IMPROVED DISTRIBUTION GRID HOSTING CAPACITY WITH OPTIMISED PV DEPLOYMENT

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ABSTRACT: Nowadays in Europe, the production from variable renewable energy sources (vRES) has seen a significant growth and the photovoltaic (PV) generation plays a central role. The unplanned proliferation of PV generators in different points of the distribution grid has caused different kind of disturbances that might compromise the correct operation and reliability of the grid. In particular, possible overvoltages caused by PV generation limit the amount of PV that can be installed in a certain node of a distribution system. In this respect, the aim of this work is twofold. First, the hosting capacity of a specific distribution network is analysed based on voltage buses, current branch and power at transformer level. Then, a suboptimal PV placement algorithm is proposed in order to reduce the overvoltage effect, thus mitigating the issues related to limited hosting capacity.

Keywords: *Phovoltaics, PV hosting capacity, power flow analysis, distribution grid*

1 INTRODUCTION

Installed global photovoltaic (PV) power capacity reached about 235 GW in 2015 and about 310 GW in 2016 [1]. This potential is able to cover 1.5% of the world electricity demand. Although the growth of renewable energy sources contributes to the decarbonisation of the energy production, high penetration of PV in the distribution grid may cause deviations from nominal operating conditions and lead to power quality issues. Thus, many studies are carried out to determine, to predict and to solve potential problems and challenges arising from such dynamic conditions. The impact of PV on the grid will depend on location, feeder parameters and nominal power installed. Different performance indicators concerning voltage, loading, protection and power quality are analysed in the literature in order to evaluate the maximum PV penetration [2]-[6]. Overvoltage at grid bus has a negative impact on customers' service as well as a possible cause of regulators failure. Moreover, high values of voltage and current have an impact on thermal limits that are important for safety reasons and insulation resistance, thus potentially disrupting the correct operation of protection devices. The aforementioned problems can be mitigated or solved by applying some solutions such as energy storage or reactive power control [4]. Reactive power control can be performed with smart inverters, on the basis of the active power related to power factor or the voltage magnitude in the point of common coupling [7]. Active transformers with tap changing are also considered as a positive asset to enable further PV growth [8]. As distinct from active methods mentioned above, hosting capacity can also be increased with some passive solutions. The most obvious and robust one is grid reinforcement. This however requires large investments and does not eliminate grid protection issues [8]. Although grid reinforcement mainly focuses on planning procedures of modernization and development, active control methods or optimal renewable energy source (RES) location scenarios may be considered as well, as a tool for minimizing the generation impact for distribution system operators.

This paper proposes an alternative method to mitigate the limit of hosting capacity based on PV sub-optimal placement. Indeed, in the literature, it is shown how optimal placement of PV arrays can minimize the power loss [9] or improve distribution grid performances through a sensitivity analysis [10]. In [11], both the voltage stability and losses indices are sensitive factors taken into account for optimal distributed generation (DG) placement. In [12], a genetic algorithm is used to find the best DG location under variable loads. However, no specific reference was found on the use of greedy algorithms to increase PV hosting capacity. The performed analysis is based on simulations using the open-source distribution grid software OpenDSS [13], which is used to compute the three-phase power-flow with high detail. It is coupled with the GridPV toolbox using a virtual COM port [14]. The proposed method is tested on the IEEE 13-bus Node Test Feeders [15] and on a larger European network.

2 METHODOLOGY

In this paragraph, first a definition of hosting capacity is given and the computational approach is presented. Then, a sub-optimal algorithm to mitigate the voltage deviations based on PV placement is described.

2.1 Hosting capacity

The hosting capacity term has become very popular and common among grid operators and researchers during the last ten years. The hosting capacity itself was already used before in completely different contexts such as networking, watermarking images or settlement of refugees [17]. In the context of distribution grids, the maximum amount of DG supported by an electric grid is defined as hosting capacity. The maximum quantity of DG (here we will refer only to PV generators) connected to the grid should guarantee reliability and voltage stability for customers and operators. The evaluation of different indicators may restrict the amount of PV that can be connected to the grid. For a given performance index, the hosting capacity is defined as the quantity of PV power that can be injected into a single grid point for which the chosen performance index does not exceed a specified limit, as shown in Fig.1.

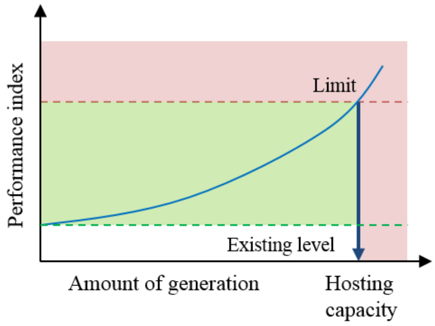


Fig. 1- Hosting capacity example with performance, which deteriorates with small PV generation [17].

There are several performance indices that can be taken into account to evaluate the quantity of power injected into a grid from a specific DG. The main ones are:

- Bus overvoltage and undervoltage levels;
- Line overcurrent level;
- Cable thermal limits (depending on the amount of current through the line);
- Maximum complex power to be transformed;
- Power quality indices (mainly due to harmonic distortion).

In this work, we evaluate the hosting capacity considering three of the abovementioned indices i.e.: the maximum or minimum bus voltage, ($V_{max\text{-}min}$), the maximum line current (I_{max}) and the maximum transformer power (S_{max}). Among them, PV generators are particularly sensitive to overvoltage (as confirmed by the simulation results reported in section III as well).

Assuming the two-node system model in Fig.2 , where the nominal phasor voltage at generator is $V_n e^{j\theta n}$ with θ_n equal to 0° and V_n 1 p.u. (per-unit), Z is the line impedance composed by the R resistance and the reactance X and $V_g e^{j\theta g}$ is the voltage phasor at the second node, the voltage deviation ΔV is given by:

$$\Delta V = V_g\text{-}V_n \qquad (1)$$

In the European Standard EN50160 (*"Voltage characteristics of electricity supplied by public distribution systems"* [18]), the magnitude voltage limits are equal to 5% of the nominal value at the slack bus, i.e. V_{max}=1.05 p.u. and V_{min}= 0.95 p.u. These are the values that will be considered in the following as overvoltage and undervoltage thresholds.

In order to evaluate how the chosen indices change as a function of the increasing amount of DG (e.g. Fig. 1), the power flows analysis is performed.

The power flow solutions give the steady-state operating conditions of an electrical grid, namely the voltage magnitude and phase at every bus as well as the real and reactive power flows through every line and transformer of the grid considered. If grid topology, generators, line parameters and loads are known, the power flow problem can be expressed as a system of non-linear algebraic equations that derive from the Kirchhoff's laws under proper constraints [19]. The most popular algorithms to solve the power flow problem are: Newton-Rapson and Gauss-Siedel [19]. However, the simulations performed in this paper are based on OpenDSS, which implements an algorithm based on harmonic analysis to compute the power flows [13]. This method has the advantage to be suitable not only for radial but also for mesh multi-phase distribution networks, which will be the most common topology in the next years [13].

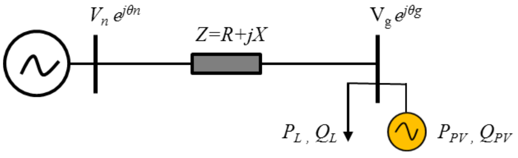


Fig. 2- Two-node system with PV generator.

If we define the PV penetration (in percentage) as:

$$PV_{\%} = \frac{\sum_{n=1}^{N_{PV}} P_{PV}(n)}{\sum_{l=1}^{N_{load}} \sqrt{P^2(l) + Q^2(l)}} \times 100 \qquad (2)$$

where *n* is the number of PV generators, *l* is the number of buses with active (P) and reactive (Q) power. The methods applied to evaluate the hosting capacity is shown in Fig.3. The first step is to model the three-phase (or single-phase) distribution network and to perform the power flow analysis without PV generators in order to have the baseline solution. After that, the PV generators are placed in some or all nodes and their power is increased by 1% steps according to (2). For each iteration, a new power flow solution is found and the results are compared with the limits for voltage, current and complex power. If at least one of these limits exceeds the threshold, the iteration stops and the maximum hosting capacity is achieved. For sure, the results strongly depend on the grid under test, e.g. on its topology, loads and admittance matrix. However, the method is quite general and can be applied to many different type of grids as shown in the literature [20].

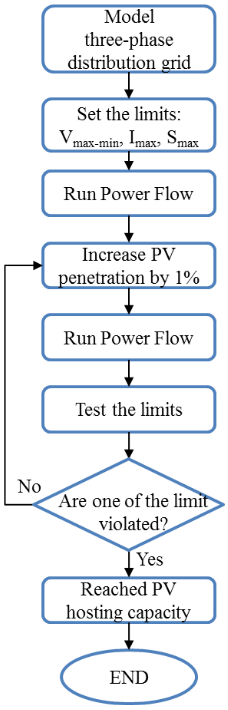


Fig. 3- Flow chart of the algorithm for hosting capacity computation.

2.3 PV placement through greedy algorithm

In the introduction, we have mentioned different kinds of methods to increase the PV hosting capacity, such as using reactive power control through smart inverters or grid line reinforcement. As mentioned in the Introduction, in literature there are also some works which maximize the hosting capacity through optimal PV placement. This approach is also used in this paper. In particular, we try to mitigate the effect of PV generators, by properly placing them using greedy algorithms.

A greedy algorithm always makes the choice that looks best at the moment. It finds a sequence of locally optimal solutions, which usually leads to a globally optimal solution. However, this method not always converges to the global optimum. Nevertheless, this kind of algorithm is computationally efficient and fast enough to be suitable for effective PV placement even though the obtained solution is sometimes sub-optimal. The idea developed in this work is to install one PV generator at a time, finding the best bus location at every iteration. In particular, a PV generator is actually placed at the bus where the chosen cost function is minimum. Since, as previously mentioned, the voltage deviations are one of the main effect caused be high PV penetration, the cost function to minimize in the case at hand will be the root average mean square (RAMS), which is defined as:

$$RAMS_V = \sqrt{\frac{1}{N_B}\sum_{n=1}^{N_B}\left|V_n - \overline{V}_n\right|^2} \qquad (3)$$

In (3) N_B indicates the number of buses, while V_n and $\overline{V}_n$ are the nominal and actual value of the interested quantity at bus *n* respectively. In simulations, we will assume that the RAMS metrics will be applied to both bus voltage magnitude-only and phasors magnitude, which means to consider not only the amplitude but also the phase angle fluctuations.

3 SIMULATION RESULTS

This section presents some simulation results to evaluate the effectiveness of the algorithm shown in Fig. 3 and the validity of the greedy placement.

3.1 Evaluation of hosting capacity

In the first test, we use the IEEE 13-bus, three-phase distribution grid shown in Fig.4 to evaluate the PV hosting capacity using the method described in section 2.2.

Initially, we consider the operational case with PV generator installed at every three-phase bus, to evaluate to what extent PV penetration affects hosting capacity. Every PV generator has the same nominal power with a total penetration level given in (2). It is assumed to operate in steady-state conditions, i.e. active and reactive power at loads are approximately constant.

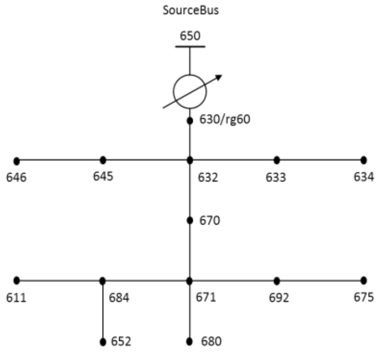


Fig. 4 - Modified IEEE 13-bus distribution feeder

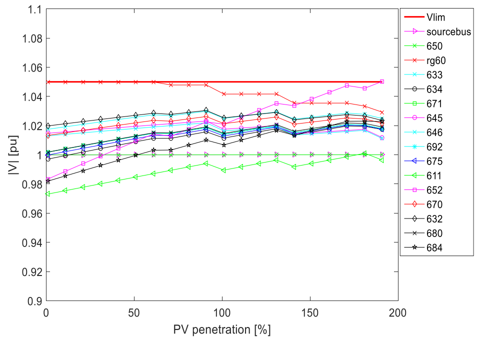
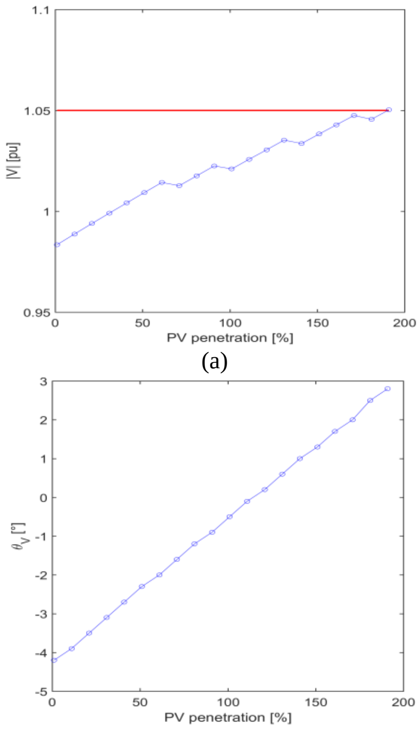


Fig. 5– Voltage magnitude for every bus by increasing PV penetration level

The penetration has been varied in the range [0%-200%] as defined in equation (2).

The limits for voltage deviations are ±5% of the nominal value as indicated in [18], while I_{max} equal to maximal line current and S_{max} equal to the maximum power at transformer. In the algorithm shown in Fig.3, after the baseline power flow computation, the PV penetration is increased iteratively by 1% steps. The limits are violated when PV penetration reaches 196%, because an overvoltage occurs at bus 652, as shown in Fig.5, which displays the average voltage magnitude of the three-phases as a function of the PV penetration at every bus. The red solid line indicates the upper -limit of the voltage (1.05 p.u. in this case).

Similar simulations (not reported for the sake of brevity) have been also performed using a smaller number of PV generators placed randomly. The results obtained in that case show that the IEEE 13-bus grid is robust to the current and power fluctuations, while the voltage limit is violated.



(a)

(b)

Fig. 6– Magnitude (a) and phase voltage (b) at bus 652, which exceed the hosting capacity limits

For this reason, the rest of the paper is focused on how to minimize voltage deviations only. It is worth noticing that as the amount of injected PV power increases, both voltage magnitude and angle at bus 652 grow linearly, as shown in Fig. 6(a)-6(b).

Therefore, even though currently just voltage magnitude deviations are taken into account in normal grid operation, in future active distribution grids, the increase of vRES, combined with time-variant loads (e.g. e-cars or storage) will require accurate bus voltage angle monitoring [16].

3.2 PV optimal placement

Previous simulations show that, in the case at hand, overvoltage is of primary concern for hosting capacity. Moreover, the linear growth of both voltage magnitude and angle shown in Fig. 6 is useful to choose the greedy algorithm optimization parameters. In particular, assuming to place one PV generator at a time in such a way that the RAMS metric at every iteration is minimum, we decide to compare the results assuming to consider either bus voltage phasors magnitude or bus voltage magnitude-only.

The corresponding percentage RAMS values are shown in Fig. 7(a)-(c), for three different PV penetration levels, i.e. 50% Fig. 7(a), 75% Fig. 7 (b) and 100% Fig. 7 (c).

Since in this case we assume to insert one PV generator at a time, the penetration percentage is equally distributed. This means that:

$$P_{PV} = \frac{PV_{\%}}{N_{PV}} \qquad (4)$$

The red lines indicate the RAMS of voltage magnitude only obtained using sequential (solid line) or greedy (dashed line) placement, respectively. Here and in the following, for sequential placement we mean that PV generators are installed simply in the order as bus numbering. Dually, the blue lines are the RAMS values of voltage phasors magnitude for sequential (solid line) and greedy (dashed line) placement.

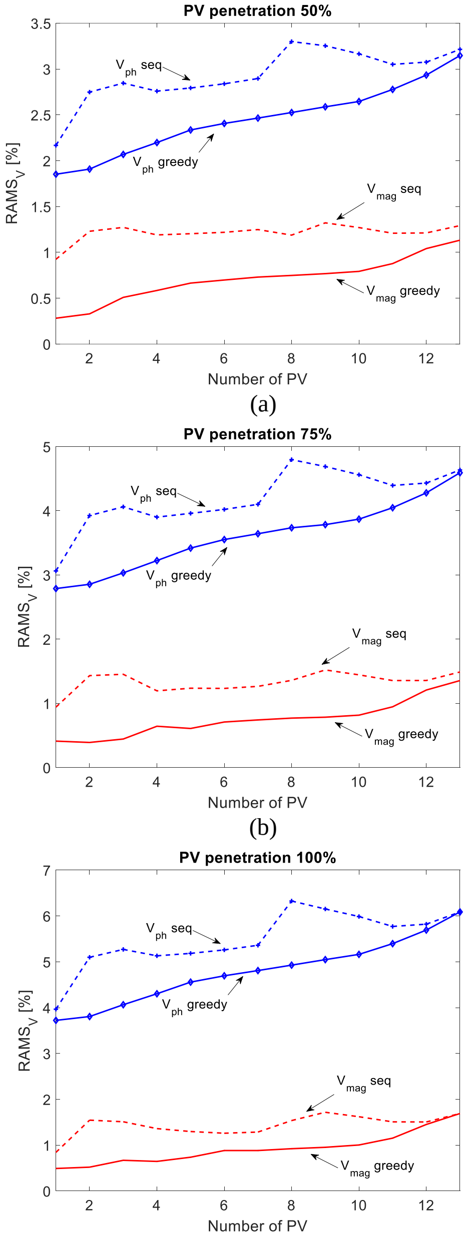
The obtained results are interesting for the following reasons.

First of all, it is evident that by increasing the amount of injected PV power the dispersion of bus voltage magnitude-only and phasors magnitude grow almost linearly with the number of generators installed (assuming that their nominal power is the same). The linear trend is particularly clear, when the greedy placement is used.

Moreover, for every considered penetration level, the red lines (voltage magnitude) are always below the blue lines (voltage phasor). This suggests that the phase fluctuations at different buses are significant in distribution grids and should be probably taken into account by Distribution System Operators (DSOs).

The greedy algorithm placement, as shown in Fig.7(a)-(c), generally returns better results (i.e. smaller fluctuations) than sequential placement. Further Monte Carlo simulations (not reported here for the sake of brevity) confirm that the greedy algorithm is highly likely to perform better than random placement.

An additional remark based on the results shown in Fig. 7 is that a small number of PV generators with high nominal power seem to have a greater impact on voltage magnitude and voltage phasor RAMS than many generators with low rated power. Indeed, for example considering Fig. 7(b) we have that even one PV with 75% of penetration caused a bus voltage deviations (both magnitude-only and phasor magnitude) higher than 13 PV with 50% of total penetration power.



(a)

(b)

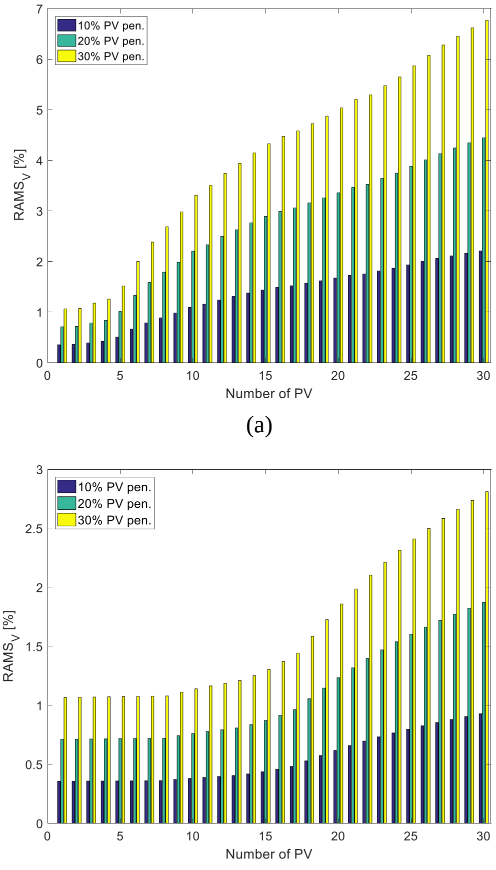
(c)

Fig. 7- Root average mean square values of bus voltage magnitude-only (red lines) and phasors magnitude (blue lines) for three different levels of PV penetration using sequential (solid line) and greedy (dashed line) placement.

In order to analyse the behaviour of the proposed method in a different context, similar simulations have been repeated using a modified version of the 130-bus LV European network available in [21]. In this case, only 30 PV generators are actually placed, varying their nominal power to provide 10%, 20% or 30% PV penetration. The RAMS values of bus voltage magnitude-only and phasors magnitude shown in Fig. 8(a)-(b) for sequential and greedy placement, respectively, essentially confirm all the previous considerations based on the results obtained using the IEEE test distribution grid.

4 CONCLUSIONS

In this paper, the impact of PV generator in terms of



(a)

(b)

Fig. 8 – Root average mean square phasor voltage for different PV penetration using sequential (a) and greedy (b) algorithm applied to the European LV grid available in[21].

distribution grid hosting capacity has been analyzed and a method to mitigate the side effects of large PV penetration (particularly large voltage fluctuations) has been proposed. In particular, a PV generator placement algorithm based on a greedy approach has been used to minimize the root average mean squared (RAMS) values of either voltage magnitude only or voltage phasor magnitude from the respective nominal values at each bus. Multiple simulations show that the greedy algorithm performs better that both random and sequential placement. Moreover, it is demonstrated that PV penetration may have a significant impact not only on voltage magnitude, but also on voltage phase fluctuations. Indeed, the phasor magnitude RAMS values are always greater than those obtained in the magnitude-only case. For the considered distribution grids, it seems that a lower number of PV generators injecting a larger amount of power causes larger voltage fluctuations than many low-power PV generators. The results of the proposed PV placement applied to an European LV grid confirm those obtained using an IEEE test distribution grid.

In conclusion, we can said that the optimal placement based on greedy algorithm is a promising technique to mitigate the effect of high PV penetration in the distribution grid.

In future, we plan to analyze more complex distribution grids and to apply the optimal placement algorithm in the presence of distributed storage systems as well, in order to enhance grid hosting capacity.

5 ACKNOWLEDGEMENT

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