

Maximum PV-penetration in low-voltage cable networks

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Maximum PV-penetration in low-voltage cable networks

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Abstract—As a consequence of the increasing amount of PV-systems connected to the LV-network the question arises whether these networks are able to cope with large amounts of PV. In this paper it is investigated whether problems have to be expected in typical LV networks in the Netherlands. It is shown that exceeding of the regulatory voltage levels is the first limiting factor for integration of PV, followed by overloading of components. In most parts of the network no problems will arise as a consequence of PV, as it is not possible to place enough PV panels to cause problems. Areas with increased risk can be identified on forehand.

I. INTRODUCTION

In a society which is increasingly focused on sustainability it is important that sufficient capacity is created in the electricity grid to integrate renewable energy sources. Over the past years the number of PV-systems connected to the LV-network has been increasing rapidly. Countries such as Italy [1] and Germany [2] already face the impact of increasing amounts of PV on their networks. An important question is whether the LV-networks are able to cope with large amounts of PV. In this paper it will be investigated whether or not problems have to be expected in typical LV-networks. A special focus will be on cable networks, as all LV-networks in the Netherlands consist of cables.

Firstly, different influences of PV on the network will be treated and an assessment is made as to what extent these could lead to problems at high penetration levels of PV. Secondly LV-network models of several representative neighbourhoods are selected and modelled with realistic values for load and the maximum installed power of PV that is possible. Loadflow calculations are carried out to determine whether and when problems arise. The final part contains the results of the calculations and the conclusion as to what the consequences are for the possibility of integration of PV.

II. IMPACT OF PV

A. Voltage level

Integration of PV in the LV-network affects the voltage variation over the cable. In a situation without PV there will be a net current flow towards the end of the cable and the voltage will decrease towards the end of the cable. When now PV is connected to the cable this will influence the magnitude of

the current. Moreover, high penetration levels of PV may even lead to an inversion of the net current flow. Under influence of the extra power infeed the voltage level will rise. The allowed variation of the voltage level is set by the grid code. For LV-networks a voltage band of $\pm 10\%$ relative to nominal voltage is allowed [3]. Research [4-6] suggests that the increase of the voltage is one of the main limiting factors for maximum penetration of PV and will therefore be treated in detail.

B. Capacity

All components in the grid such as cables and transformers have a certain nominal load. (Sustained) overloading can lead to damage, failure or shortened life expectancies of these components. Grids are usually designed with a large margin for loading to account for future growth of connected load. If however large amounts of PV are installed, the generated power may exceed the allowed loading. This may clearly limit the maximum allowable amount of installed PV and is also investigated further.

III. NETWORK MODELS

A. Neighbourhoods

To make an assessment of the influence of PV on the Dutch LV grid, Vision (loadflow program) network models of several real neighbourhoods are used. The different neighbourhoods range from rural areas with a low household density and mainly detached houses and farms, up to densely populated urban areas with mainly apartment buildings. These neighbourhoods form a representative mix of the different types of networks that exist in the Netherlands [7]. Each household was assigned a consumption and PV production value based on the household type.

B. Load

To assign proper load and generation values first a division was made between different household types as in [7] with corresponding average yearly consumption given in table I.

To determine whether a certain amount of PV would lead to problems we are interested in the instantaneous load. The values are used that occur during the two most extreme situations in a grid with high PV penetration:



Fig. 1. Satellite images to determine available roof area for PV (courtesy of Google Maps).

TABLE I
AVERAGE YEARLY CONSUMPTION PER HOUSEHOLD TYPE

	Household type	Average yearly consumption (kWh)
A	Detached house	5000
B	Semi-detached house	4000
C	Terraced house	3500
D	Apartment	3000

TABLE II
CONSUMPTION PER HOUSEHOLD TYPE

Household type	Consumption (W)	
	At maximum generation	At maximum load
A	500	1239
B	400	991
C	350	867
D	300	743

- Moment of maximum generation: Sunny summer day between 12:00-13:00 hours, at this moment the maximum amount of PV power is produced and load is relatively low.
- Moment of maximum load: Winter day between 18:00-19:00 hours, at this moment there is virtually no PV power produced and the load is at its peak.

Load profiles in fractions of yearly consumption were used to determine the instantaneous load for the different types of households. Table II gives these instantaneous values for the moment of maximum generation and moment of maximum load.

C. Generation

In order to obtain a realistic estimate for the potential amount of installed PV several factors must be taken into account, such as total useable surface area, orientation of the roof and the efficiency of the solar panels. Satellite images were used to estimate the average effectively useable roof area for different household types, as illustrated in figure 1.

Several factors were taken into account when determining useable surface area:

- Presence of (dormer) windows.
- Shading by adjacent buildings, trees or constructions on the roof.
- The surface of flat roofs cannot be used completely, because solar panels are usually placed under an angle. Enough room must be kept between panels to avoid mutual shading.
- The roof area per apartment is calculated by dividing the total useable roof area of the total flat by the number of apartments.

The average efficiency of commercial solar panels at this time is around 15-16%, which amounts to approximately 150 Wp/m² in the Netherlands. Combined with the useable surface area this gives the maximum PV power in kWp that can be placed on average. Table III gives the average useable roof area and the corresponding PV power for the different household types.

The maximum PV power can only be obtained when the solar panels are very well oriented. Perfect orientation would be a few degrees west of perfect south at an inclination of angle of approximately 35 degrees [8]. Analysis of the satellite images showed a high diversity in the orientation of roofs, especially in the areas with a relatively high amount

TABLE III
USEABLE ROOF AREA AND CORRESPONDING MAXIMUM PV POWER THAT
CAN BE PLACED ON AVERAGE

Household type	Effective roof area (m^2)	PV power (kWp)
A	20-25	3.3
B	15-18	2.5
C	10-15	1.8
D	2-5	0.5

of (semi-)detached houses.¹ To obtain a worst-case scenario in the rest of this paper 100% south-oriented roofs will be assumed.

D. Boundaries

To check whether problems occur it must be identified what is allowable, and proper boundaries must be set. Considering voltage level, clear boundaries are given by the Dutch grid code [3]:

- $U_n \pm 10\%$ for 95% of 10-minute averages during one week.
- $U_n +10/-15\%$ for all 10-minute averages.

This effectively means that the voltage during the moment of maximum generation must be below 110% of nominal voltage on all points of the cable, while during the moment of maximum load the voltage may not fall below 90% of nominal voltage. However it must also be taken into account that the voltage level of the MV-network may also vary and the voltage on the MV/LV transformer is also dependent on the location upon the MV cable. As a rule of thumb it is used that in existing LV-networks there is room for an increase in voltage of at least 3%.

The amount of PV that can be integrated before voltage limits are exceeded also depends on the location of the PV on the cable. If all generation is connected at the end of the cable we can make use of

$$\Delta U_{cable} = \frac{P_{end}}{U_{end}} \cdot R_{cable}. \quad (1)$$

Where ΔU_{cable} is the voltage drop over the length of the cable, P_{end} is the total power injected at the end of the cable, U_{end} is the voltage at the end of the cable and R_{cable} is the resistance over the total cable length.

If the points of connection of PV are spread over the length of the cable, more power can be connected. If we assume the points of connection to be evenly spread over the length of the cable, according to [4] the power may be multiplied by a division factor as given by

$$\frac{N^2}{\sum_{i=1}^N i} = \frac{2N}{N+1}. \quad (2)$$

Where N is the number of connections on the cable.

¹Urban areas have relatively more households with flat surfaces, which are counted as south oriented because the position of the solar panels may then be chosen freely.

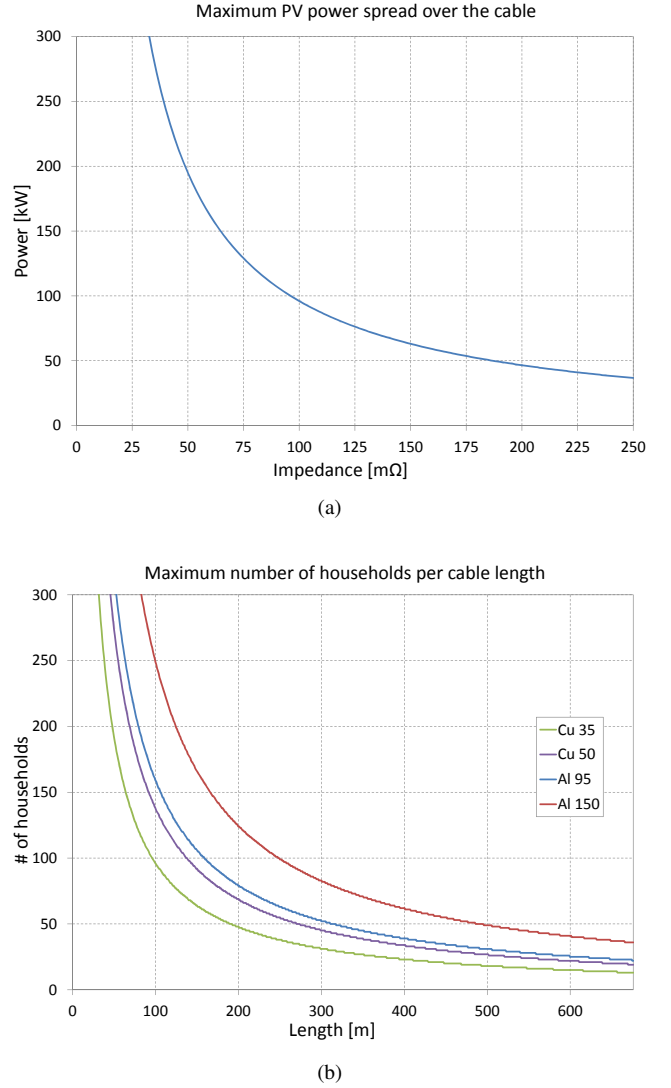


Fig. 2. (a) Maximum PV power vs cable impedance with a maximum voltage increase of 3% (b) Maximum number of households vs cable length for several different cable types.

Adding the division factor and taking the generated PV power per household ($P_{household}$) constant, the number of households that may be connected to a single cable may be determined with

$$N = \frac{2 \cdot \Delta U_{cable} \cdot U_{end}}{R_{cable} \cdot P_{household}} - 1. \quad (3)$$

Considering capacity problems the maximum allowable loading of components must be taken into account. The loading of cables and transformers is investigated and a problem is observed when the maximum allowable current is exceeded. The value of this allowable current depends on the type of cable or transformer and may differ per network. For the capacity it is less important where the PV power is injected into the grid. The maximum allowable current of the cable part at the start of the cable, between transformer and first node, is the determining factor for the maximum PV power per cable.

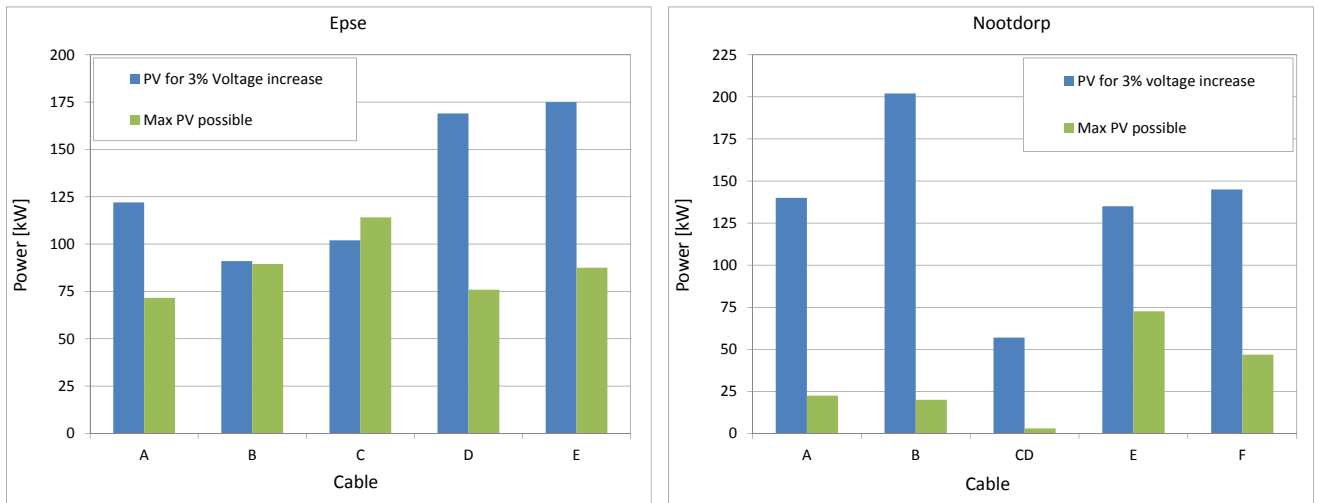


Fig. 3. Maximum allowed PV power per cable under constraint of 3% voltage increase, compared to maximum realistically possible PV power in two of the investigated neighbourhoods.

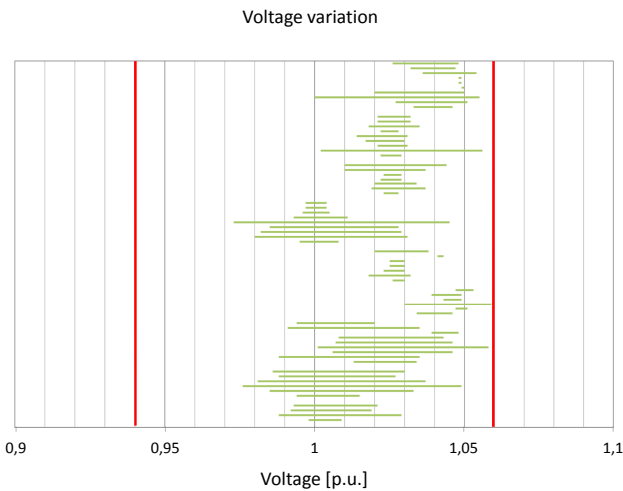


Fig. 4. Voltage variations at the end of the modeled cables between the moment of maximum generation and the moment of maximum load.

IV. RESULTS

A. Voltage level

With the total impedance of a cable we can calculate how much PV power can be connected, and consequentially how many households are allowed to be connected if these are all equipped with solar panels. Figure 2 shows the maximum allowed PV power versus the impedance of the cable and the maximum number of households that may be connected depending on cable length for several different cable types. The number of households shown in figure 2b is for terraced houses and all households are assumed to be evenly distributed over the length of the cable.

Total cable impedances were obtained from the models of the different neighbourhoods. With these impedances the maximum PV power per cable was determined when a maximum

increase in voltage of 3% is allowed. These values were then compared to the maximum PV power that can realistically be connected to these cables, assuming all households using their maximum potential for PV and all roofs are south-oriented for maximal efficiency. Figure 3 shows the results of this comparison for two of the nine investigated neighbourhoods. In nearly all investigated LV-cables the voltage increase was calculated to stay under the 3% margin as a consequence of the added PV. Only in a few cases it was observed that the maximum potential for PV would cause the voltage to rise by more than 3%.

To verify the calculations and check whether regulatory limits could be respected, simulations were carried out in Vision. In these simulations loadflow calculations were done for the moment of maximum generation and moment of maximum load. By comparing the results of the loadflows the maximum voltage variations that occur at the end of the cables are determined; these are shown in figure 4. The results show that in all simulated neighbourhoods it is possible to stay within regulatory voltage limits, although in several cases a (one-time) change in tap setting of the transformer is required. The largest variation in voltage is 7.3%, thus with correct tap setting it is possible to stay within +3% and -6% relative to nominal voltage. The largest variations occur on cables that have a large number of households relative to cable length and are operated radially. Moreover, the cables where the largest variations occur all consist of smaller conductor cross-sections towards the end of the cable.

B. Capacity

The other possible limitation for integration of PV investigated in this paper is the maximum allowable loading of cables and transformers. In figure 2b we showed the maximum number of households with PV that could be connected to a cable of certain length, under constraint of a 3% voltage increase. The influence of the addition of the constraint of

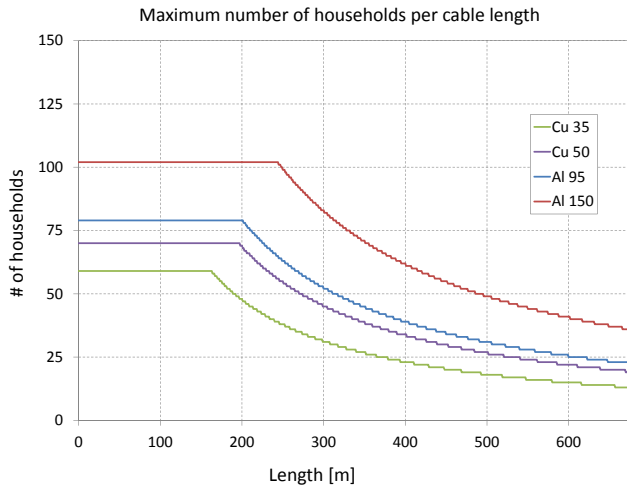


Fig. 5. Maximum number of households vs cable length, limited by 3% voltage increase and maximum cable loading.

maximum cable loading is shown in figure 5. The graph shows that for shorter cables the maximum loading is determinative for the amount of households that may be connected to the cable, although this would require a very high amount of households on a relatively short cable. The simulations showed no overloading of any cables in the investigated neighbourhood models.

In one case an overloading of the transformer supplying the LV-network was observed. However this overloading would only occur for the duration of an hour around the moment of maximum generation. Because in most cases it is allowed to overload a transformer for a while, this overloading would not directly be a large issue.

V. CONCLUSION

Goal of this research was to investigate whether a large penetration of PV in LV cable networks could cause problems considering quality and reliability of the electricity supply. It was shown that the increase of the voltage due to the infeed of PV power is one of the first limiting factors. Overloading of transformers might occur in rare situations, however this would require a very high penetration level on all supplied cables. Overloading of cables will not be a bottleneck, because in realistic situations the maximum allowed voltage would be exceeded earlier. In most parts of the network no problems will arise as a consequence of PV alone, as it is not possible to place enough PV panels to cause problems. Areas which have an increased risk can be identified on forehand. The highest risk for problems occurs in radial networks with long cable connections and a high density of (semi-)detached or terraced houses. These types of networks tend to occur in villages and suburbs.

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