Hosting Capacity Analysis: A Review and A New Evaluation Method in Case of Parameters Uncertainty and Multi-Generator

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***Abstract*—The rapid growth of distributed energy resources exploitation can cause voltage violations and overloading on distribution grids due to the uncontrolled and unprogrammable power injections associated with dispersed generators. To overcome these issues, distributed system operators have to evaluate the maximum generation that can be hosted by distribution grids without violating the technical constraints and find the ways to increase it. In this paper, different methodologies for hosting capacity evaluation are reviewed, and a novel model to determine the hosting capacity considering grid parameters uncertainties and multi-generator connection is proposed.**

***Index Terms*—hosting capacity; dispersed generation; hosting capacity increasing; bricks approach; multi-generator.**

I. Introduction

The increasing penetration of Dispersed Generation (DG), mainly based on Renewable Energy Sources (RES) on both Low and Medium Voltage (LV-MV) levels, gives challenges in the modeling and operation of distribution grids. Low greenhouse gas emissions, better sustainability and less maintenance strongly motivates the instalation of DGs, but the massive DG connection and its uncontrolled and unprogrammable power injections may cause power quality and reliability issues (e.g. voltage profile and conductors' ampacity problems, harmonics, unwanted island phenomena, etc.), due to neglecting the actual distribution grid power needs, and consequently it may require new interventions on the grid to improve its ability to accept local generation without incurring in technical problems [1]–[4]. However, at operational level, efforts are made to turn the distribution grids into smart grids in order to achieve an optimal real-time managment of these resources [5]–[7].

Since a proper management of DGs is vital, strong research activities based on statistical, deterministic and heuristic approaches have been done in order to ensure that, with a given amount of DG connected to the distribution grid, the network is still working within the admitted operational ranges imposed by technical standards and regulatory agencies [8], [9]. Although grid regulations do not allow Distributed System Operator (DSO) to refuse any request of DG connection [10], the goal of many research works is determining the optimal DG sizing and siting [11], [12], but these studies have a scarce applicability in real-life. In this regard, evaluation of the maximum generation that can be hosted by the distribution grid without violating the grid constraints is one of the main performance indicators that should be considered for planning and operation of the grid. This indicator is commonly known as $Hosting\ Capacity\ (HC)$.

Generaly, power system performance is affected by changes in the generation and load patterns. Hence, the HC is defined by an algorithm which determines the amount of acceptable DG without endangering the grid power quality and reliability with respect to some limits, i.e. steady-state voltage limits, transformer and lines thermal limits and fast voltage variations [1], [13]–[15]. The proposed approaches in the literature are mainly based on iterative calculations, aiming at estimating the maximum DG penetration admitted in every bus according to the considered technical limits; the HC is evaluated for a single constraint at each time and the overall HC is defined as the minimum HC over all the constraints. Hereinafter, this index will be referred as "$Nodal\ HC\ (NHC)$". Although NHC gives us a right view of the power injection admitted in each node of the grid, it does not asses the impact of DG units installed in different nodes of the network on its operational parameters, as usually occurs in real life scenarios [16]. Thus, evaluating "$Multi\ Generator\ HC\ (MGHC)$" is inevitable in distribution grids. This is an up-to-date approach and very few works could be found in literature in such a direction.

The aim of this paper is reviewing the literature of different HC evaluation research works, as none of them cover all the HC topics and the ways to increase it. Moreover, it proposes a novel model to evaluate HC in case of grid parameters uncertainties. To do so, a literature overview with a span of one decade from 2007 until 2018 has been carried out using IEEE/IET/Elsevier and thesis databases. The structure of this paper is as follows: section II represents HC methodology, and section III is devoted to increasing HC approaches. The proposed approaches and its results have been explained in section IV. At the end, section V concludes this study.

II. Hosting Capacity Methodology

The Hosting Capacity is the amount of new production that can be connected to the grid in a specific location or over a given area without exceeding the technical limits of

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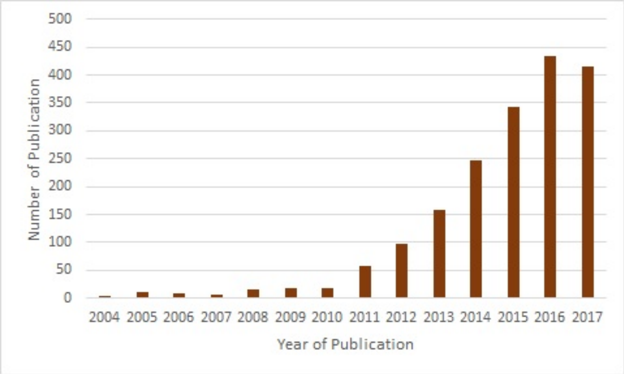

Fig. 1. Number of publication using term "Hosting Capacity".

the network during operation. The HC method was originally discussed as part of EU-DEEP project by STRI in 2004 [1], [17]–[19]. The histogram of Fig. 1 depicts the number of publications per year using the exact term "$Hosting\ Capacity$"; the histogram covers the years from 2004 until 2017 and was plotted using the data available on Google Scholar.

Typically, in literature the HC approach is presented as shown in Fig. 2 [20]. The amount of HC is defined when the blue curve is going to violate the red dashed line, representing the system limits, as better detailed in the following: 1) choose one or more suitable performance indicators (e.g. voltage or current amplitude); 2) define appropriate limits; 3) compute the performance indicators as a function of generation; 4) obtain HC with the highest amount of generation where none of the performance indicators violate their admitted thresholds [21].

Estimating the NHC for LV Italian grid with iterative calculations (1 kW step) has been studied in [22]: the NHC is evaluated considering a single constraint at each time and assuming the overall HC as the minimum HC obtained for all the constraints. The paper concludes that the maximum HC is observed near HV/MV substations. Moreover, the rural networks have a limited HC compared to urban networks, due to the limited cross sections and long length of their lines. Different softwares for performing Power Flow (PF) have been used by researchers, e.g. a NHC evaluation has been discussed for 73-node and 19-node Jordanian network grid with high (X/R) ratio in [23] using Newton-raphson in MATPOWER. Paper [24] calculates NHC using the software SimPow for a distribution grid at the centre of Sweden. MATPOWER and

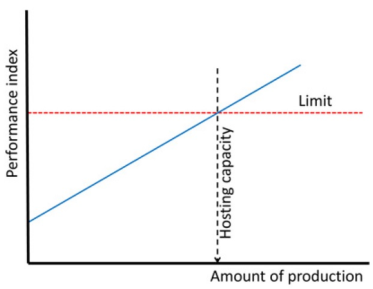

Fig. 2. Basic description of HC.

MADGTPOWER for nonlinear numerical methodes have been used in [25] for NHC estimation. Eventually, Swedish regional distribution grid in [13] used commercially available power system simulation software for assessing NHC.

In order to define the possible injection into the grid by DGs, it is very important to choose suitable performance indicators including directly related (such as upper bound and lower bound of RMS voltage) or indirect ones (such as transformer thermal limits) [21]. Typically, researchers consider the main technical constraints such as Steady State Voltage Variations (SSV), thermal limits and Rapid Voltage Change (RVC) [3], [13], [22]–[29]. In [13], the most limiting factor for the HC are the overcurrents. The authors in [26] mentioned that the factors limiting the HC depend on the type of network and its voltage level. In weak MV networks (i.e. characterized by long lines), the voltage rise is usually the main limiting factor, while in stronger networks (e.g. urban grids) the feeder and transformer overloading are the main limiting factors. In [30] author uses an exhaustive method to evaluate the NHC considering voltage levels and conductor's current flows as technical constraints. For each node at each time a defined maximum value of HC is selected and a PF is performed to check the compliance of voltage and current constraints; in case of violation, HC is reduced via bisection method until a viable value is found. Since the dynamic behavior of background distortion (e.g. harmonics) may change HC, the harmonic distortion phenomenon has been considered as the technical constraint in [31], in order to have a more efficient distributed generation planning.

Solving optimization problems to obtain HC has been considered in some research papers [29], [32]–[34]. A novel Optimal Power Flow (OPF) with the objective of maximizing the nodal loading parameters to evaluate NHC and to define the DG control rules has been proposed in [29], [32]. The authors of these papers conclude that the maximum HC is obtained at the location where the feeder is most loaded. The more distant from the MV Primary Substation (PS), less increase of HC occurs, since the nodes at the end of the feeder experience severe problems of undervoltage. The authors in [33] mentioned that the best location for connecting a DG unit is close to the load center and two optimization models using Primal-dual interior-point method to calculate and optimize the voltage profile and line losses have been proposed. The objective functions in [34] are the energy purchased and the operation and maintenance cost of a wind farm; the problem is solved by NSGA-II algorithm. In this paper, the network parameters uncertainty has been considered as input and a two-stage stochastic method has been used in order to make decisions under uncertainty.

The stochastic nature of the loads and generation and DG location has been considered in [35] where Monte Carlo simulation was used. Probabilistic PF may be more adequate compared to Deterministic PF, because of the realistic representation of the inputs and the probabilistic margins obtained with respect to the technical constraints violation. In [36], probabilistic load modeling and costumer's hourly power request probability have been considered. Then, the probability density function of each technical constraints for DGs has been estimated by Monte Carlo simulation. The Swedish distribution grid in [37] has been divided into rural, residential and city areas; Monte Carlo has been used in this study to assess the probability of the technical constraints at different voltage levels. A LV Slovenian distribution network has been modeled in [38] using statistical Monte Carlo simulation. In this study, the probability of voltage violation with respect to installed PV capacity is evaluated. A probabilistic method has been proposed in [39] for assessing the impact of Low Carbon Technologies in LV networks considering network parameters uncertainty. This work highlights that the Cumulative Density Functions for each feeder could show to DSO the customers with high probability to cause voltage or thermal problems.

The authors of [14] proposed an approach to consider the "$equivalent$" maximum injection to the generators downstream the bus under examination. This method is useful for considering MGHC where the total injection is equal to the equivalent generator.

III. Hosting Capacity Increasing

For planning issues it is a major concern to evaluate the upper limit of total RES injection to the grid and the ways to increase it without reinforcement. In the following, HC increasing approaches are detailed.

A. Voltage Control

Local voltage control by using local information allows to increase HC; it is also called decentralized method. The local voltage control may be performed by the regulatory of on load tap changer (OLTC) in Primary Substation (PS) and the Power Factor Control (PFC) of DG.

The voltage set-point of MV bus-bar at PS could be controlled by OLTC through offline OPF [40]. The authors in [41] have compared a real network case study with no OLTC, five tap position on OLTC and nine tap position on OLTC. The results show that HC could be increased more than 50% in 16% of the analised scenarios and more than 100% in about 3%. Moreover, no significant difference between 5 and 9 tap position has been reported, meaning that the OLTC HC impact neighter depends on the size of network, nor the level of loading. In [42] different modern control schemes are discussed including Enhanced Transformer Automatic Paralleling Package (TAPP) and super TAPP n+ relay, to reduce the circulating current between transformers and to estimate the RES output current respectively. In [43] state estimation approach is suggested for OLTC controlling.

DG injections cause voltage rise in the MV feeders and PFC could control the system's voltage by increasing the HC of the distribution grid. In [44]–[47], Static compensators (STATCOM), D-STATCOM, static VAR compensators (SVC), fixed capacitor banks and shunt capacitor banks have been investigated as generator compensators to regulate the voltage. Four different local control schemes are discussed in [6], [48], [49]. These schemes have been modified according to European technical standards, as listed in the following: $LawA$) control of tangent of ϕ according to the PCC voltage ($\tan\phi = f(u)$); $LawB$) control of reactive power according to the PCC voltage ($q = f(u)$); $LawC$) control of tangent of ϕ according to the real power injected ($\tan\phi = f(p)$); $LawD$) control of reactive power according to the real power injected ($q = f(p)$).

B. Network Reconfiguration

In [50] network reconfiguration is used for HC increasing by multi period optimal power flow. The proposed method in this paper, first solves the problem for periods with worst case scenarios, the resulting configuration is then assessed for the remaining time periods to check if it complies with the given constraints. The authors in [51], [52] purposed Genetic Algorithm (GA) based network reconfiguration to maximize HC at selected nodes. In this paper objective function is built to penalize network configurations leading to overloads of distribution lines and over or under voltages at buses. For a given network configuration, the fitness function is obtained by considering both the maximum allowed power supplied by DG sources and the exploitation of the lines together with the bus voltage profiles. Uniform Voltage Distribution Algorithm (UVDA) based constructive reconfiguration is used as heuristic in [53], [54]. Objective of the problem is to reconfigure the network and DG sizing to maximize network power loss reduction and HC. Particle Swarm Optimization (PSO) technique is used to find the best solution of the proposed multi-objective problem.

C. RES Curtailment

Active power curtailment was studied in some papers and is also finding its ways into national regulatory framework. RES curtailment includes decreasing the output power of specific resources which exceed the HC limitations [13]. Another major advantage of RES curtailment is preventing inverters disconnection due to overvoltage tripping. In [55] two methods are compared for active power limitation: fixed percentage of the nominal power and VoltWatt control where the active power depends on voltage. The results show that fixed curtailment has better performance compare to that VoltWatt control. In [56], optimal setting of DG curtailment based on multi-period OPF has been investigated for economic benefits.

IV. The proposed Approach

The novelty of the method proposed in this paper consists in the definition of a model easy to manage and which can be applied to generic network structures without losing the accuracy of results. This model is used to perform a set of PF computations aimed to evaluate the HC with respect to Steady State Voltage Variations (SSV), Rapid Voltage Change (RVC) and thermal limits of transformers and lines.

A. Modeling of Distribution Grid

1) Nodal Hosting Capacity: As already mentioned, HC is impacted by the topology of the grid, by its parameters

TABLE I
BRICKS APPROACH COMPONENTS.

Components	Remarks
Feeders	Feeders are categorized according to their impedance characteristic into three groups: Short Feeder, Medium Feeder and Long Feeder. The feeders characteristic mean value in each category is considered as the main characteristic of the Bricks approach feeders.
Collaterals	Collaterals are divided into two groups: Short Collateral and Long Collateral. Short feeders can only have a short collateral.
Nodes	Basically, the HC is higher at the beginning of the feeder close to the primary substation, whereas it decreases to the end and collaterals. Therefore, three critical nodes in each feeder, at the 10%, 50% and 90% of the total amount of feeders impedance, and two significant nodes in each collateral, at its middle and at its end are considered. Figure 3 shows the defined nodes.
Loads	Loads are divided into three groups: the yearly minimum value, the mean value and the peak value with power factor of 0.9.
Generators	A generator is added to each defined-node, then the injected power to the grid is changed in the simulation to evaluate the HC. Thanks to the proposed approach, in order to evaluate a general network topology a number of grid configurations equal to 10449 (ex. For long feeder and long collateral at its end, 3 combinations of load for each 5 nodes and 5 combinations of placing DG which represents 1215 combinations) needs to be assessed through PF computations. Actually, MV distribution grids could have hundreds of nodes, in order to evaluate their HC in different working conditions (e.g. sampling a calendar year hourly) a significant higher number of PF computations would be required.
Load Flow Calculation	HC evaluation is based on bisectional method by root-finding behavior, the load flow iteration will continue until its convergence.

and also by load and generation power profiles; moreover, its evaluation requires a complete network model which results in a quite heavy data set which is therefore difficult to managed. In practical terms, the DSOs could not have easy access to all the required data. Thus, a novel approach is proposed for the distribution grid modeling, namely Bricks approach.

Actually, the standard structure of distribution grids comprises of a main feeder starting from MV busbars in PS, to which many branches, typically named collaterals, connected to it. A mathematical model has been developed in order to represent the grid network with a conventional approach, so to evaluate the HC in a shorter time and in a practical way. The new method is based on the assumption that HC on one feeder is marginally affected by the behavior of other feeders. Moreover, in order to limit the computational effort of the study, the grid is modeled in a simplified way, i.e. is modeled as an aggregation of "bricks", each one representing a portion of the grid which can be added, removed and replaced stochastically to evaluate all the possible configurations of the grid structure. In addition, only the critical nodes of the grid (i.e. the busses actually representative of the network's behavior) are assessed by the Bricks approach. Table I represents the grid model adopted in the Bricks approach [57].

2) Multi-Generator Hosting Capacity: In real life, by increasing the number of renewable energy integration at the same time many DG are connecting to the grid which affects other DGs and the grid [16]. The procedure developed in this research takes into account that DGs could be connected to the grid through different plants of different size and connected to various nodes. To evaluate if the distribution grid can host this capacity or if its installation will compromise the performances of the grid, a stochastic approach has been adopted, in particular Monte Carlo simulation is exploited in order to properly consider all the variables.

Once Monte Carlo scenarios are created, the hourly PF computation is carried out considering defined technical constraints. By performing PF computation, system power losses, maximum voltage and maximum current of the grid is calculated. The Monte Carlo procedure is based on an iterative behavior which (1) and (2) represent the convergence criterion which is used in this study. μ_{Loss} and σ_{Loss} are the losses mean value, and the losses standard deviation respectively. The variation of these two value should be placed lower than ϵ.

$$|\frac{\mu_{Loss}(i) - \mu_{Loss}(i-1)}{\mu_{Loss}(i-1)}| < \epsilon_{\mu} \tag{1}$$

$$|\frac{\sigma_{Loss}(i) - \sigma_{Loss}(i-1)}{\sigma_{Loss}(i-1)}| < \epsilon_{\sigma} \tag{2}$$

When Monte Carlo simulation for a specific capacity stops, total number of scenarios and the number of scenario which violated each technical constraint can be assessed. Hence, Hosting Capacity Violation Probability (HCVP) through equation 3 can be evaluated which the acceptable probability

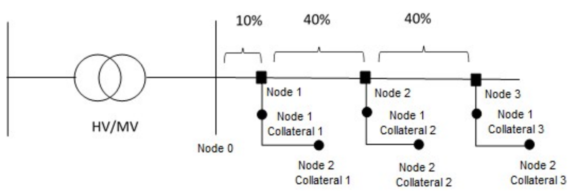

Fig. 3. Long feeder with three long collateral and its define nodes.

to violate the limit such as many stochastic approaches is considered 5%.

$$HCVP = \frac{Total\ no.\ of\ scenario}{No.\ of\ scenario\ violate\ each\ constraint} \quad (3)$$

B. Validation of the Proposed Approach

The formulated approach is applied to the MV network of Aosta city in north of Italy, departing from the Ponte Pietra PS that is located in the East of the city. The Aosta grid is supplied by two 25 kVA transformers 132/15 kV, and is composed by 16 main feeders with an overall of 486 nodes; 9 feeders are connected to one transformer, and the other 7 are connected to the second one.

Fig. 4 represents the error of the Bricks approach in evaluating the HC. From the mentioned results, Bricks approach error did not go beyond 0.03 pu., which can be a proof of promising results. Moreover, computation time for Bricks approach was 5 minutes and 37 seconds, whereas for Real-Grid approach it was 92 hours and 43 minutes and 86 seconds.

In addition, Fig. 5 shows the HCVP for this grid according to defined technical constraints. From this picture, it is obvious thermal limits its a dominant constraint in this grid and the total HC is less than 10 MW.

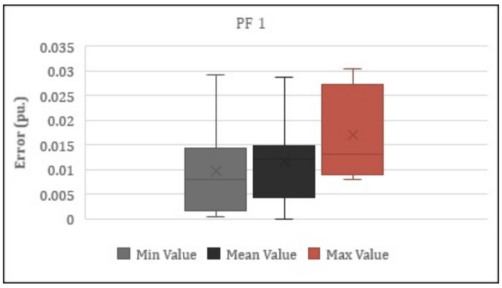

Fig. 4. Errors in HC evaluation adopting the Bricks model.

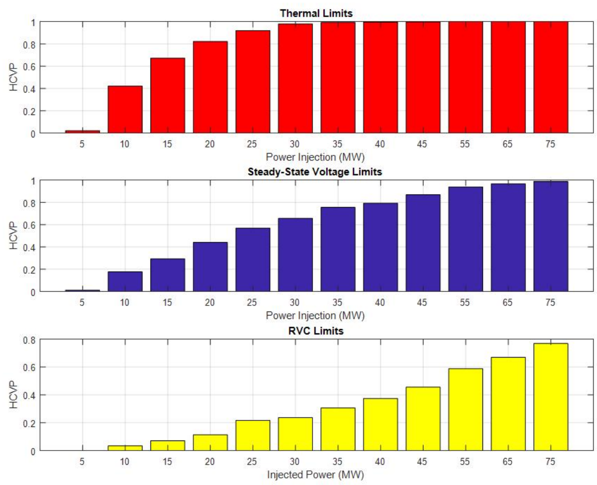

Fig. 5. HCVP of Aosta grid for each technical constraints.

V. Conclusion

Increasing penetration of distributed energy resources in distribution network needs active network management as it could cause system voltage violations and overloading. Hence, nowadays evaluating the maximum hosted generation by distribution grid (Hosting Capacity) is vital for distribution system operators. This paper reviewed the different hosting capacity analysis and the different ways to increase it. At the end, a new effective computative method to evaluate the hosting capacity in case of grid parameter uncertainties and multi-generator connection was proposed.

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