Evaluation of PV Hosting Capacities of Distribution Grids with Utilization of Solar-Roof-Potential-Analyses

Falko EBE
Ulm University of Applied Sciences
Germany
ebe@hs-ulm.de

Basem IDLBI
Ulm University of Applied Sciences
Germany
idlbi@hs-ulm.de

Jeromie MORRIS
Ulm University of Applied Sciences
Germany
morris@mail.hs-ulm.de

Gerd HEILSCHER
Ulm University of Applied Sciences
Germany
heilscher@hs-ulm.de

Florian MEIER
Stadtwerke Ulm/Neu-Ulm Netze GmbH
Germany
florian.meier@ulm-netze.de

ABSTRACT

Increasing distributed photovoltaic (PV) systems can lead to voltage violations and overloading of grid assets in distribution grids. This raises the necessity to consider the future growth of installed PV capacity for the planning process of distribution system operators (DSOs). This paper proposes the combination of a solar roof potential analysis and grid integration studies at the medium voltage (MV) level. Three different methods are developed to assume the distribution of PV along the feeders based on the solar roof potential, and subsequently to estimate the PV hosting capacity of these feeders. The results show that the approach with an even distribution of PV systems along the feeders leads to higher hosting capacity of PV for the analysed grids. In addition, for most analysed feeders in this study, an overloading of MV/LV (low voltage) transformers is expected to be the limitation of hosting capacity for potential PV systems.

INTRODUCTION

A strategic target, set by the German government, is the transition from the centralized energy system based on fossil fuel to a decentralized energy supply based on renewable resources [1], [2]. According to the high installation rate of distributed generators (DGs) in the distribution system, voltage violations and overloading of grid components can be observed. In other words, if the installation of DGs in a distribution grid exceeds its hosting capacity, a renewal of network assets (e.g., replacement of lines or transformers) is required which can lead to considerable costs for the distribution system operators [3], [4]. For example, the distribution grid extension in Germany until the year 2030 is estimated [4] to be higher than 27 billion €. Considering these high costs, several studies investigate many approaches to increase the hosting capacity of distribution grids, such as active on-load tap changing of transformers, reactive power provision and power curtailment of DGs, e.g. [5], [6]. Therefore the estimation of the hosting capacity of distribution grids has a crucial importance for grid planning, cost estimations as well as decision making. The concept of the hosting capacity can be defined as the maximum installed power of DGs that a network can host without the need for grid reinforcement [5]. In order to estimate grid extension costs and to evaluate possible alternatives, DSOs have to consider DGs installation in future scenarios. However, the allocation of upcoming installed capacity of DGs per medium voltage and low voltage connection points is hard to be accurately predicted. In addition to statistical or expert knowledge approaches like in [4], [7], methods of the domain of geoscience and remote sensing can be applied. By using light detection and ranging (LIDAR) methods, it is possible to create a detailed 3-dimensional map of the investigated area. Subsequently, it is possible to extract the most relevant parameters for each single potential PV-system (e.g., roof area, orientation and inclination) [8], [9]. The focus of this paper is on how to evaluate the hosting capacity when having a solar roof potential analysis. When modelling a PV installation scenario within a distribution network, it is necessary to define the allocation of installed PV power to grid connection points. Some studies used the Monte Carlo analysis to represent the random process of PV installations in distribution networks. For example, [5] introduced several analyses that show the increase of the grid hosting capacity through some PV control strategies. Thus, the hosting capacity is estimated here through Monte Carlo analyses, considering random distributions of PV systems with discrete nominal powers.
The first objective of this contribution is the utilization of solar roof potential in distribution system studies in order to increase the accuracy of predicted PV scenarios. The second objective is the neutralization of the effect of random distribution of PV systems on the estimation of grid hosting capacity. Therefore, deterministic methods will be developed and evaluated based on a real MV grids. This paper is structured in four sections. This section presents the topic and motivation of the study. The second section illustrates the methodology followed in the paper. The last two sections introduce the results and findings of the study.

METHODOLOGY

The steps and assumptions defined to perform the hosting capacity analysis are introduced hereinafter.

Defined Methods

For the analyses of grid hosting capacity, a realistic set of scenarios should be assumed, considering the derived Solar Roof Potential Analysis. A typical method is the probabilistic distribution of PV systems at random connection points in the grid, then the repetition of the distribution several times in a Monte Carlo analysis. This leads to a huge number of different scenarios, and thus a simpler method is targeted in this study. The purpose here is the evaluation of the maximal and minimal hosting capacity using a deterministic method, focusing on the medium voltage feeders. The hosting capacities are obtained by increasing the utilization factor of the solar roof potential analysis per secondary MV/LV substation until a local congestion occurs (e.g., transformer overload or voltage band violation). By using a utilization factor (UF), i.e. rate of installed PV power proportional to the analysed roof potential capacity, three "Upscaling Methods" have been/will be defined as follows:

Forward PV increase: the installation of PV potential power starts from the secondary bus bar of the high voltage (HV)/MV transformer. Then the UF is increased each iteration until the maximum potential is reached.

Backward PV increase: the installation of PV potential starts from the furthest connection point of the secondary bus bar of the HV/MV transformer.

Even PV increase (**All Together**): an equal utilization factor for all the PV systems will be defined. The UF will be increased by a certain step at each iteration.

The 'Backward' method is expected to lead to a minimal hosting capacity since higher voltage rise can be expected. Moreover, the reverse feed-in powers go through more lines in the feeder so that overloading is more likely. Fig. 1 shows an illustration of these methods.

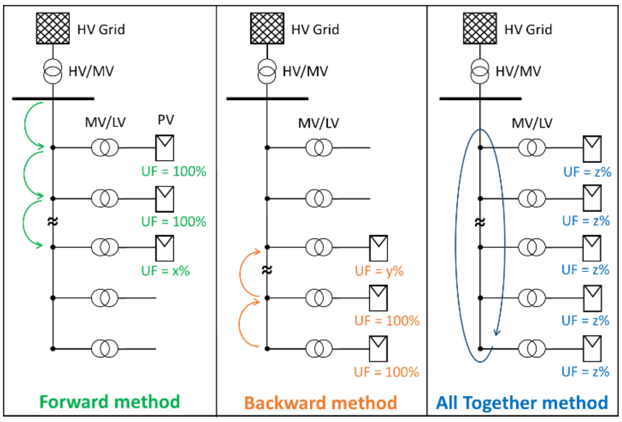

Figure 1. Schematic overview of the the implemented methods. x and y indicates the UF for the directed methods. z indicates the UF for the equal utilitsation

Topology Analysis

One key element of this study is the topology analysis, which assigns the individual PV potential power to a level structure as a function of the nodal distance from the primary substation (HV/MV). As a part of the developed methods, the PV systems within a single level are scaled up with the same scaling factor for the three defined methods. Fig. 2 illustrates the used level concept.

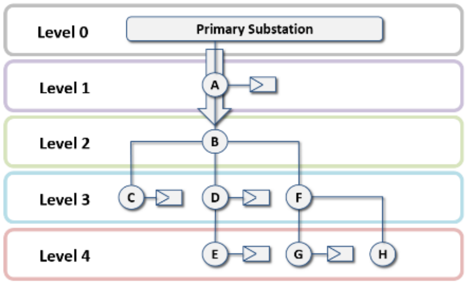

Figure 2. Exemplary illustration of the level concept used in the topology analysis. Each circle represents an MV/LV substation.

The topology analysis as well as the overall algorithms is implemented as a Python script, which utilizes the functions and the grid model implemented in power systems analysis software (PSAS) DIgSILENT PowerFactory 2016 and uses its solver for loadflow calculations. Fig. 3 illustrates the script as a flowchart. For every single defined feeder, the script runs a series of functions in order to determine the maximum tolerated PV hosting capacity.

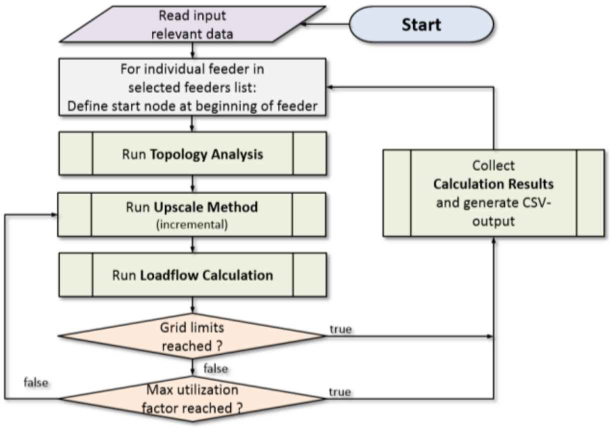

Figure 3. Schematic overview of key functions implemented

The main functions blocks in Fig. 3 are:

Input: defined grid limits, modification methods and feeders within the script's input provide the possibility of creating individual scenarios and thereby form the basis for every hosting capacity calculation.

Topology Analysis: This function sequentially runs through a determined feeder and gathers all calculation-relevant data that is the PV-potential-systems (c.f. Fig. 4). The result is a sorted table of the PV-potential-systems based on their location along the branch, beginning with

the system closest to the feeder's start.
The basic principle of the topology analysis is to read in nodes connected to an element and evaluating the unknown node. The unknown node is applied as a new input value when calling the topology analysis function again, accordingly topology analysis runs recursive. Therefore, the analysis always moves in the direction of the undiscovered elements. In case the topology analysis detects a load switch (i.e. coupler), it assumes to have discovered a substation, which then is examined for PV-potential-systems. The detected PV-potential-system is stored in a dictionary along with a corresponding level, which represents the location along the branch. In case of a branching, the respective terminal is marked together with the corresponding level and processed whenever the function reaches the end of a branch.
Loadflow Calculation: PowerFactory's load flow calculation is utilized throughout the "Upscaling Method". Whenever a PV-potential-system's power is upscaled, a load flow calculation is executed. During the active loadflow calculation, the initially determined grid limits are evaluated. These can be: line loading [%], transformer loading [%] and voltage band [p.u.]. As long as these grid limits are not reached, the grid is considered to be in a stable state and the upscaling of the PV-potential-systems is continued.

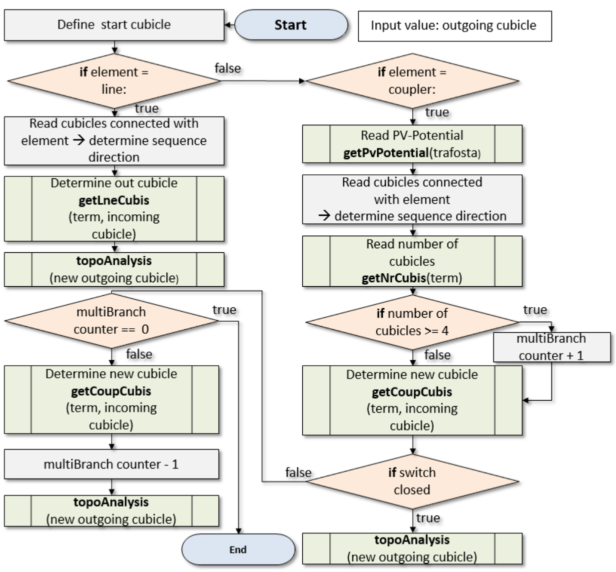

Figure 4. Schematic overview of the topology analysis function

Utilized Grid Modell and Assumptions

Based on the grid data provided by the local grid operator in Ulm (i.e. Stadtwerke Ulm/Neu-Ulm Netze GmbH), a detailed real MV grid is modelled and analysed. The examined part of the MV grid area consists mainly of urban and industrial areas. Table 1 provides some key figures of the examined grid. The analysis of solar roof potential is described in [8].
The boundaries of the modelled grid are the MV bus bar of the main HV/MV substation and the LV bus bars of the MV/LV substations. The model assumes the connected PV plants in the LV grids as aggregated PV systems connected at the LV side of the MV/LV substations. The overlaying HV grid is modelled as a slack element connected to the medium voltage bus bar of the primary substations. Therefore, each feeder can be analysed independently from other feeders because the voltage rise across a HV/MV transformer is assumed to be neglected for simplification purposes. According to this simplification, the iterations for the loadflow calculations, which are caused by the regulations of the tap-changer of the HV/MV transformer, can be avoided.
Besides the aforementioned assumptions, the technical guidelines for decentralized power plants connected to the medium voltage grid are considered [10]. The guidelines describe a simple method for the assessment of grid connection request for a DG. The limitation of the voltage rise in the MV grid to a maximum of 2 % for all connected stations is considered in this study. These limits imply that all potential PV-systems are connected to the MV grid. Therefore, there is no consideration of the additional 3 % voltage rise in the LV grid introduced by the relevant German technical guideline VDE AR4105 [11]. In addition, the wind power feed-in is not considered in the analysed grid, since the wind potential in the grid area is negligible compared to the PV potential [12]. Furthermore, the voltage setpoint for the slack element is assumed to be a constant value of 1.0. p.u.. The derating factor for transformers, cables and overhead lines is assumed to be 1.0 p.u..

Table 1. Key Parameters of analysed MV grids

Parameter	**Value**
MV Feeders	243 pcs
Primary Substations	7 pcs
Public Substations supplied	543 pcs
Private Substations supplied	332 pc
MV line length (cable / overhead line)	892 / 79 km
Total MV/LV Transformer capacity	1340 MVA

RESULTS

The calculated results as well as the main derivations are presented in the section hereinafter.

Scenario and Setpoint Selection

Numerous hosting capacity calculations have been carried out considering the number of feeders in Table 1, three methods as well as three assumed scenarios. The scenarios differ in the used setpoint value of the maximum loading of MV/LV transformers and there are three different setpoints assumed. The first two are used to represent the present situation and the possibility to replace a transformer with a higher rated transformer. The third scenario neglects the transformer overloading as a termination reason for the extension process. The assumed scenarios regarding the setpoints are illustrated in Table 2. The aim of the second and third setpoint is to show the hosting capacity only for the MV feeder grid components, regardless of the nominal capacity of the MV/LV transformers.

Limitation of Hosting Capacity

In order to give an overview on the limitations of the analysed MV grid, a distribution of the MV feeders numbers based on the termination reason for the method 'All Together' is depicted in Fig. 5. The distribution is classified according to the defined scenarios in Table 2 as well as to the connected primary HV/MV substations (SS). Considering a transformer loading limit of 1.0 p.u., the main termination reason is the LV/MV transformer overloading except for few feeders having a line overloading or voltage violation as a termination reason. As a result for the analysed grids, the costs of transformer replacement should be taken into account for the future scenarios. For Example, the SS7 is directly located in the city center, hence lines are relatively short, and thus the main congestion reason is transformer overloading. When setting the transformer loading limit to 2.5 p.u., more line loading congestions and voltage band violations occur. Therefore, line replacement should also be taken into consideration also for the long-term scenarios.

Evaluation of Calculated Hosting Capacities

The hosting capacities for the analysed feeders are illustrated statistically in Fig. 6. Theoretically, the 'Backward' method is likely to lead to minimal hosting capacity, since voltage violation and line overloading is more probable. In contrast to what is anticipated, the 'Forward' method results in the lowest hosting capacity for Scenario 1 (orange rectangle in Fig. 6). This can be justified by the fact that the Transformer overloading is independent from the connection point of PV systems, and also the PV potential for the analysed feeders can be higher close to the primary substation, so that the transformer can be overloaded. Due to the even distribution of PV used in method 'All Together', a single transformer is less burdened which leads to higher hosting capacity. A more detailed examination of this circumstance is illustrated in Fig. 7.

For each feeder, the difference in hosting capacity resulted by the methods 'All Together' and 'Forward' is calculated. With the increase of the permissible transformer loading, the difference between the methods decreases. For Scenario 3, when neglecting the transformer overloading congestion, the 'Backward' method results in a lower hosting capacity mainly due to early voltage violations (see Fig. 6). For this scenario, the 'All Together' method results in higher hosting capacity due to the even distribution of PV power along the feeders.

Table 2. Setpoint values for the assumed scenarios

Scenario	Voltage Band	Line Overload	Transformer Overload
1	1.02 p.u.	1.0 p.u.	1.0 p.u.
2	1.02 p.u.	1.0 p.u.	2.5 p.u.
3	1.02 p.u.	1.0 p.u.	unlimited

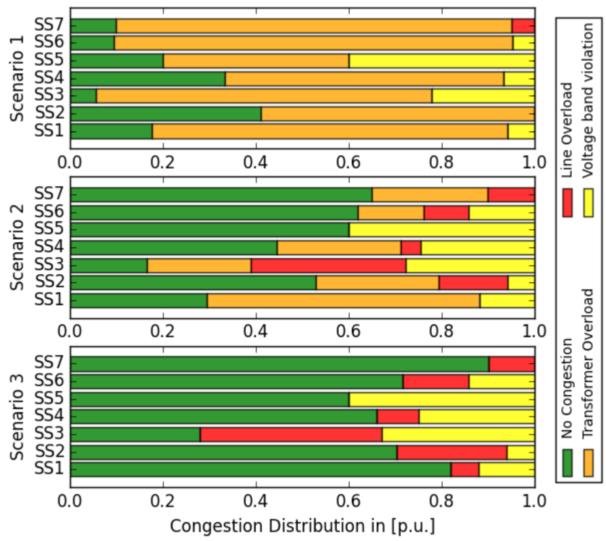

Figure 5. Distribution of the feeder numbers according to the congestion reason, for the scenarios in Table 2, cosidering the 'All Together' method. The feeders are grouped by specific SS

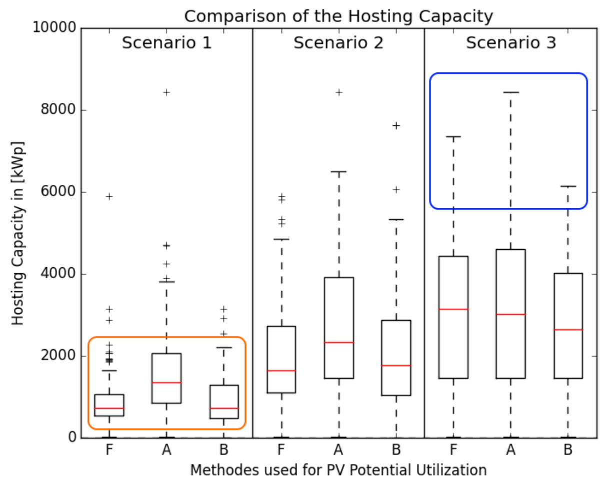

Figure 6. Boxplots of calculated hosting capacities for the scenarios of Table 2 and utilizing the developed methods. 'A' for All Together, 'B' for Backward and 'F' for Forward. One Box represents the interquartile range (IQR) from 25 % to 75 % and whiskers are at 1.5 * IQR

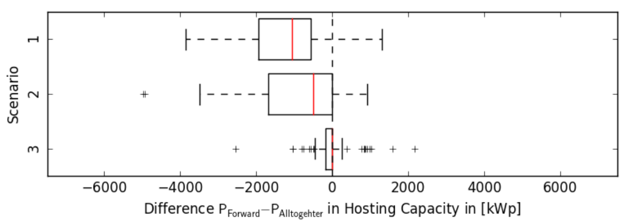

Figure 7. Boxplots comparing the differences of the methods 'All Together' and 'Forward'. Box represents the IQR from 25 % to 75 % and whiskers are at 1.5 * IQR

Illustrative Example for a Single Feeder

Using the built-in plotting function of PowerFactory (i.e. the voltage profile plot), the profile of a single feeder is depicted in Fig. 7 in order to illustrate the effect of the three developed methods. The selected feeder consists of a main branch supplying a suburban area via cables and a side branch with overhead lines and 2 small MV/LV transformers, which supply farmsteads with a decent amount of PV already installed. The plotted data is derived from three loadflow calculations at the hosting capacity power for Scenario 2 which considers a transformer loading of 2.5 p.u. as a termination reason. Fig. 8 shows the voltage at the MV lines, bus bars and the LV bus bars. The vertical lines represent the voltage rise at the transformers, while the red-colored lines represent overloaded components which are loaded more than 1.0. p.u. of their nominal capacity. For the 'All Together' method, the termination is based on the overloading of the MV/LV transformers of the side branch. A crucial voltage rise over these tow transformers can also be observed. The 'Forward' method terminates due to the same reason but a smaller amount of PV power is integrated as the extension process directed. On the other hand, the voltage violation at the main branch is the termination reason for the 'Backward' method in this example.

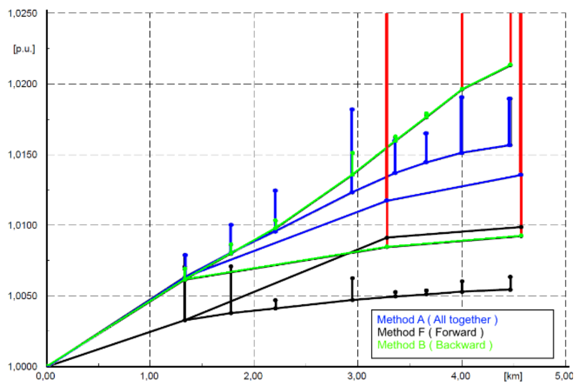

Figure 8. Voltage profile of a single feeder according to Scenario 2 (Transformer overloading: 2.5 p.u.).

CONCLUSION AND OUTLOOK

The paper at hand proposed three methods for the utilization of solar roof potential analysis for the calculations of PV hosting capacity on the medium voltage feeder level. For the analysed grid area and assumptions made in this study, it is not possible to predict which method can provide the minimal hosting capacity value. However, the method with an even installation of PV systems along the feeder results in higher hosting capacity of PV for the analysed grids.

In addition, for most analysed feeders in this study, an overloading of MV/LV transformers is expected to be the limitation reason for the exploitation of potential PV power. Therefore, the cost of transformer replacement should be taken into account for future scenarios.

The developed methods will be further examined, considering the targeted increase of spatial resolution for the roof potential analysis. The next step will be to implement this study on LV grids as well and to compare other methods for the calculation of PV hosting capacity, such as a probabilistic PV distribution in the grid considering the Monte Carlo analysis. In a further step, the analysis of the hosting capacity can consider the effect of charging stations of electric vehicles.

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