# SHORT-TERM NETWORK PLANNING OF DISTRIBUTION SYSTEM WITH PHOTOVOLTAIC

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## *ABSTRACT*

*The number of connections of photovoltaic (PV) to distribution network is increasing. Very few PV connection guidelines that distribution system operators (DSOs) can refer to have been found. This paper deals with network planning guidelines for distribution networks with PV. The paper aims to identify planning rules that are relatively easy to implement.*

## INTRODUCTION

The amount of power that a solar panel can produce strongly depends on the location of the sun and on the amount of clouds in the sky. The power production is predictable, but there is limited experience with prediction for it [1]. Many researchers have focused on applying random simulation on PV production and load flow, for example in [2] [3]. Some researchers have focused on modelling PV generation, for example in [4] [5]. Those results are very important to understand the impact of PV integration. However, very few publications have been found on network planning with a large amount of small scale PV integration.

Small PV is usually installed in low voltage network (<10kV), the low voltage (LV) network is used to be planned according to practical experience. In the LV distribution network where PV installation is increasing, the DSOs are seeking for safe and simple guidelines to integrate PV. Due to the lack of knowledge on PV production prediction, the guidelines for PV connection are preferred to be based on "worst-case" scenario, which ensures the voltage constraints are not violated even when the highest production meets lowest consumption. Only voltage constraints are considered in this paper since it has been identified as the most relevant issue in [6] [7]. Network planning methods cannot be developed without considering the regulation in the system. This paper first describes the relevant regulation in Sweden, and then the studied network. Simplified PV connection guidelines satisfying the Swedish regulation are shown in the third section, along with verification and evaluation of the guidelines. Finally, the conclusions are drawn in the end.

## REGULATION OF PV CONNECTION

In Sweden, the electric power system was deregulated in 1996. Since then the distribution system was highly market-oriented under the supervision of regulation. The DSOs are responsible for planning and operation of their networks while fulfilling the quality regulation and the revenue regulation. DSOs are required to connect distributed generation (DG) and are not allowed to own DG. However, in some other countries, for example in China, where DSOs are allowed to own DG or influence the DG connection points and sizes of DG, then the optimal placement of DG is essential for the DSO [8].

The penetration of renewable energy is encouraged by the energy policy in Sweden; moreover, the new installed renewable energy from DG is increasing, for example PV DG. In some distribution network, the small scale PV owners do not pay for the connection. A higher PV DG penetration in the near future is foreseen by many DSOs, so it becomes important to develop simple and safe guidelines to connect PV DG.

## NETWORK MODEL

A Swedish distribution network which has a high potential for hosting PV connection is analysed. It is a 400V network with 19 buses. The feed-in transformer 10/0.4 kV has a rated apparent power of 200kVA. A single-phase equivalent circuit of the three-phase network is represented in Figure 1.

### Typical Swedish low voltage network

The distribution lines are represented only by resistance. The voltage drop along a line or between two buses caused by the DG connection is limited by Swedish standards. If one of the two buses is a household (HH) node the voltage drop limit is 5%, for example Bus18, while if there is a point of common connection (PCC) the voltage drop limit is 3% [9]. PCC is a bus in the network electrically nearest to a producer and to another consumer or producer. For example the PCC of Bus18 is Bus5; and the PCC of Bus7 is Bus 2.

### Load model

In the LV network, it is preferred to use simple guidelines, while in the same time ensure the quality requirement. So in this paper, the worst case scenario is applied to obtain the limits for PV connection. The worst case in this network is when the load is zero and the PV produces the maximum power. Only the overvoltage limits are necessary to be considered.

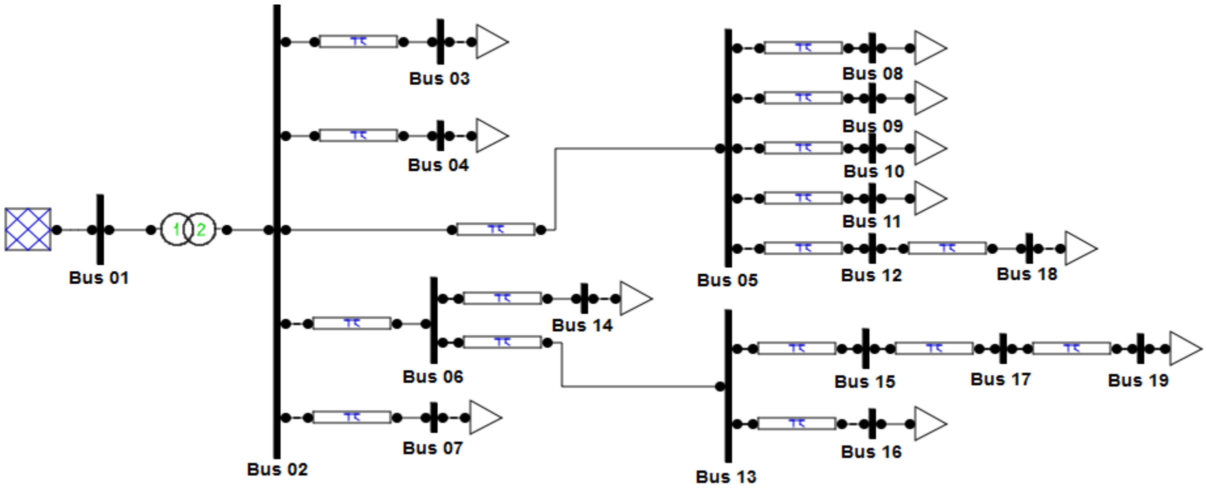


Figure 1: A representative distribution network

## INTEGRATE A LARGE AMOUNT OF PV

This section first analyse the maximum allowed PV installation in the current network. The capacity of PV is decided by the PV owner, if it is larger than the maximum allowed generation, critical lines which need reinforcement are identified.

### One PV connection

When the first PV applies for a connection, the network can be equivalent as in Figure 2. The loss on the resistance is ignored and $X << R$. The voltage drop along a line can be calculated using:

$$\frac{\Delta U}{U_1} \cong \frac{R \cdot P}{U_1^2} \cdot 100\% \qquad [11] \qquad \text{Eq (1)}$$

$\Delta U$ is the voltage change on node 1 due to the DG connection on node 2, $U_1$ is the voltage without the DG connection and load, which is the rated voltage, $R$ is the line resistance and $P$ is the active power inserted from DG. Given the maximum voltage drop at each bus, the maximum installed capacity of DG can be easily obtained. This has been done in [9]. Applying *per unit* calculation, Eq(1) can be simplified and generalized for every bus of the network as:

$$\Delta U_i \cong R_i \cdot P \qquad \text{Eq (2)}$$

$\Delta U_i$ denotes the voltage drop between Bus $i$ and the slack bus. For a given Bus $i$, having a voltage drop of $\Delta U_i$, the voltage at Bus $i$ will be 1+ $\Delta U_i$ pu. $R_i$ denotes resistance between Bus $i$ and slack bus, which is a series connection of all resistances belonging to all lines connecting Bus 1 to Bus $i$. The resistance of the transformer is also included. For example, for Bus 8:

$$R_8 = R_{transformer} + R_{linefrom2to5} + R_{linefrom5to8} \qquad \text{Eq (3)}$$

A general rule can be further developed to reduce the calculations. The critical bus can be identified given the DG connection bus. For a given connection of a DG with capacity $P$, applying Eq (2) to both its HH and PCC buses, the following relationship is found:

$$\frac{\Delta U_{pcc}}{\Delta U_{hh}} = \frac{R_{pcc}P}{R_{hh}P} = \frac{R_{pcc}}{R_{hh}} \qquad \text{Eq (4)}$$

According to the different voltage drop limits on HH and PCC, the HH will be the critical bus only if,

$$\frac{R_{pcc}}{R_{hh}} < 0.6 \qquad \text{Eq (5)}$$

Given the location of the DG, only two simple calculations need to be done to obtain the maximum allowed DG without grid reinforcement. First, use Eq (5) to identify the critical bus; second, apply Eq (2) to calculate maximum allowed capacity.

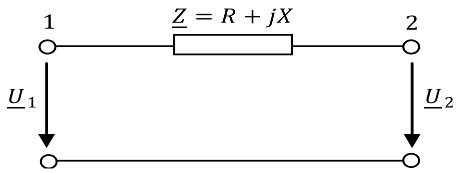


Figure 2: Simplified distribution line equivalent

### More PV connections

The above guideline for one PV can be developed for more PV connections. In this subsection, the proposed method is presented, and the results from this simplified method are compared with the simulation results.

**Proposed method for more PVs**

*Step 1 – Check the voltages at the critical PCCs*

*Path* here refers to the line between any bus and the slack bus. The critical PCCs are the ones at the end of PV paths which are closer to the PV connection buses. This is because the voltage drop at that end is higher than at other buses on the path. For example, PVs have been installed on Bus 3, 4, 8, 9 in the network in Figure 1, and a new PV on Bus 19 applies for connection. The critical

PCCs are Bus 5 and 13. For each installed PV in the network, the voltage impact on the PCCs can be calculated according to Eq (2). To obtain the voltage impact on Bus 5 due to the PV that is installed on the other bus (Bus 3), $R_i$ should be the resistance of the common line of the two paths (from the slack bus to Bus 2 is the common line of PV 3 path and Bus 5 path).

For a PCC the total voltage impact is limited to 3%, and how much capacity a PCC bus can host can be calculated using:

$$P_{new} = \frac{1}{R}\left(0.03 - \sum_i^{nrPV} \Delta U_i\right) \qquad \text{Eq (6)}$$

*nrPV* represents the number of already installed PVs in the network. $\Delta U_i$ is the voltage drop on this PCC due to the already installed PVs. *R* refers to the resistance of the common line between the PCC path and the new PV path.

*Step 2 – Check the voltages at the HH buses*

The voltage limits of household buses need to be checked separately. However, due to Eq (5) there are cases when only the limiting HH buses are necessary to be calculated. In the above example, the HH buses are Bus 3, 4, 8, 9 and 19. In this example, the resistance from the slack bus to bus 13 is 0.1 ohm and to bus 19 0.41 ohm. According to Eq (5) the HH at bus 19 will break before the PCC so it needs to be checked. The maximum allowed installed PV on Bus 19 is limited by

$$P_{new} = \frac{1}{R}\left(0.05 - \sum_i^{nrPV} \Delta U_i\right) \qquad \text{Eq (7)}$$

Here $\Delta U_i$ is the voltage drop on the HH bus due to the already installed PVs.

*Step 3 – Obtain the maximum*

After all the calculations, the maximum allowed installed capacity without any reinforcement in the network is the minimum of all the $P_{new}$.

## Verification and evaluation

In order to verify the proposed method, a case study has been done. In the case study, nine PVs are randomly placed in the grid, and the capacities of these nine PVs are assigned random values within the limits. The power for the tenth PV is determined by the above proposed method. The voltage variations on each bus are shown in Figure 3. The simulations, using Power System Analysis Toolbox (PSAT) for MATLAB, showed that using the proposed method the voltage level will never break the limits at any point. The PCC buses are presented in red colour.

In order to evaluate the proposed method for more PVs, the results from the simulation and the simplified calculation have been compared. Simulation results are obtained by increasing the power on the tenth PV until any voltage limit is violated. The difference between the result from simulation and the proposed method can be obtained and is denoted as the error estimate.

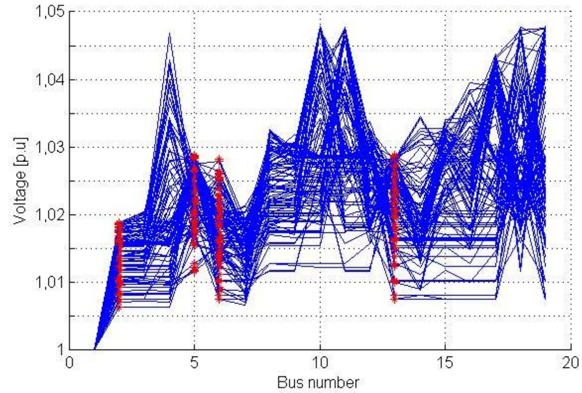


Figure 3: Voltage variations on each bus

Different connection buses can be represented by the line resistance between that bus and the slack bus. The error estimate is drawn versus the resistance for every simulation. In Figure 4 the blue and red dots represent results obtained from two different grids. The blue dots are from the grid in Figure 1 and the red dots are from a bigger grid with 74 buses and a transformer with a rated apparent power of 630kVA. The bigger grid involves more buses and more resistance values, so the curve is more continuous. It can be seen that with higher resistance to the last bus the error will be lower.

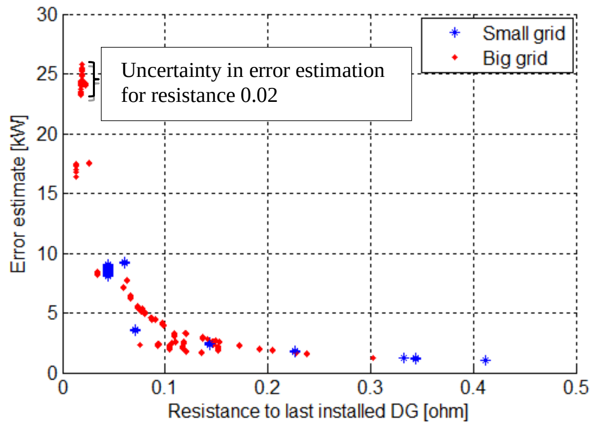


Figure 4: Accuracy of the proposed method

The error is due to how losses in the grid are treated. When using the proposed method, voltages in critical points are below voltage limits, due to the ignored losses. The error is then given by the amount of power that can be installed in the last node to compensate for this uncounted voltage drop. The lower the resistance to the last node the more power you can install per voltage increase.

However, even when knowing the resistance to the last bus it will still result in uncertainties in the error estimation. This can be seen as the vertical lines for each value of the resistance (for example, error for the bus with resistance 0.02 is shown in Figure 4). The spread on y axis varies with the location and power of the earlier DGs. These relations are still unknown.

In the simulation random powers have been chosen and the histogram for the power installed in the network from Figure 1 can be seen in Figure 6. The blue bars represent the distribution of power resulting in the error estimate in Figure 4. The red bars represent a distribution with higher power resulting in higher error estimate, see Figure 5.

The relation between the penetration level and the allowed installed power on the last DG is shown in Figure 7. The distribution with higher power is used for this simulation. The penetration level is based on the transformer rating. No clear relation can be seen.

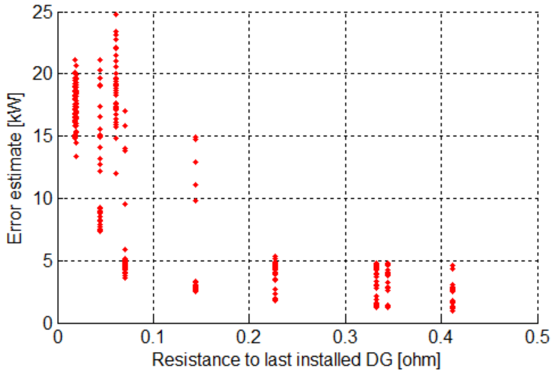


Figure 5: Accuracy of the proposed method with a higher power of the installed DG

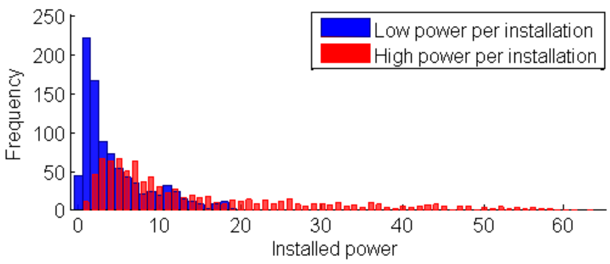


Figure 6: Distribution of the installed power in the grid

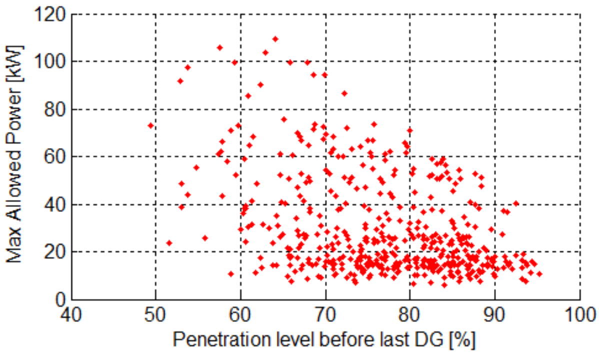


Figure 7: Allowed power as a function of the penetration level

## CONCLUSION

The proposed method will provide a good result for estimating the maximum acceptable power for a new DG in a network with several DGs already installed. The result has been proven to always be within the given voltage limits. However, it should be noted that the actual power the grid can handle is higher than what the guidelines suggest. The proposed method also can be used to identify the critical points, where reinforcement is needed. This study has shown that the locations of the PV can impact on the hosting capacity. The proposed method provides conservative results, so if a PV has higher capacity than the guideline suggests, a more detailed study is necessary. The relation between the resistance to the last DG and the error estimate will be useful when using the proposed method in the planning of LV networks. Results show that penetration level is difficult to use when estimating maximum allowed power. Furthermore, the guidelines can be further developed for other DG than PV.

## ACKNOWLEDGMENTS

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