformers are getting bigger because of the differences of the varied parameters at the points of common coupling. However the curves look still similar. In the multi feeder case the voltage from each feeder sums up at the transformer bus bar or any other connection point of different feeders. This sum of voltage rise decreases the allowed voltage range in each single feeder. As a matter of this for each feeder the maximum permissible connection power is reduced. However the total permissible PV power of the network is bigger compared to the single feeder case. These results are shown in Fig.5.

The superposition principle can be used for networks with more than one PV-system to determine the whole voltage rise at one point quite good. According to this the voltage range for one feeder of a multi-feeder network can be determined by this equation:

$$\Delta u_{feeder} = \Delta u_{allowable} - \sum_{x=0}^{n-1} \Delta u_{substation\ lv,x} \qquad \text{(eq.2)}$$

With $\Delta u_{feeder}$ stands for the allowable voltage rise along one feeder. $\Delta u_{allowable}$ stands for the allowable voltage rise within the network and $\Delta u_{substation\ lv,x}$ for the voltage rise at the low voltage side of the MV/LV-transformer. The number of all feeders connected to the transformer is represented by n.

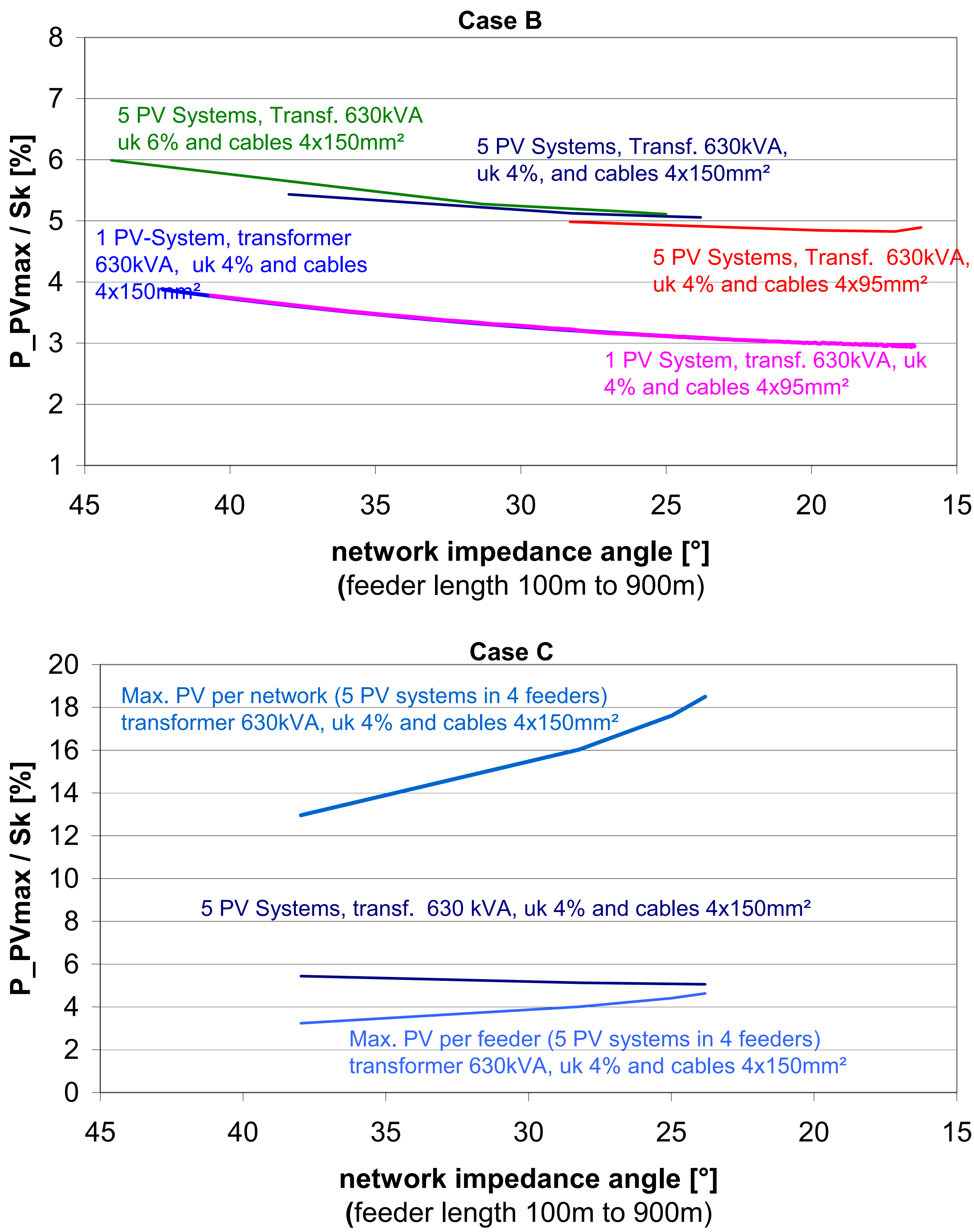


**Fig. 5: Results of Case B (top) und Case C (bottom) for different cables.**

### 4. Potential of reactive power to compensate voltage rise

If PV systems are used which can provide reactive power to the network the voltage rise depending on PV Systems in the network can be regulated. According to the German FNN requirements for generators connected to LV networks (FNN2011) PV-systems with a rated power greater than 13.8 kVA are required to provide a power factor of up to cos φ = 0.90. Fig. 6 shows the effect of reactive power (under-excited) provision by a single PV system (Case A) for different values of power factor cos φ. Each curve is a result from reaching either the upper voltage limit at the network connection point, right part of the curve, or by a voltage decrease at the transformer which is larger than 3%. The effectiveness of voltage control by reactive power clearly depends on the network parameters $S_k$, $\psi_k$. Similar relations can be found for Case B (Fig. 7, single feeder, multi PV system case). Fig. 8 shows the relative increase of the permissible connection power for a power factor cos φ = 0.90 compared with cos φ = 1. In the analysed cases the increase of the PV hosting capacity due to reactive power provision is between a factor 1.5 and more than 2.5. It should however be noted, that in the latter case the thermal limits of transformer and cables may be exceeded.

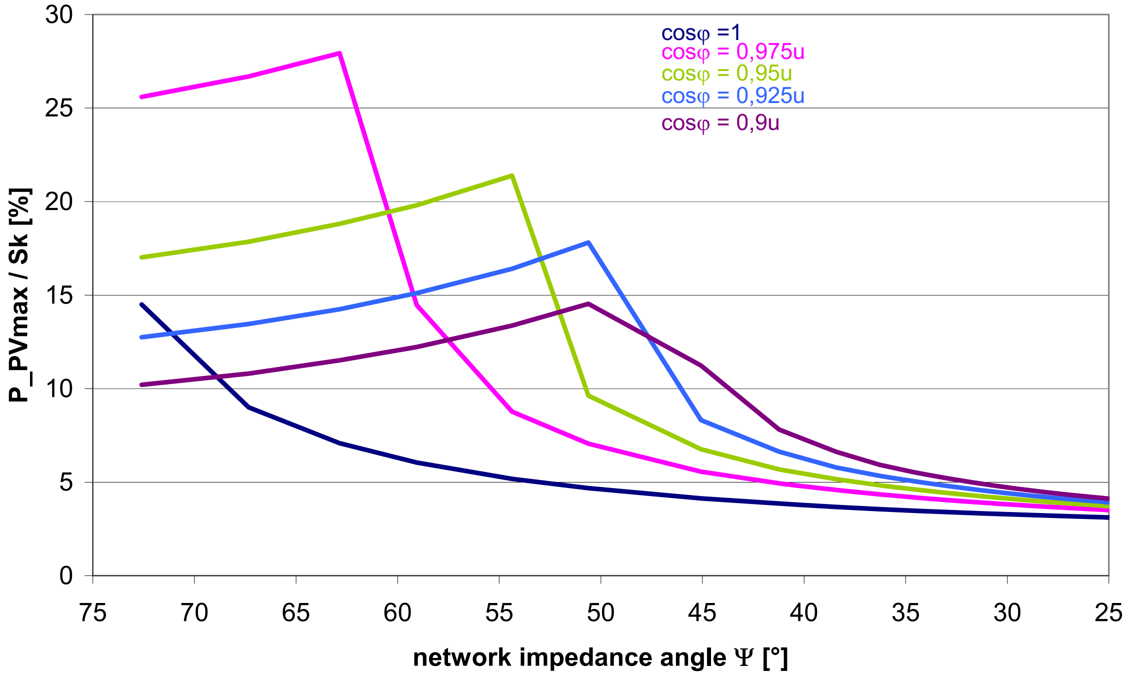


**Fig. 6: Maximum permissible PV power for different power factors of the PV system for Case A (single PV system, single feeder)**

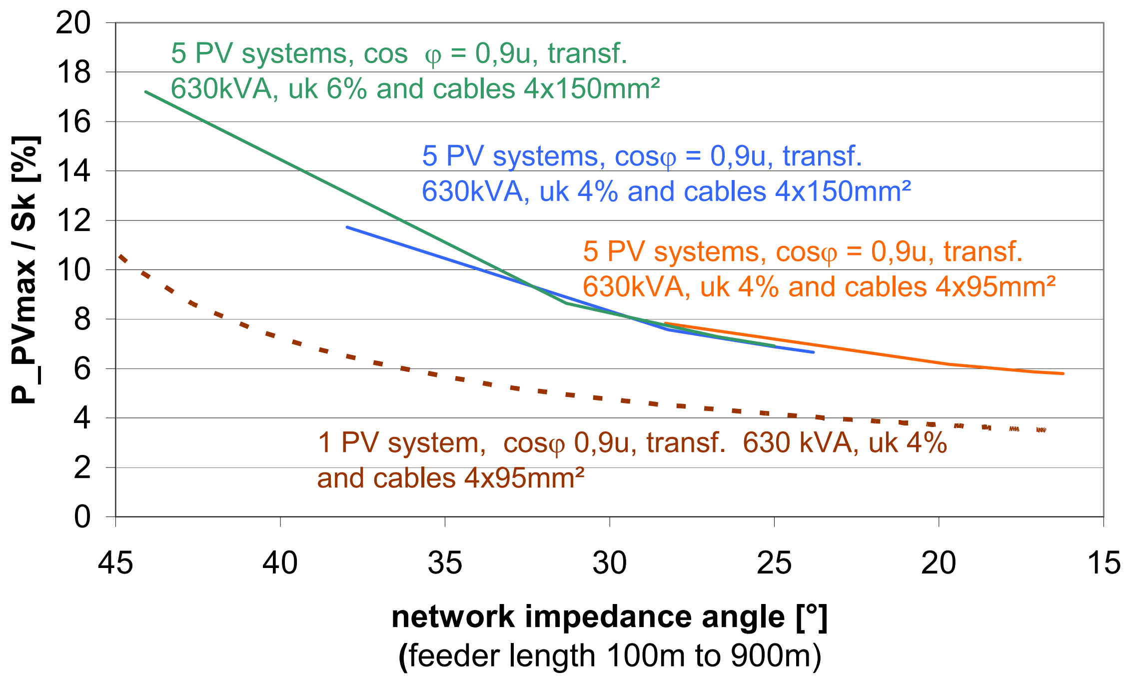


**Fig. 7: Maximum permissible PV power for PV systems with power factor 0.90 Case A, and Case B (single feeder, multiple PV systems.**

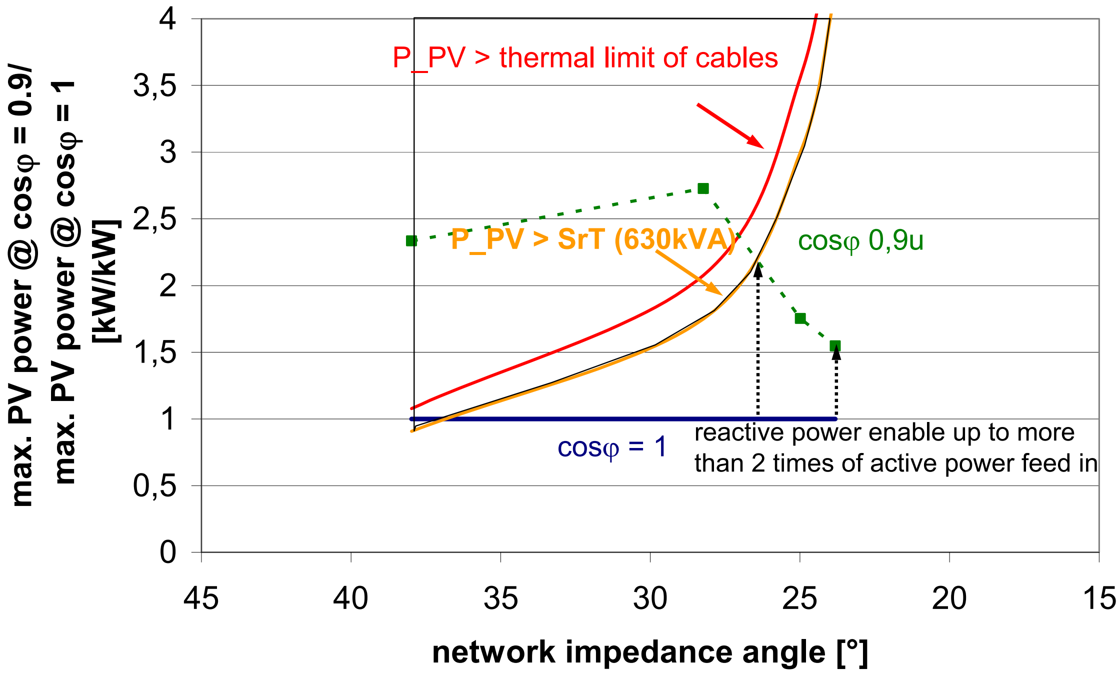


**Fig. 8: Maximum permissible PV power for PV systems with power factor 0.9 as a multiple of PV power with power factor 1 (Case C).**

In general not all low voltage grids have such a simple structure like Fig.3 e.g. some networks have meshed parts. For these networks it is more complicated to calculate the network parameters and the maximum of permissible connection power. For inhomogeneous load flows in different feeders there is an advantage for the permissible connection power by using meshed structures.

## 5. Permissible connection power for a network with existing PV-systems using reactive power or active MV/LV transformers

In many low voltage grids like Fig. 9 (see also Paper "Intelligent Local Grids for High PV Penetration") some PV-systems are already installed. This "old" PV-systems don't provide reactive power. If we want to calculate how much apparent power can additionally be connected to the grid, the already existing PV-systems have to be considered. For the calculations we considered 3 cases. For case 1 the new PV-systems connected to the network provide power with a cosφ = 1. For case 2 the new PV-Systems provide power with a cosφ = 0.90 (under-excited). For both cases we used the criteria of the German FNN requirements for generators connected to LV networks (FNN2011). Instead of reactive power provision from the PV-systems a controllable MV/LV transformer is used in case 3. This transformer has a tap changer with 4 taps, 2.5 % p.u. each. So the transformer can reduce the voltage for up to 10% at the low voltage side bus bar. For the calculations a voltage band from 0.95 p.u. at the low voltage side bus bar up to 1.05 p.u. at any customers connection point is allowed. This voltage band is chosen to conform to the requirements of the EN50160 (DIN EN 50160 2010) (0.90 p.u. to 1.10 p.u.) for each customer of the network. If there is another voltage band needed because of a stronger voltage decrease by load in any feeder, it can be modified without a great change in the result as long as the span is also 10%.

The results are shown in Fig. 10. For the considered network with the chosen locations for the new PV-systems, there isn't much capacity for the new PV-systems using case 1 or case 2. It can be seen that the already installed PV-systems use the major part of the hosting capacity of the network in this configuration. For case 1 the hosting capacity is 114% of the already installed power, for case 2 the hosting capacity can be improved to 124% (or 192% if all PV-systems (old and new) provide reactive power by cosφ = 0.90 (under-excited)). The influence of the reactive power is extremely limited by the existing voltage rise from the already existing PV-systems. For the real network the hosting capacity gets improved using reactive power by a factor of up to two. For case 3 the allowed voltage rise is bigger so the hosting capacity of the network will become much bigger. With the controllable transformer the hosting capacity will be increased up to 341% of the already installed power. In case 3 under the assumed conditions the power flow over the transformer will be up to 116% of the rated power.

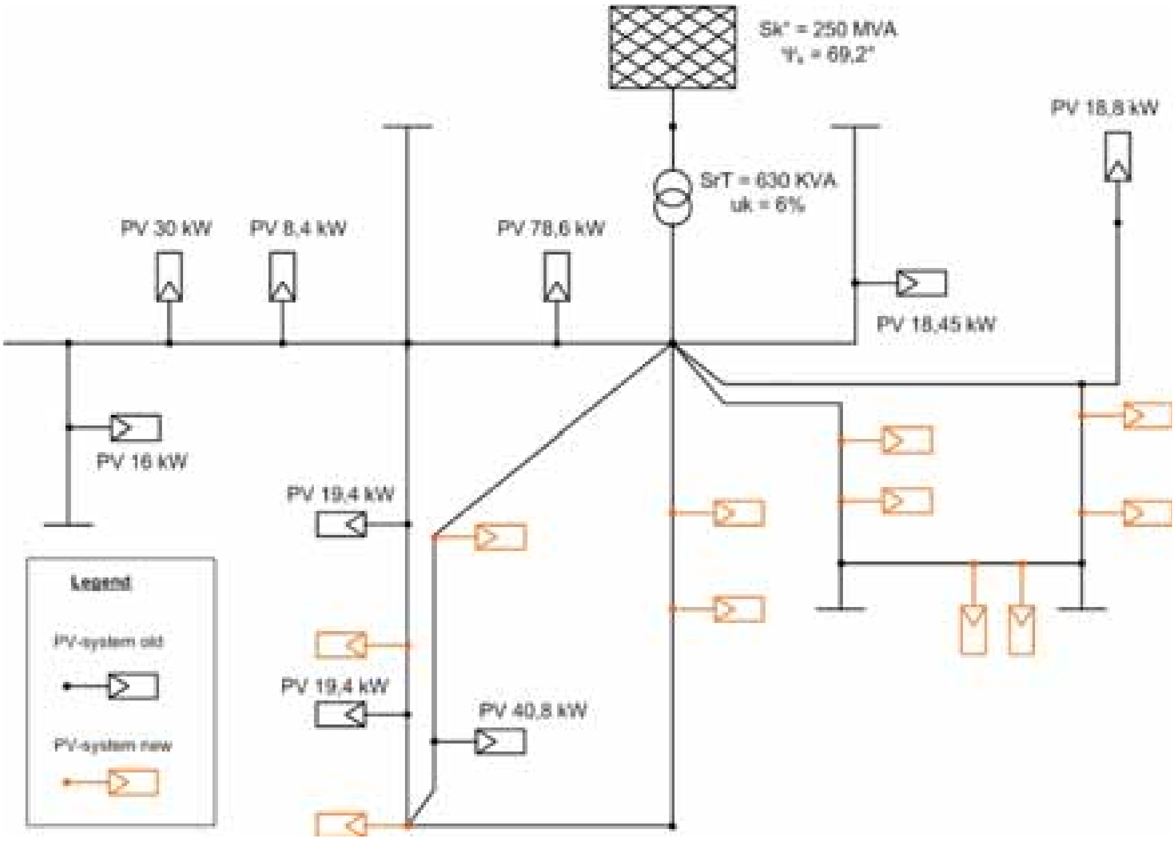


**Fig. 9: Network topology for calculation of permissible connection power in a network based on real data**

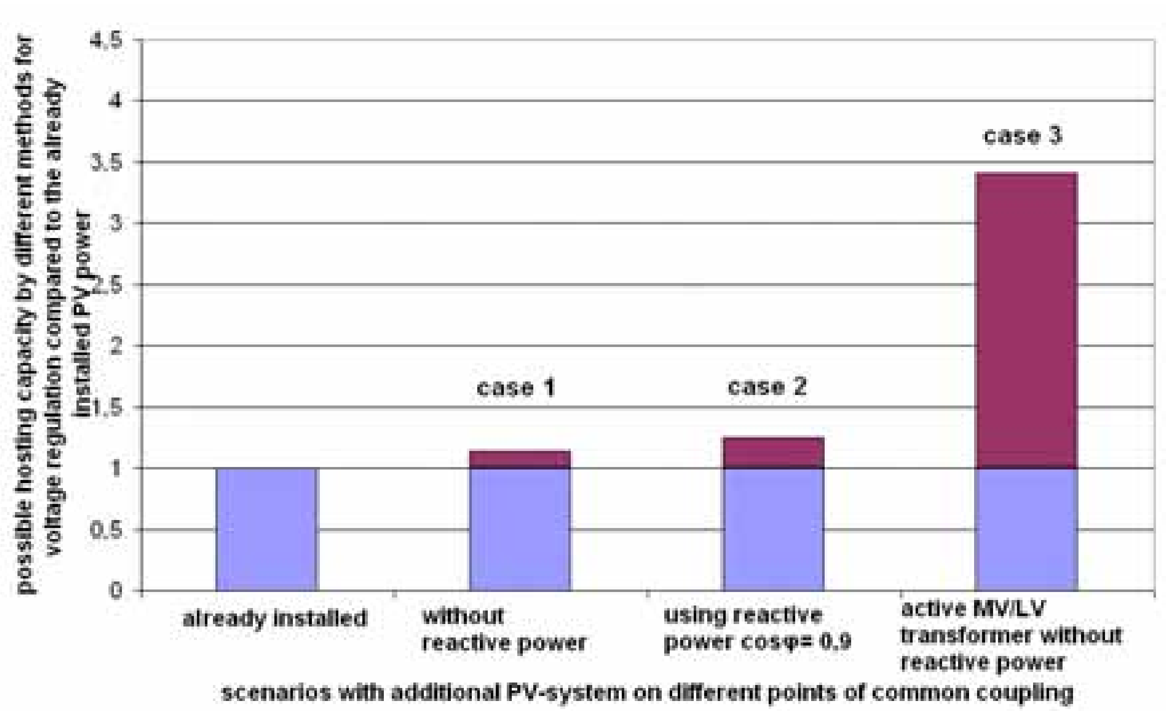


**Fig. 10: possible hosting capacity in relation to the already installed PV power**

A combination of voltage control by reactive power and by a controllable transformer is possible but the results show that it is possible to reach the rated power of the operation resources installed in the network by case 3 only. The additional reactive power will produce additional stress for the operation resources.

## 6. Conclusions

In our contribution we show general diagrams concerning the maximum permissible connection power from distributed generators into low voltage radial distribution networks. Network short circuit power and network impedance angle at the end of the feeder turn out to be appropriate parameters for the diagrams.

By using reactive power voltage control the maximum permissible PV power may be increased. The possible increase depends on the network parameters at the PCC. Ideally the hosting capacity can be doubled using reactive power. In real networks especially with PV-systems which don't provide reactive power the possibilities can be smaller. If the requirements will allow a bigger voltage rise to satisfy the EN 50160 (DIN EN 50160 2010), the hosting capacity of low voltage grids can become limited by thermal limits of the network components. While voltage control by reactive power is quite limited in long feeders a controllable MV/LV transformer allows to connect PV power to the network depending on the available voltage range. An additional advantage of a controllable transformer is that the benefit of hosting capacity will not be influenced by already installed PV-systems, which don't provide reactive power as the voltage control by reactive power from new PV-systems does. To fully utilise the advantages of controllable transformer however would require allowing a voltage change caused by PV power of more than 3%.

## 7. Acknowledgments

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## 8. References

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