Distributed Energy Resources Hosting Capacity Assessment - An Industry Perspective

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***Abstract*—Hosting Capacity (HC) analysis is a recent methodology that is used by many Low Voltage Distribution Network (LVDN) operators to address the technical limits associated with Distributed Energy Resources (DER) integration into the grid. In the literature, several techniques and methodologies have been proposed to perform the HC analysis. However, there is a gap between existing approaches in the literature and those which are utilised in the industry to assess HC. In this paper, the HC techniques used by the industry have been reviewed. The main industrial HC techniques are, namely, iterative HC, stochastic HC and streamlined HC. Unlike other papers, the methods have been presented in a more technical way to help other researchers and engineers reproduce the algorithms. Moreover, the three methods have been applied to the European low-voltage test feeder to compare their performance against accuracy, processing efficiency and complexity. It was found that the iterative method has the highest accuracy while the Streamlined approach possesses the lowest processing time.**

***Index Terms*—Hosting capacity, Low voltage distribution networks, Distributed energy resources, PV**

I. INTRODUCTION

Australia is considered one of the leading countries in growing the share of renewable resources in total energy production across the country. Australia even put a more ambitious target than other countries which is to cut 43 per cent of emissions below 2005 levels by 2030 [1]. Australia has doubled its renewable electricity production between the years 2017 and 2021, raising it from 16.9 per cent to 32.5 per cent of the total electricity generated in 2021 [2].

Despite the environmental motivation behind the adoption of Distributed Energy Resources (DERs), the electric networks started to experience unconventional power quality issues [3]. Voltage regulation, exceeding thermal limits of the equipment, and stability are among the negative impacts of the increasing penetration of DERs [4]. In response, Low Voltage Distribution Network (LVDN) operators have started to introduce conservative limits on DERs deployment within their networks' domain. However, the increasing need for more renewable dependent energy is forcing LVDN operators to look for less relaxing limits.

Hosting Capacity (HC) analysis is a way to accurately assess the electric networks' ability to accommodate more DERs. Although it is recently introduced in the literature, hosting capacity analysis has been addressed sufficiently for the taxonomy to be reviewed and established, however, the terminology is still debatable among researchers [5–8]. The main reason behind the differences is the fact that hosting capacity analysis is being developed by almost two independent streams of research: academia and industry. In order for the taxonomy to get mature and be more generally accepted by researchers, the need for in-depth addressing of the origin and characteristics of different hosting capacity methods is a necessity. This paper presents an attempt to provide researchers with a better understanding and distinction of hosting capacity methods found in the literature.

In this paper, the term HC is investigated from an industrial point of view. The main approaches used by LVDN operators and that found in the commercial tools are thoroughly discussed. Hence, it is expected that the readers of the paper will find it useful to help free the taxonomy of HC analysis. In the end, the methods were applied to a case study to compare against key criteria such as accuracy, computation efficiency, and complexity. The remainder of this paper is structured in the following way: first, the term Hosting Capacity (HC) is explained in section II. In the same section, some of the main positive and negative impacts of DERs on the electric grid are addressed. In section III, the main HC techniques that are used in the industry are thoroughly reviewed and their algorithms are rebuilt. Finally, a case study is introduced in section IV where the discussed HC techniques are applied to it and compared accordingly.

II. HOSTING CAPACITY

A. *Definition of Hosting Capacity*

The term hosting capacity, in the context of DERs, was first defined as the maximum amount of DERs that can be integrated into the system while maintaining satisfactory operation [4]. In a more technical form, it is an indicator that evaluates the maximum generation caused by DERs that the Low Voltage Distribution Network (LVDN) can absorb without breaching the grid's limits [9]. In the literature, multiple definitions of the term hosting capacity can be found [10]. The variation in the definitions' articulation refers to the end user's scope, reference values, impact factors, and use of the HC analysis results. According to the National Renewable Energy Laboratory (NREL), HC for PV systems is the amount of distributed PVs that can be added to the LVDN before requiring upgrades or coordination to safely and reliably integrate additional units [11]. HC is considered a complex process that goes beyond analysis to include the collection of data such as loads and generation profiles, defining the network parameters and modelling, and the selection of the impact factors that will shape the results of HC [12]. Till now, the exact technical definition of HC is still debatable and can have multiple forms depending on the case under study. Some definitions include transformer rating, energy consumption, number of customers, and total active power.

B. *Recap on the Impact of DERs on LVDNs*

In general, DERs can have multiple positive effects on distribution networks. These advantages of DERs can be technical, economical, and environmental [13, 14]. On the technical side, DERs can reduce the lines losses when it feeds local loads, improve the voltage profile due to less voltage drop on the lines, enhance the system reliability due to the redundancy of generator sets, and relieve the congestion of the transmission lines [15]. Economically, Distribution Generation (DG) can lower network improvement expenditures, lower fuel costs as a result of improved overall efficiency and reduce operational expenses as a result of peak shaving. Finally, renewable DERs can help reduce overall greenhouse gas emissions.

Despite the benefits of DERs, if proper planning and coordination between the various network components are not taken into account, they can have a significant negative impact on distribution networks. Furthermore, the intermittent nature of renewable DERs makes the network more prone to power quality violations. Some of the most notable impacts of DERs on the LVDNs are:

- Voltage Regulation: the increased integration of DERs into the distribution networks can lead to unwanted steady state voltage rise, fast voltage dips (flickers) and voltage imbalance [3]. Distribution networks were traditionally designed for unidirectional power flow, from generators to load through the transmission and distribution transformers and lines. However, with the advent of DERs and their expanding integration with the grid, bidirectional power flow has become more frequent in some parts of the network. Bidirectional power flow can adversely affect the power and distribution networks regarding voltage regulation and protection coordination [16].
- Reverse Power Flow: reverse power flow occurs when the DERs start injecting power upstream of the network because their generated power is greater than the local load. The reverse power flow has many impacts on the distribution and transmission networks such as increasing the voltage in LV and MV networks, increasing the losses in the LV network elements and overloading them, decreasing the life span of transformers [17], affecting the protection devices setting and causing false tripping [18].
- Thermal limits: all equipment in the distribution network has a certain amperage rating above which this equipment can be severely damaged. This is often referred to as the thermal capacity of an equipment. Thus, increasing the penetration of DERs in the LVDN can put some of this equipment at its thermal capacity limit. In general, the voltage rise and thermal capacity limits are considered the most limiting factors for more DERs integration into the grid [5].
- Harmonics: most DERs are highly reliant on switching power converters to interface the DERs with the network. These converters are necessary since DERs are producing power either in a different form such as dc as in photovoltaic (PV) systems or out of synchronization as in variable ac in wind power. Despite the sophistication of the power electronic-based converters, they are still a source of harmonic distortion in the network due to their switching nature. The converters can be viewed as a negative nonlinear load where it injects rich in harmonics current into the grid [19]. These higher frequency harmonics can interact with other equipment such as capacitor banks to produce resonance which can adversely affect the power quality in the network.

III. HOSTING CAPACITY TECHNIQUES USED IN THE INDUSTRY

From an industrial point of view, multiple methods were developed to perform HC analysis. These methods, however, should not be taken as separate categories of HC analysis, since the distinction was made upon the details behind the methods themselves rather than the common features. Some of the notable methods mentioned in the literature include:

- Stochastic [20]: it is one of the first methods used in the industry to evaluate the impacts of DERs integration on a feeder level. It starts by performing a baseline power flow study that can be the existing network without any DERs connected, or it can be as-built status where all existing DERs are added to the model. The size of DER systems, the maximum penetration level and the penetration increase step are all user-defined at the start of the study. In the next step, the algorithm starts adding DERs to randomly selected locations and performing a power flow study. Then, the size of the penetration level is incremented and the DER systems are randomly placed at each iteration. The stochastic method incorporates more realistic scenarios which consider many nodes at each simulation step. However, the scenarios can be in the order of 1000s for each study which makes the algorithm very time computationally expensive.

- Iterative [21]: in this method, the DER is deployed at a certain location at a time. At each location, the DER capacity is increased iteratively until violation issues start to occur. It does not consider DERs deployment at multiple nodes simultaneously. The iterative method is the most adopted method by many software tools and is accepted by many DNSPs due to its high accuracy and confidence in its results. In California, for example, the public utilities commission has made the decision to use the iterative method as the primary HC estimation technique and ruled out the streamlined method that was suggested by PG&E [22].
- Streamlined [23]: it performs a baseline simulation where its results are assessed under previously defined equations and algorithms that estimate the impact of DERs on the network. As suggested by the Pacific Gas and Electric Company (PG&E), an American electric utility, the streamlined method makes the hosting capacity analysis more efficient since it does not directly model the DERs performance. It is considered a high-speed technique where it takes minutes to execute the analysis. A big misconception in the literature is that the streamlined method was developed by EPRI. Whereas, it refers to the way HC is implemented using certain sets of equations and algorithms to evaluate the HC of DERs. However, the streamlined method in its basic form lacks the accuracy that other methods deliver. It is also a single-node technique where the results are node-specific which is similar to the iterative approach. For steady-state voltage rise, a suggested streamlined equation can be used to check for the export limit at a certain node:

$$HC(t) = \frac{V_{room}(V_{LL})^2}{RPF_{DER} + Xsin(cos^{-1}(PF_{DER}))} PF_{DER} \tag{1}$$

$$V_{room}(t) = \frac{Limit - V_{node}(t)}{V_{base}} \tag{2}$$

where V_{room} is the allowed voltage rise before hitting the upper limit of the voltage permissible values. X and R are the reactance and impedance of the network as seen from the node under investigation while all other nodes are at no load conditions. These values can be evaluated by performing a fault study at each node and getting the fault impedance. The only value that is needed at the beginning of performing the algorithm is to get $V_{node}(t)$ at the baseline status, then use this voltage profile to calculate the allowable voltage room at each instance.

Algorithm 1 Stochastic Method

```
Input: $PF \;||\; \delta_{PV} \;||\; \delta_N \;||\; PV_o \;||\; HC \;||\; PI = (0,0,...,0)_s$
Input: $Nodes = (N_1, N_2, ..., N_n)$
  % $\delta_n$: the increment of nodes with PV systems
  % $PI$: max performance index value for each scenario across all nodes
  % $HC$: the PV hosting capacity for the whole network
  $k = 0$
  while $k < N$ do
    $L = Random(Nodes, k)$ %Choosing $k$ random nodes
    $PV = PVo \rightarrow L$
    while $PV < PV_{max}$ do
      $PF$
      $PI(s) = max(PI)$ %Saving the maximum PI for this scenario
      $PV = PV + \delta PV$
    end while
    $k = k + \delta_n$
  end while
  $HC = max(PV)\ Given\ PI < PI_{max}$
  print $HC$ %Print the final HC for the whole network
```

Algorithm 2 Iterative Method

```
Input: $PF \;||\; \delta_{PV} \;||\; PV_o \;||\; PI \;||\; HC = (0,0,...)_n \;||\; CN \;||\; NN$
  % $PF$: the power flow solver (load flow software API)
  % $\delta_{PV}$: the increment of PV system size (in kW)
  % $PV_o$: the initial PV system size (in kW)
  % $PI$: performance index (voltage, thermal limit ... etc)
  % $HC$: the PV hosting capacity for each node (in kW)
  % $CN$: pointer for the current node
  % $NN$: pointer for the next node
  $CN \rightarrow 1^{st}\ Node$
  $NN \rightarrow 2^{nd}\ Node$
  while $CN \neq NN$ do
    $HC(1) = 0$
    $PV = PVo \rightarrow CN$ %Assign a PV system to the current node
    while $PI < PI_{max}$ do
      $PV = PV + \delta PV$
      $PF$ %Solve the network model
    end while
    $HC(1) = PV$
    $CN \rightarrow NN$
    $NN \rightarrow NN + 1$
  end while
  print $HC$ %Print the final HC values for each node
```

Algorithm 3 Streamlined Method

```
Input: $PF \;||\; \delta_{PV} \;||\; PV_o \;||\; PI \;||\; HC = (0,0,...)_n \;||\; CN \;||\; NN|| \; SL$
  % $SL$: streamlined equations or model
  $CN \rightarrow 1^{st}\ Node$
  $NN \rightarrow 2^{nd}\ Node$
  $PF$ %Solve the network model outside the loop
  while $CN \neq NN$ do
    $HC(1) = 0$
    $PV = PVo \rightarrow CN$ %Assign a PV system to the current node
    while $PI < PI_{max}$ do
      $SL$
      $PV = PV + \delta PV$
    end while
    $HC(1) = PV$
    $CN \rightarrow NN$
    $NN \rightarrow NN + 1$
  end while
  print $HC$ %Print the final HC values for each node
```

IV. CASE STUDY

In order to test the aforementioned methods, the algorithms were applied to a case study that represents a typical low-voltage network. In this study, the European low-voltage test feeder is constructed to do the analysis. The feeder, as shown in Fig. 1, consists of 55 loads connected at the enumerated nodes. The feeder is fed through an 11/0.416 kV transformer at 50 Hz. The loads are assumed to be single-phased throughout the analysis. The average X/R ratio in this feeder is 0.328, which is expected for a low-voltage network where the resistive part of the distribution lines is dominant. OpenDSS was used to model the network and run power flow simulations. The hosting capacity techniques were scripted in Python and OpenDSS COM was used to interface the script with OpenDSS.

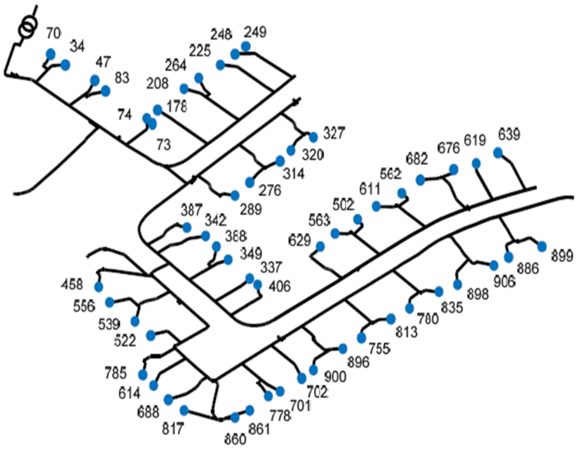

Fig. 1. European low voltage test feeder single line diagram.

The loads have been considered as 24-hour time series profiles. Multiple profiles have been used and randomly assigned to the respective nodes. A sample of these profiles can be seen in Fig. 2. The power factor has been fixed at 0.95 lagging for all loads.

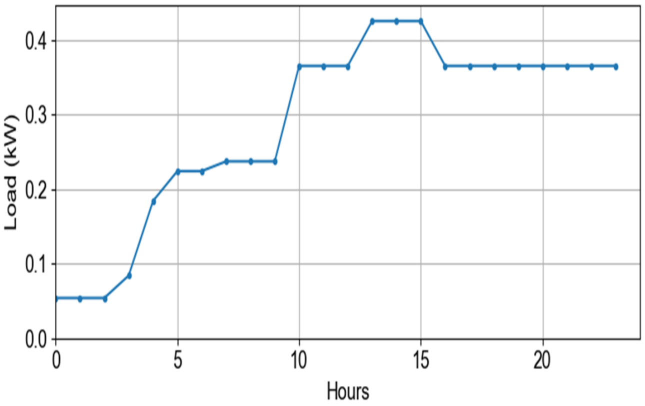

Fig. 2. Time series daily load profile.

Also, only one type of DERs has been considered in this study which is PV systems. The deployed PV systems are three-phase generators that are dependent on the irradiance value at a certain time instant. The daily profile of the irradiance is shown in Fig. 3, where it is the same for all deployed PV systems. However, the total capacity of the PV systems is left for the algorithms to decide as demonstrated in the previous section. The power factor is fixed at unity for all considered scenarios. To apply the method, the performance index has to be decided. In this study, the relevant performance index was chosen to be the voltage rise at the load nodes where the limit is set at ±10% above the standard value i.e. 1 p.u.

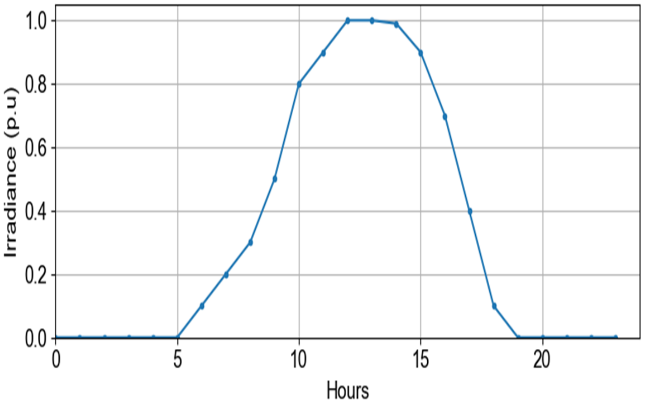

Fig. 3. Time series daily irradiance profile.

Starting with the first algorithm, the iterative method was implemented, and the results, shown in Fig. 4, capture the HC capacity for each node independent of the other nodes. This is what is meant by node-specific results, where the value of HC is only valid when the installation of the related DER is only implemented at that node. It can also be seen that the HC value is greater at nodes that are closest to the transformer. This is well expected since it takes a higher current to cause voltage rise long the short connecting line between the load and the transformer. Consequently, the farther the DER is located from the feeder the lower its HC limit will be. The stochastic method, on the other hand, depends on scenarios where multiple deployments of DERs take place at the same time. Fig. 5 depicts how the increasing total installed capacity across different nodes approaches the network operation from breaching the performance index which is voltage in this case. Here, the voltage considered in the figure is the maximum voltage found at the nodes with connected PV. The most important feature of this method is it mimics a real scenario where multiple PV systems are expected at different nodes. This is also referred to as inter-node HC results.

Similar to the iterative method, the suggested streamlined method is also node-specific in terms of the results. However, it is well evident that it is less accurate than the iterative method. That being said, the streamlined method's most important advantage is its speed of processing. The processing time for

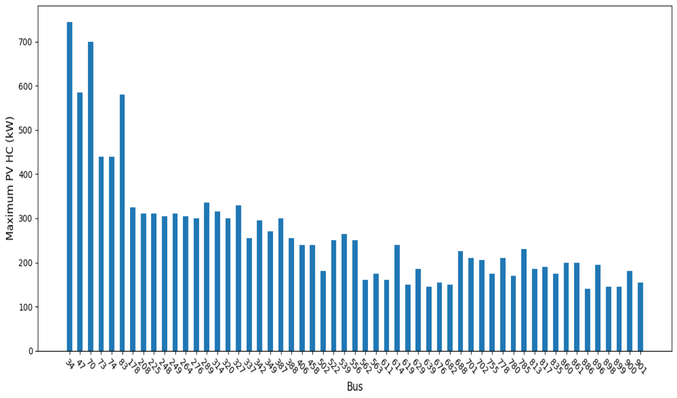

Fig. 4. The iterative hosting capacity results in (kW) for each node.

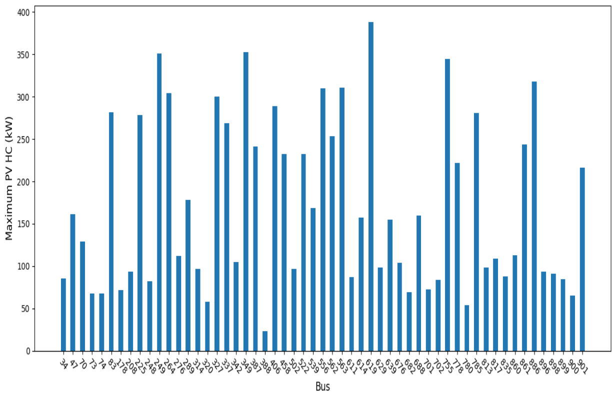

Fig. 6. The streamlined hosting capacity results in (kW) for each node.

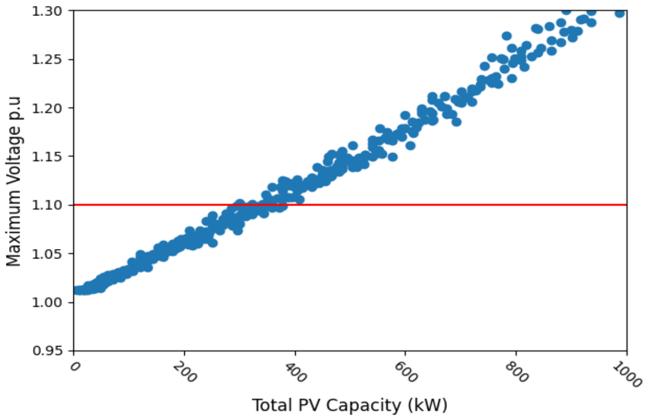

Fig. 5. The stochastic hosting capacity estimation in (kw) for the whole network.

TABLE I
QUALITATIVE COMPARISON BETWEEN THE THREE METHODS OF HC ESTIMATION

HC Method	**Characteristics**		
	Accuracy	***Processing Time***	***Results***
Iterative	High	High (50 sec)	Node Specific
Stochastic	Medium	High (15 sec)	Inter Node
Streamlined	Low	Low (0.035 sec)	Node Specific

the streamlined method is remarkably lower than the other two methods. Hence, if this method was further modified to increase its accuracy while preserving its computing efficiency would be an interesting research gap to be investigated. The complete comparison between the three methods in terms of processing requirements is found in Table. 1.

From the simulation results and comparison, it is clear how the currently used hosting capacity techniques in the industry may need further research and development to fast-track the simulation without compromising accuracy. Till now, most attempts to increase the computational efficiency of hosting capacity calculations have been faced with a huge decrease in the accuracy of the results. Moreover, the interpretation of the distinct results between iterative and stochastic methods requires any newly developed methods to combine the node-specific and inter-node results into their estimation reports.

V. CONCLUSION

In this paper, three main techniques of hosting capacity analysis have been reviewed and evaluated. It was found that the iterative method has the highest accuracy due to the power flow calculations done at a specific node each time. While the streamlined approach possesses the lowest processing time. The iterative and stochastic methods are well-known and established in the industry. However, their results are interpreted in completely two different ways. While the iterative methods are node-specific in terms of the results, the stochastic methods are inter-node. The node-specific results are useful for interconnection studies where it is needed to know the maximum amount of DER that can be connected to a certain node. The inter-node results, on the other hand, are quite useful for LVDNs that allow the installation of DERs at multiple nodes, which is the case with roof-top residential PV systems. Finally, the previous two methods' main disadvantage is their heavy computing burden. This is expected to be solved by utilising a streamlined approach. However, streamlined methods still need development to satisfy the minimum accuracy thresholds.

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