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Review

State-of-the-art of hosting capacity in modern power systems with distributed generation

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A B S T R A C T

Currently, renewable energy is rapidly developing across the world in response to technical, economic and environmental developments, as well as political and social initiatives. On the other hand, excessive penetration of distributed generation (DG) systems into electrical networks may lead to various problems and operational limit violations, such as over and under voltages, excessive line losses, overloading of transformers and feeders, protection failure and high harmonic distortion levels exceeding the limits of international standards. These problems occur when the system exceeds its hosting capacity (HC) limit. The HC is a transactive approach that provides a way for the distribution network to be integrated with different types of energy systems. Accordingly, HC assessment and enhancements become an essential target for both distribution system operators and DG investors. This paper provides, for the first time, a systematic and extensive overview of the HC research, developments, assessment techniques and enhancement technologies. The paper consists of four HC principal sections: historical developments, performance limits, perceptions and enhancement techniques. Besides, practical experiences of system operators, energy markets and outcomes gained from real case studies are presented and discussed. It was concluded that success in integrating more distributed generation hinges on accurate hosting capacity assessment.

Contents

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Abbreviations

ADN	Active distribution networks
BESS	Battery energy storage system
CHP	Combined heat and power cogeneration
DER	Distributed energy resources
DG	Distributed generation
DSO	Distribution system operator
EPRI	Electric power research institute
EV	Electrical vehicle
HC	Hosting capacity
HPR	Harmonics penetration ratio
HV	High voltage
LV	Low voltage
MC	Monte Carlo simulation
MV	Medium voltage
OLTC	On-load tap changer
PCC	Point of common coupling
PV	Photo-voltaic
RVC	Rapid voltage changes
SM	Smart metering
SVC	Static VAr compensator
SSVV	Steady state voltage variations
STATCOM	Static compensator

Nomenclature

ΔV_{drop}	Voltage drop at the base case of the system (no DG)
ΔV_{rise}	Voltage rise at maximum DG penetration
P_{DG}	Active power of the DG
P_{load}	Active power demand of the load
S_{load}	Apparent power of the load
F_d	Distribution factor
N_a, N_b, N_c	Number of DG units connected to phase a, b and c respectively
N_{tot}	Total number of DG units connected to all phases
P, Q	Active and reactive power respectively
R, X	Line resistance and reactance respectively
V_n	Nominal voltage of the system
P_{DG}^{nl}	Maximum allowable DG capacity under non-sinusoidal conditions
P_{DG}^{l}	Maximum allowable DG capacity under sinusoidal conditions

Terminology

Absorption capacity	The maximum DG capacity that can be installed without having to reinforce any segment of the distribution system
DG Penetration	The amount of DG that is being integrated into the distribution system. Penetration concept looks from the DG side. Penetration is considered as a DG oriented term
Hosting Capacity (HC)	The amount of distributed generation, integrated into the power system, above which the system performance becomes unacceptable. HC is considered as a power system oriented term
HC Coefficient (HCC)	Defines the ratio between the curtailed energy and the installed capacity above the initial HC. HCC can also be used to compare various schemes for active power curtailment
HC maps	HC maps are produced on the geographical feeder routing layouts and network singe line diagrams. These maps indicate how HC varies at each bus or feeder segment by using appropriate color coding. Many important observations could be obtained from these maps such as loading percentage of each feeder segment, HC of the various feeder segments, and the feeder segments that suffer from limits' violation
HC uncertainty	Uncertainty in the assessment of HC arises due to many aspects such as lack of confirmed real-time system when performing the power system calculations, the intermittent nature of the DG output power, uncertain DG integration location, uncertain DG rating, and variations loading profiles. Accordingly, HC will not be a single value, but multiple values will be introduced according to the uncertainty degree examined. Many related terms were proposed in the literature to consider these uncertainties such as Probabilistic HC (PHC) and Stochastic HC (SHC)
Locational HC (LHC)	Hosting of new DG's in some locations can be accepted, while in other locations, same DG's cannot be hosted. Thus, the HC is considered as a location-dependent concept. HC maps can be utilized to visualize the LHC results
Active power curtailment	Shedding or reducing the generated electrical power from DG units, usually used in case of exceeding the system HC
Prosumer	A recently-developed term which defines the electrical user that consumes and produces electricity
Streamlined HC (SLHC)	SLHC was developed by EPRI to provide a tool to evaluate the HC on a system-wide basis with lower computational efforts and time. The SLHC approach is not a replacement to the conventional detailed HC studies but it provides quick simplified screens which assist the DSO to decide if they need to perform further detailed studies or not

1. Introduction

In the past, distribution systems were distinguished by the unidirectional power flow from centralized power generation stations to transmission and distribution networks. Nowadays, the deployment of DG technologies such as photovoltaic (PV) and wind energy resources in electrical power systems changed the conventional power flow directions. The evolution of the renewable DG technologies has been driven by political, social, economic, technical and environmental goals [1–6]. However, excessive DG penetration may negatively impact the performance of the system and may lead to serious overvoltage problems, thermal overloading of network equipment, increased risk of exceeding equipment short circuit capacity and maloperation of protection equipment [7–12]. Therefore, it is important to evaluate the system capacity to host these newcomers (DG's) without exceeding the operational performance limits of the system.

In deregulated energy markets, a conflict of interest has been found among the DG owners/investors and distribution system operators (DSOs), as the DG investors are looking forward to more and more DG integration into electrical networks, while DSOs are concerned about excessive DG penetration problems.

To resolve this conflict, a fair and transparent solution was needed to clearly decide when to accept or to reject new DG integration requests. Thus, the HC concept was proposed. Historically, the HC idea was proposed by André Even then in 2011 the concept was clearly refined by Math Bollen et al. [14]. HC as a terminology was not previously used in electrical applications. However, it has been used in other domains, such as the computer sciences, where it is used to define the capacity of a web server to host many incoming access requests. In electric power system applications, similar terms were proposed such as the absorption capacity [15], which is the maximum PV capacity that can be installed without having to reinforce any segment of the distribution system. However, this term was generic and not measurable. Later, Stetz et al. [15] moved to the HC concept in their work [16,17]. The great benefit of the HC concept is the ease of use of clear performance indicators/limits as assessment criteria for the DG penetration, which makes the HC concept specific, measurable and practical.

An extensive literature review over the past fourteen years reveals that there is no significant systematic research that provides an overview and joins the principal categories of the HC concept such as the assessment and enhancement technologies. To address this gap, we provided this needed overview. We also focused on different goals, such as providing an extensive literature review of the HC concept and its developments, defining the main HC performance limits, presenting the HC assessment procedure and demonstrating the HC enhancement techniques. In addition, practical experiences of system operators, energy markets and outcomes gained from real case studies are presented and discussed.

The literature review was based on many databases, such as IEEE Xplore, ScienceDirect and Google Scholar. The keywords used were high DG penetration impacts, hosting capacity of electrical network, hosting capacity limits and hosting capacity enhancement. Over 140 publications were chosen from these databases and only the articles written in the English language were considered. The research performed in this paper has considered a time span starting from the concept creation in 2004 until the present time. This literature was organized in chronological order according to the year of publication, and a systematic review was performed.

2. Hosting capacity basics and historical developments

The HC idea was primarily originated in 2004. Bollen et al. [18] introduced the HC approach in 2005 for specifying the impacts of increasing DER penetration on power systems. The basis of this approach was to gather the technical limitations imposed by both system operators and customers. The authors defined the HC as the maximum DER penetration at which the power system operates satisfactorily. The HC calculation is not a fixed calculation with a single result. Thus, it should be calculated for various performance indices such as voltage and frequency variations, thermal overload, power quality and protection problems. Deuse et al. [19] described the methodology presented in the European Distributed Energy Partnership project (EU-DEEP) to assess the integration of DERs in the European distribution systems for a 10-year time span (2010–2020). The project focused on the DERs that are connected on MV or LV distribution networks with rating 10 MW and below and the idea of the HC concept was initiated during this project. In Bollen and Hassan [14], the HC is defined as the maximum amount of DG units that can be integrated into the power system at which point the system performance becomes unacceptable above this amount of penetration. The HC calculation criterion is described while focusing on the performance index upon which it has been calculated using illustrative power system models.

The HC concept is illustrated in Fig. 1 and it is clear that enhancing the system's HC may allow for more DG additions while complying with the system's performance limits.

Walla [20] discussed the hosted PV capacities in Swedish distribution networks using the HC concept while identifying the challenges related to high PV penetration. Simulation, modeling and calculation of HC for three distribution grids are presented. It was concluded that the overvoltage is the main performance limit for HC calculations. Also, it was found that reactive power control and adjustments of transformer tap changers can be useful techniques for increasing the HC and overcoming the overvoltage problems. Papathanassiou et al. [21] presented the outcomes of the CIGRÉ working group (C6-24) on the HC of distribution feeders. The performance limits that could reduce the system's ability to host new DG sources were studied. Table 1 presents an executive summary for the experiences gained by international DSOs and their rules of thumb for DG interconnections and preliminary HC assessments [21].

Etherden [22] examined the increase of HC using active power curtailment, energy storage, and communication systems while focusing on both theoretical and practical aspects of the HC problem. A practical case study for a smart grid research project that considered the integration of battery storage systems into a MV

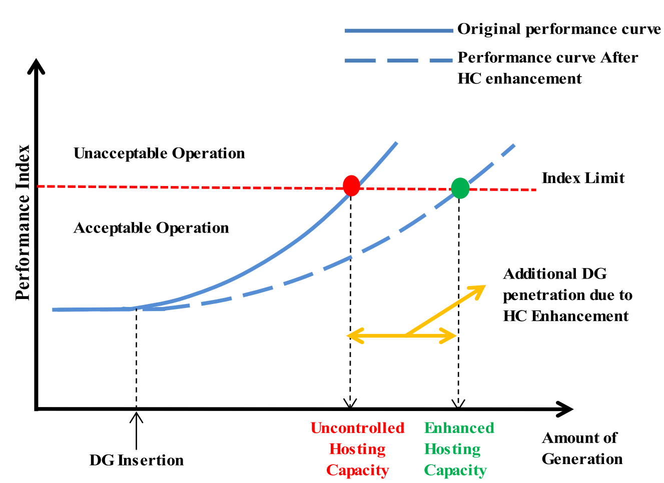


Fig. 1. HC concept and the effect of its enhancement.

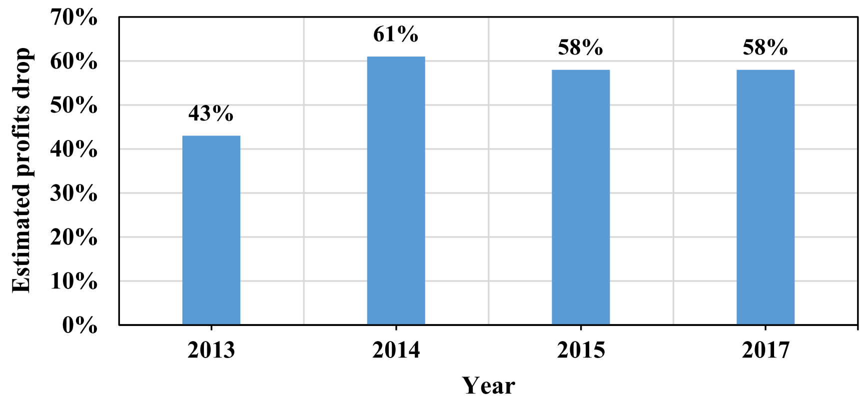
Table 1
International DSOs experiences and rules of thumb for DG interconnections.

Country	DSOs practical rules of thumb: Preliminary HC estimation		
	Based on thermal limits considerations	Based on short-circuit capacity considerations	Based on (loading/generation) percentage
South Korea	• For MV networks, the total DG ratings should be lower than 20% of the HV/MV transformer rating, i.e. ($P_{DG} > 0.2P_{tr}$)	• For MV networks, the total DG ratings should be lower than 15% of the HV/MV transformer rating, i.e. ($P_{DG} > 0.15P_{tr}$) • The total DG ratings should be lower than 15% of the thermal limit of the affected feeders, i.e. ($P_{DG} > 0.15P_{thermal\_line}$)	Not documented
Spain	• The total DG ratings should be lower than 50% of the MV/LV transformer rating ($P_{DG} > 0.5P_{tr}$) • The total DG ratings should be lower than 50% of the thermal limit of the affected feeders, i.e. ($P_{DG} > 0.5P_{thermal\_line}$)	The total DG ratings should be lower than 10% of the short-circuit capacity at the PCC ($P_{DG} > 0.1MVA_{SC}$)	Not documented
South Africa	• For LV networks, the total DG ratings should be lower than 25% of the MV/LV transformer rating, i.e. ($P_{DG} > 0.25P_{tr}$) • For LV networks, the total DG ratings should be lower than 25% of the feeding circuit breaker (CB) rating, i.e. ($P_{DG} > 0.25$CB rating) in case of shared feeder with other loads. • For LV networks, the total DG ratings should be lower than 75% of the feeding circuit breaker (CB) rating, i.e. ($P_{DG} > 0.75$CB rating) in case of dedicated feeder for the DGs.	Not documented	The total DG ratings should be lower than 15% of the feeder peak load ($P_{DG} > 0.15$ feeder's peak load)
China	Not documented	The total DG ratings should be lower than 10% of the short circuit capacity at the PCC, i.e.($P_{DG} > 0.1$ MVA_{SC})	Not documented
USA	Not documented	• The total DG ratings should be lower than 10% of the short-circuit capacity at the PCC, i.e. (PDG > 0.1MVASC) • The total short-circuit capacity of the DGs should be lower than 25% of the short-circuit capacity of the feeder at the PCC, i.e. (MVASC_DG > 0.25 MVASC_feeder)	• For radial circuits, the total DG ratings should be lower than (15%) of the feeder annual peak load (PDG > 0.15 connected feeder's peak load) • The total DG ratings on a feeder should be lower than (5%) of the total circuit annual peak load (PDG > 0.05 times circuit annual peak load) • For DGs fed from 3-phase, 4-wire feeding system, the total DG ratings on a feeder should be lower than (10%) of the total line section peak load (PDG > 0.1 line section's peak load)
Belgium	For LV networks, total DG ratings should be lower than the MV/LV transformer rating, i.e. $P_{DG} > P_{tr}$	Not documented	Not documented
Canada	Reverse power flow occurred due to DG integration should not exceed 60% of the transformer rating at the main substation and the minimum substation load, i.e. $P_{DG} > 0.6$ (P_{tr} + minimum substation load)	Not documented	The total DG ratings should be lower than (50% −100%) of the feeder capacity or the substation annual minimum load, i.e. ($P_{DG} > (0.5-1)$ Min. substation load), or ($P_{DG} > (0.5-1)$ connected feeder capacity)
Czech	At the 110 kV networks, the total DG ratings should be lower than the HV transformer rating and the minimum substation load, i.e. $P_{DG} > (P_{tr}$ + minimum substation load)	Not documented	Not documented
Italy	• The total DG ratings should be lower than 65% of the MV/LV transformer rating ($P_{DG} > 0.65P_{tr}$) • The total DG ratings should be lower than 60% of the thermal limit of the affected feeders, i.e. ($P_{DG} > 0.6$ $P_{thermal\_line}$)	Not documented	Not documented
Portugal	For LV networks, the total DG ratings should be lower than 25% of the MV/LV transformer rating, i.e. ($P_{DG} > 0.25P_{tr}$)	Not documented	Not documented

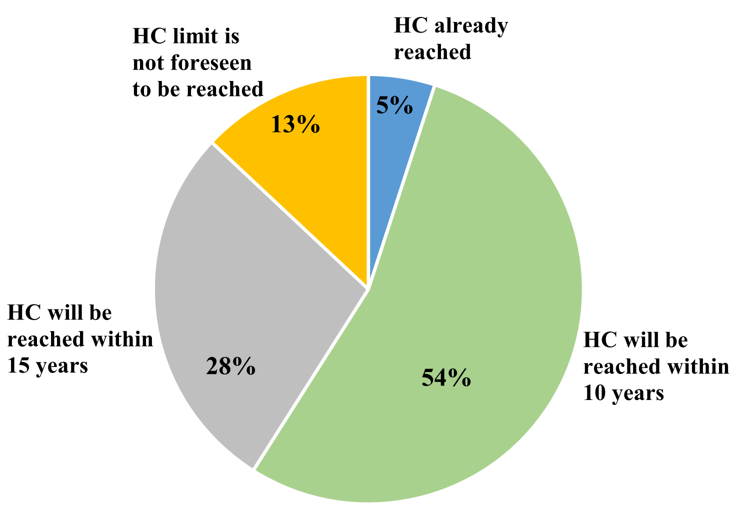
grid connected with wind and solar sources was included.

Sun [23] presented the HC of electrical networks and its enhancement techniques. It was highlighted that the intermittent nature of the DER output power complicates the design and operation of electrical control systems. Accordingly, the assessment and enhancement of HC can be formulated as an optimization problem that requires suitable optimization techniques to solve it. Bollen et al. [24] presented an early introduction for the relation between harmonic distortions and their impacts on the HC. DER high-frequency distortions and its impact on limiting the HC of the electrical systems were examined. Alamat [25] provided a simple assessment of the HC problem in Jordan. Different HC improvement techniques were investigated such as reactive power compensation and cable reinforcement. It was concluded that the overvoltage is the main performance limit that governs the selection of the optimum HC enhancement technique.

A recent survey performed on more than 100 electric utilities across 23 countries, it was noticed that DSO's raised their techno-economic concerns regarding the booming DG deployment worldwide. Utilities believe that they will suffer from revenues drop as a consequence for high DG penetration as illustrated in Fig. 2(a) [13]. DSOs highlighted that the biggest DG-related impact on a utility network's HC comes from small-scale energy prosumers who are driving low voltage DG units (mentioned by 59% of survey's contributors), followed by medium or high-voltage connected DG such as a large-scale solar plant. As well, DSO's gave their feedback about when they expect to meet HC limits within their systems, as per Fig. 2(b).



(a)



(b)

Fig. 2. Survey results from different DSOs, (a) Estimated profit drops due to high DG penetration, (b) Opinions when DSOs expect to meet the HC limit.

Later, Etherden et al. [26] addressed the HC importance to DSOs and introduced a new hypothetical figure (for explanation only) that mixes multiple HC curves based on various performance indices on one graph. They highlighted that the overall system's HC will be chosen as the lowest HC value indicated by these various curves. New HC terminologies were presented in Ref. [26], such as:

2.1. The HC uncertainty

EPRI explained that the uncertainty in the assessment of HC arises due to the unknown DG location, variety of unit ratings and their unpredictability, intermittent nature of DG output power due to climate changes, alteration of load profiles and lack of confirmed system parameters when performing the power system calculations [27]. Accordingly, the resulting HC will not be a single value, but multiple values will be introduced according to the uncertainty percentage.

2.2. The HC Coefficient (HCC)

The authors explained the possible active power curtailment techniques to increase the HC, such as hard and soft curtailments, and introduced the HCC index. This index defines the ratio between the curtailed energy and the installed capacity above the initial HC, in order to compare the various schemes for curtailment.

$$HCC \cong \frac{\text{Energy to be curtailed}}{\text{Capacity above initial HC}} \tag{1}$$

Palmintier et al. [27] studied the challenges of integrating solar power sources into the USA electrical distribution networks. The impact of high PV penetration was recognized. The authors highlighted that prior to the HC concept development, many DSOs used a rule of thumb called the 15% rule. This rule says that penetration levels of a system higher than 15% of its peak load should be avoided and should be investigated through supplemental studies. The authors defined the HC as the quantity of DG that can be integrated into the system without imposing any changes to the existing infrastructure and without prematurely wearing out existing equipment. Furthermore, some interesting terminologies for the HC were presented in Ref. [27] such as:

2.3. The stochastic HC (SHC)

EPRI developed an advanced distribution planning tool that provides comprehensive estimates of HC using stochastic methodologies that evaluates thousands of scenarios of the size and location of small-scale PV sources. The stochastic HC assessment approach has been investigated in many works [28–34] due to the uncertainties faced by the DSOs regarding the DG integration location, size and the variation in loading capacity. Rabiee et al. [28] introduced a stochastic multi-objective optimization approach to maximize the HC while considering both technical and economic aspects. The stochastic approach developed by EPRI to assess the PV impacts on system feeders is presented in Refs. [29,30]. The key lessons learnt from the California's integrated capacity analyses are presented in Ref. [31]. Dubey et al. [32] presented a stochastic methodology that simulates various DG deployment scenarios while calculating the HC considering various limits such as over-voltages, voltage deviations and voltage unbalance. A three-step probabilistic HC assessment procedure is proposed by Le Baut et al. in Ref. [33]. In Ref. [34], a high-resolution methodology has been introduced by Palacios et al. to assess the DG and storage systems integration into the distribution networks while considering a stochastic demand model.

2.4. The locational HC (LHC)

The HC is a location-dependent concept, *i.e.* hosting of new DGs can be accepted in some locations, but not in others. The voltage profile along the feeder plays an important role in defining the LHC. As an illustrative application of the LHC [27], proposed the idea of creating HC maps. As shown in Fig. 3, these maps can be implemented on the geographical feeder routing layouts or network single-line diagrams. Results for some case studies performed in some US cities were included which emphasize that the HC approach can provide a more accurate and measurable alternative to the 15% rule. Many DSO's availed their regularly-updated HC maps online through their website in order to present the most valuable locations for renewables integration to drive further investment in renewables innovation in a cost-effective way, as presented in Ref. [88].

In summary, HC maps can indicate how HC varies along feeder segments using appropriate color coding in regards to the loading percentage of each segment. It can also take into consideration HC of the various feeder segments and the main bottlenecks along the feeder routes, *i.e.* the points that have performance index violation. Rylander et al. [35] explained that EPRI developed a comprehensive method for the planning and calculation of HC called the streamlined HC (SLHC) method. It is used to calculate the HC of a feeder while taking into account various DER sizes and locations, feeder physical characteristics and DER integration technologies. This SLHC method is an intermediate calculation between the quick estimations and extensive analytical studies. Finally, the authors enhanced the SLHC methodology to be systematic and ready for use in commercial planning tools. The SLHC approach was studied in detail in Refs. [35,37]. A comparison between these various HC calculation methods as well as some DSOs in the US endorsing them is presented in Table 2.

Fig. 4 shows an illustrative flowchart for the HC assessment and enhancement procedure.

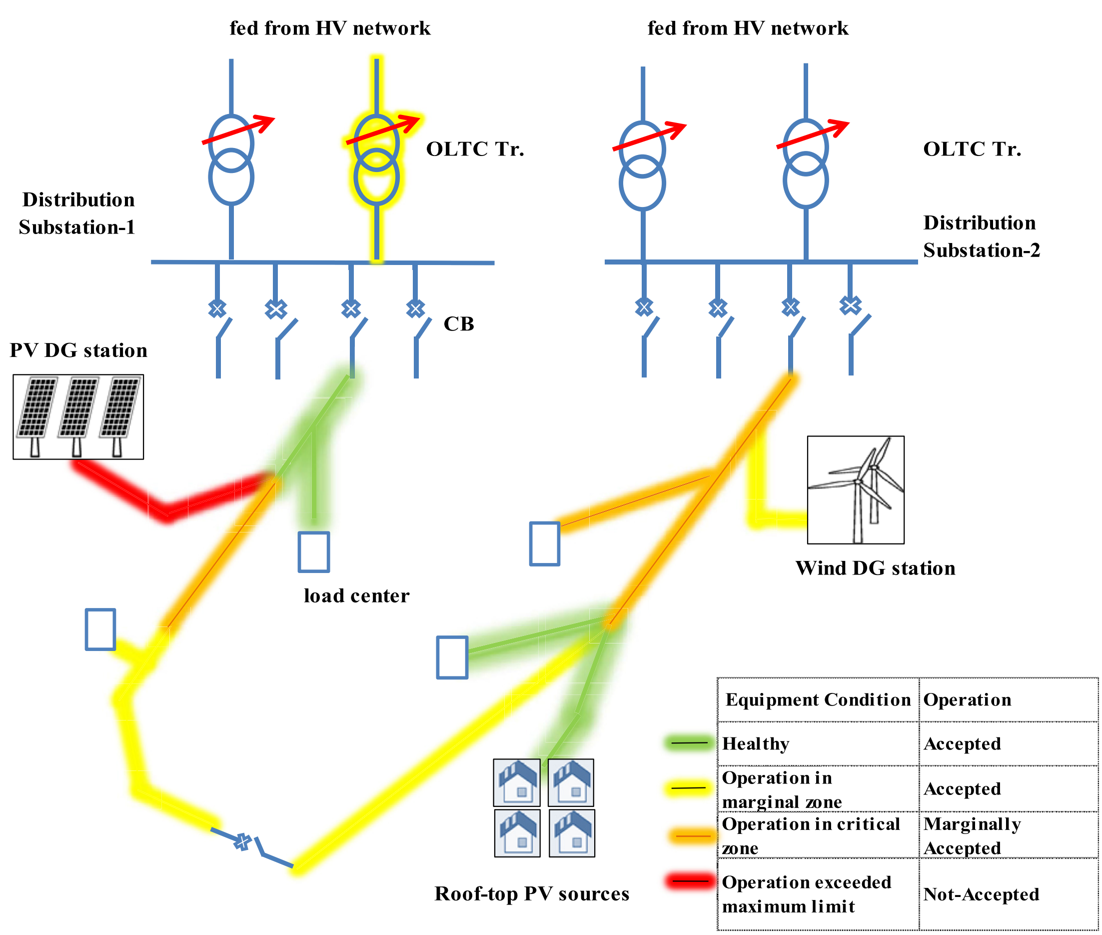


Fig. 3. HC illustrative map based on feeders routing layouts and single-line diagrams.

Table 2
Comparison between the available HC assessment methods.

Method	Analytic	Stochastic	Streamlined
Description	- A systematic procedure is followed by iteratively increasing the DG penetration in a pre-defined step at a selected bus, then performing load flow calculations and checking the operating limits at each iteration until they violate; hence, finding the HC of that bus. - Sequentially, another bus is chosen and the same procedure is repeated until all the system buses are investigated.	- Stochastic approaches such as MC are used to simulate the uncertainties in DG integration location, rating, and load variations. - Multiple scenarios are estimated to encounter for the various uncertainties in the problem.	- SLHC was developed by EPRI in 2014 to provide a tool to evaluate the HC on a system-wide basis with lower computational efforts and time. - SLHC approach is not a replacement to the conventional detailed HC studies but it provides quick simplified screens which assist the DSO to decide if they need to perform further detailed studies or not.
Complexity	Complex, for a single individual feeder, multiple scenarios exist for HC assessment.	Complexity degree depends upon the required accuracy level and the number of calculation scenarios.	- Simple and effective for system-wide assessments. - Utilized in many commercial planning tools.
Accuracy	Accurate.	Selective accuracy that depends on the computational time and the tool to run.	It had accuracy issues, especially for complex systems.
Computational time	Large, time-consuming.	Time-dependent according to the considered uncertainty level and accuracy degrees.	Relatively small. The streamlined analysis of a single feeder would take in the order of minutes compared to hours for a detailed analysis [35].
DSOs using this method in USA [3]	Pacific Gas & Electric (PG&E).	PEPCO Holdings, Inc.	Southern California Edison (SCE) and San Diego Gas & Electric Company (SDG&E).

To generalize, the HC of a specific distribution system can be calculated as follows [14,42].
a. Choose a performance index for the system.
b. Determine a limit for this index (according to country regulations or applied standards).
c. Calculate the performance index as a function of the amount of DG.
d. Obtain the HC, the penetration level for which the performance becomes unacceptable.
e. Choose an appropriate HC enhancement technique and apply it considering its optimum rating and location.
f. Obtain the enhanced HC.

3. Hosting capacity: performance limits

The adverse impacts of high DG penetration levels on electrical networks have been investigated in many studies [38–44]. This section addresses the main HC performance limits.

3.1. Overvoltage problems

HC performance limits, such as thermal overloading, voltage variations, power quality and protection problems are explained in Refs. [14,44]. When the output power of a DG unit is greater than the load demand, the surplus power is injected back to the network. Thus, a voltage rise may occur at the load bus, with a possible overloading at the nearby feeder.

Shayani et al. [38], investigated the high PV penetration impact on the electrical networks. The authors found that the increase of voltage and the continuous maximum current of the conductor (conductor ampacity) were the main indices that surpass the allowable limits in presence of high DG penetration. After various simulations, the authors concluded that it is possible to install DG values between 1 and 2 pu of the load power. Practical rules of thumb were proposed in Ref. [38] to determine the maximum allowable DG penetration according to the specified performance limit selected by the operator. From the voltage rise perspective, they proposed that the voltage drop at the base case of the system (no DG) and the voltage rise that will occur at the maximum DG penetration and have approximately the same value, as shown in Eq. (2):

$$\left|\Delta V_{drop}\right| \cong \left|\Delta V_{rise}\right| \tag{2}$$

From the feeder ampacity perspective, the authors proposed the following equation to estimate the maximum DG capacity for a feeder without exceeding its thermal limits, as shown in Equation (3):

$$P_{DG} = 2 \times P_{load} + (1 - S_{load}) \tag{3}$$

Bertini et al. [42] presented a systematic methodology to calculate the HC, while considering thermal overloading, steady state voltage violations and fast voltage variations. In addition, the authors applied their proposed method to estimate the HC of an existing Italian distribution network using simplified simulation models that can be configured upon changing parameters such as feeder cross-section and length, system loading and transformer rating. Degner et al. [45] addressed the high PV integration into LV distribution networks in Germany while focusing on the overvoltage problems. The authors highlighted that the upper voltage limit is usually reached even if the thermal capacity of the distribution system has not been reached yet. The authors concluded that by using an appropriate control of the reactive power, the system HC may be increased by a factor of 1.5 to more than 2. Moneta et al. [46] highlighted that the integration of large-scale DG into MV distribution networks impacts the feeder voltage profiles and may lead to increased overvoltage risks at the DG integration bus. Possible voltage improvement techniques were introduced and the impact of these techniques on the HC was explored.

The HC assessment in unbalanced systems was discussed in Refs. [47–49]. De Jaeger et al. [47] investigated the overvoltage and voltage unbalance problems that may arise due to high DG penetrations. The authors concluded that the overvoltage and unbalance problems are governed by many factors, such as the number of connected DG units, their rating, locations and the way of connection (single-phase or three-phase). A distribution factor (F_d) was proposed to identify the unbalance in radial distribution systems due to DG integration, as shown in Equation (4).

$$F_d = \left|\frac{N_a}{N_{tot}} + a\left(\frac{N_b}{N_{tot}}\right) + a^2\left(\frac{N_c}{N_{tot}}\right)\right|, \quad a = e^{j\left(\frac{\pi}{2}\right)} \tag{4}$$

It was concluded in Refs. [48,49] that the contribution from PV

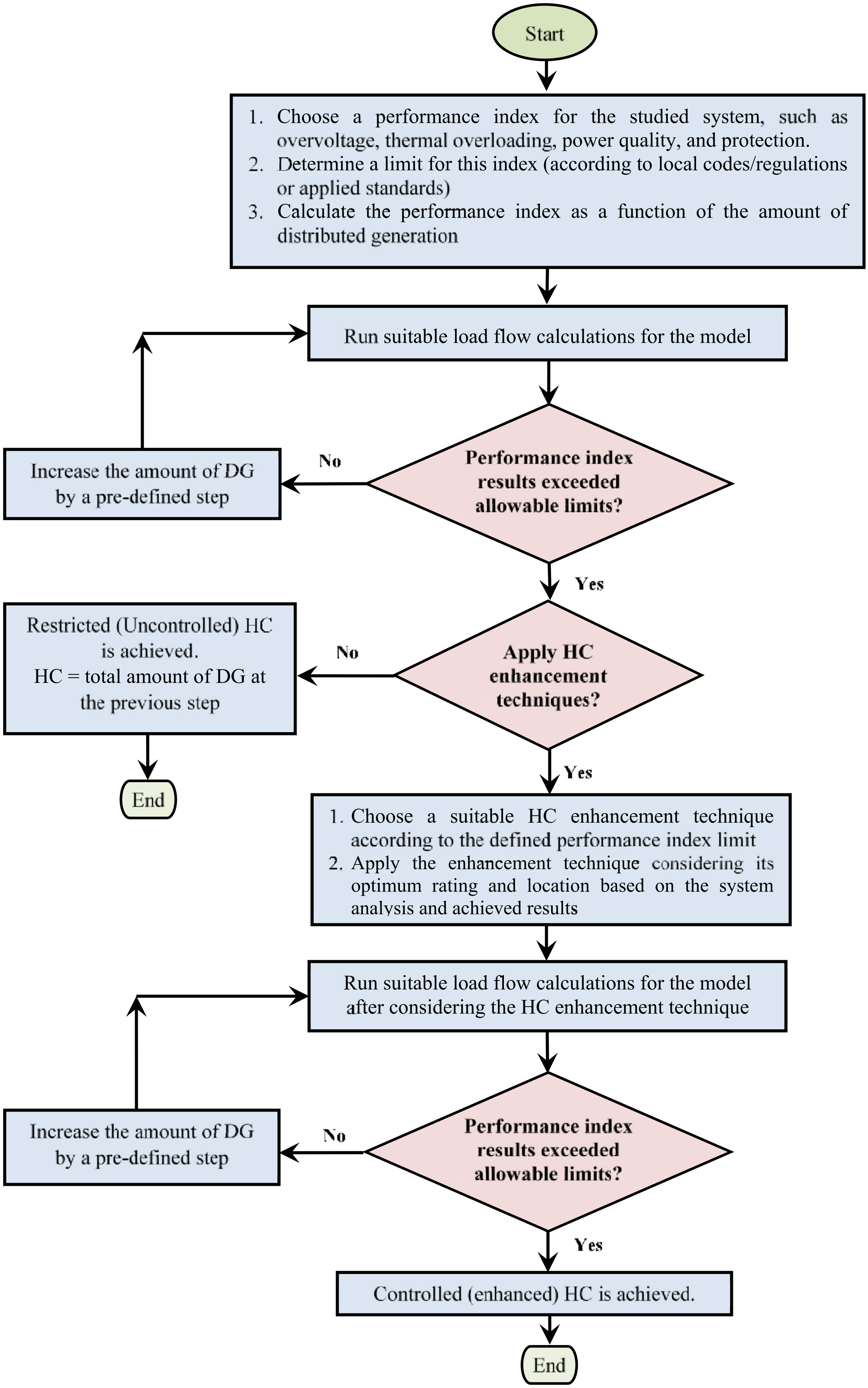


Fig. 4. HC assessment and enhancement procedure.

inverters to the overall system voltage unbalance may exceed 1%. In addition, impacts of DG penetration on the voltage profile of the network are discussed in Ref. [25] and the voltage rise (ΔV_{rise}) at different buses was approximated, as given in Equation (5).

$$\Delta V_{rise} \cong \frac{(P*R)+(Q*X)}{|V_n|} \tag{5}$$

As shown in Eq. (5), there are two main terms that determine the amount of voltage rise at the bus, namely (P^*R) and (Q^*X). The dominant term determines the appropriate method for reducing the voltage rise. $|V_n|$ is a system parameter specified by the DSO and can be adjusted by controlling the set-point of the OLTC in the upstream transformer. R and X depend on the system's characteristics. To reduce the voltage rise, the system resistance and reactance can be reduced through cable reinforcement. However, this solution is not always possible because of economic considerations and the construction difficulties associated with replacing existing cables in crowded cities. The ratio (X/R) is a constant value that depends on the distribution system's characteristics. High (X/R) ratio means that the dominant term is (Q^*X). Accordingly, controlling the system's reactive power can be an appropriate solution to limit the overvoltage. On contrary, low (X/R) ratio means that the term (P^*R) would be the main factor in controlling the overvoltage. Reducing the overvoltage can be done by either reducing value of R through cable reinforcement, decreasing the amount of active power (P) by using active power curtailment techniques or by employing suitable energy storage technologies. Collins et al. [50] investigated the effect of real and reactive power control techniques on mitigation of the overvoltage problems due to high PV integration. Seguin et al. [51] explained the various effects of high PV penetration to the DSO planners. It was concluded that overvoltage and fast voltage variation problems arise noticeably when large numbers of PV systems are connected near the end of long and lightly loaded feeders.

3.2. Overloading and power loss problems

Proper location of DG units reduces the feeder losses and decreases the loading of the feeding transformers. As common in research studies, minimizing the feeder's losses by adding DGs is usually formulated as an optimization problem. Practically, both DG location and rating are mostly decided by the DG investor/owner. The most beneficial situation occurs when the DG is connected close to the load being served [44]. The integration of DG units can then reduce the overloading risks, minimize the system's losses, maintain the lifetime of the equipment and improve the thermal properties of feeders and transformers [14,23]. The worst-case scenario which leads to the highest risk of overloading occurs with the maximum generation and minimum loading case [51]. If the DG output power is higher than the local load power, *i.e.* $P_{DG} > P_{load}$; the DG starts to inject power to the upstream network after satisfying the load demand. Therefore, reverse power flow will arise and may lead to exceeding the thermal capacity of the equipment (transformers and feeders).

3.3. Power quality problems

Power quality is concerned with the interaction between the electrical utility and its customers. Voltage and current disturbances are considered as deviations from the pure sinusoidal waveform that will consequently impact the network and the customer alike. Voltage quality is concerned with delivering the supply voltage to the customer within acceptable limits. The excessive DG penetration may lead to many power quality disturbances such as power system harmonics, SSVV, RVC, voltage dips and flickers [14].

Current quality focuses on the way in which the load current impacts the upstream system. Bollen et al. [18] discussed the power quality concerns with and without DER integration. It was found that DER units are impacted by the network voltage disturbances as all other passive equipment. Excessive voltage disturbances may shorten the lifetime of the DER and cause maloperation. Most of the DER units utilize inverter-based interfaces with the grid, and hence, these inverter-based DER units are considered as harmonic sources that impact the current quality in the network. Bollen et al. [24] focused on the high-frequency distortions emitted from inverter-based DG sources and studied their HC limiting impacts.

Sharma et al. [52] investigated the voltage flicker problems that resulted from high DG penetration and its recommended mitigation techniques. Sun et al. [53] presented the importance of including harmonic distortion limits in the HC assessment. The greater the inverter-based DG penetration into distribution networks, the higher the risk of harmonic distortion problems. The authors highlighted that the traditional harmonic analysis studies performed at the initial planning stage of the project may not be appropriate when DG penetration is present. This is because the DG unit's location and rating are unknown during the planning stages, as well as the intermittent nature of the output power of the DG units, which make their harmonic emissions variable. Hence, the harmonic assessments and harmonic mitigation techniques in distribution networks containing DGs should be dynamic and flexible operations adapted to the actual harmonic emissions. Santos et al. [54] introduced an explanatory methodology for determining the harmonic HC supported by a case study that examines the minimum and maximum HC of the system. Bollen et al. [55] discussed the role of power quality in future smart grids. The authors concluded that power quality will play an important role in smart grids to ensure delivering electrical power to customers within acceptable limits and strict quality measures. Santos et al. [56] addressed the DG harmonic distortions and its limitations on the system's HC and a method for HC determination in the presence of harmonic distortions was introduced. The power quality disturbances that result from inverter-based DG sources are explored in Refs. [57–61].

Sakar et al. [62] examined the harmonic-constrained HC assessment and enhancement. A typical industrial system was considered as a simulation model to study the harmonic HC while considering the effect of the source and load nonlinearities. In addition, the other performance limits were examined such as overvoltage and thermal overloading. The authors concluded that harmonic distortion constraints greatly affect the system's HC, especially in the presence of high levels of load nonlinearity. Finally, the authors proposed a *C*-type filter that assisted in mitigating the harmonic distortions, damping the resonances and increasing the harmonic-constrained HC. The HC calculations in the presence of converter-based wind turbines are presented taking into account various background distortions in Refs. [63,64].

3.4. Protection problems

When DG output power exceeds the local demand requirements, reverse power flow and protection problems may occur. Excessive DG penetration changes the magnitude and direction of the fault currents. Thus, it may increase the risk of failure of the protection system either by unwanted operation during healthy conditions or failure to operate during fault conditions.

Deuse et al. [65] highlighted that DG sources connected to radial parts of the distribution network are often considered as a cause for fail-to-trip as well as the incorrect trip of existing over-current protection relays. The authors performed detailed simulations to investigate the risks that could face the protection systems in the presence of excessive DG penetration, and they concluded that some modifications for the existing protection schemes may be required to encounter for the DG presence. Also, the protection-constrained HC assessment could be performed considering the following DG penetration level precautions:

- The DG penetration level at which the current setting or time-delay setting of any of the existing protection relays needs to be changed
- The penetration level at which it becomes advisable to install additional circuit breakers or protection elements in the existing network
- The penetration level at which it becomes advisable to replace the existing protection relay with a new one.

Walling et al. [66] discussed many protection problems such as protective device coordination, the impact of DER on the interrupting rating of the devices, fault detection systems, automatic reclosures coordination and islanding problems. The authors highlighted that adverse impacts are not foreseen at low DER penetration levels. However, at high DER penetration, these impacts are noticeably found and should be considered by DSOs. The DG penetration into distribution networks may complicate the protection system design. The DG interface technology also impacts the DG contribution to the network fault currents [14], as summarized below:

- Synchronous generators produce a continuous short-circuit current.
- Induction generators contribute to the fault currents, but for limited durations.
- Inverter-based DG units have a very limited contribution to the fault current, and in many cases, their contribution can be neglected.

Sun [23] clarified that the classical protection coordination settings need to be revised after high DG penetration into electrical networks to ensure the effectiveness of the protection system

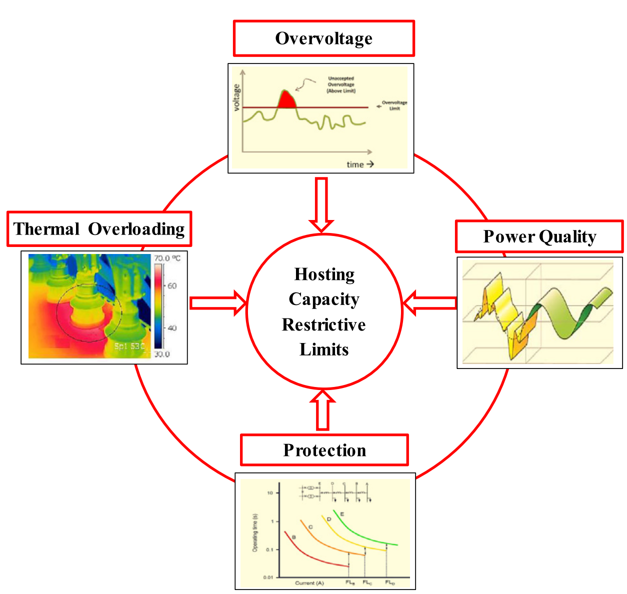


Fig. 5. Performance indices that can be considered in the HC assessment.

operation. Furthermore, the intermittent output power and unplanned shutdown of the DG sources are other challenges that face the protection system designers. For that reason, some national grid codes require that the DG remains in operation during fault conditions (ride-through) for specified durations. Accordingly, the DG unit should be capable of withstanding the pre-defined fault current for the specified durations without any damage to its inherent components. Zhan et al. [67] presented an optimal DG sizing and integration procedure to minimize the adverse impact of high DG penetrations on existing protection systems. Finally, one can notice that there are few studies that address the impact of the DG penetration on protective equipment and the system HC. Fig. 5 shows an illustrative representation of the various performance indices that can be considered in the HC assessment.

4. Hosting capacity: perceptions and outlooks

This section presents the HC calculation methodologies, their perceptions and outlooks. Haesen et al. [68] investigated the impacts of motor starting on weak electrical grids fed from DG sources. The large starting currents drawn by induction motors may exceed the current limit of the DG unit. The performance index upon which the HC has been applied was selected as the ability of the grid to withstand the starting impacts of large motors.

Since DG interconnection standards differ from one country to another, Van et al. [69] presented an overview of some standards such as the IEEE 1547, IEEE 519 and IEC 61400, in addition to the national electrical regulations in France and Belgium. The authors highlighted that a harmonized DG interconnection standard is needed to help DG technologies to become more unified and marketed in all countries.

Menniti et al. [70] explained the HC approach while considering variable loading profile. The relation between the HC and loading capacity were investigated using mathematical models. A techno-economic assessment of different active and reactive power control systems used to improve the PV integration in Germany was presented in Ref. [16]. The presented simulations revealed that the reactive power control is an effective method to increase the HC. The main results of an Italian project aimed to enhance the HC of MV networks by utilizing advanced control systems were demonstrated in Refs. [71–73]. Alturki et al. [74] introduced a novel optimization-based procedure for HC calculations. Salih et al. [75] discussed the optimum HC of a system fed from wind power resources using cost-benefit analysis to maximize the economic benefits to both DSO and DG owners. It was concluded that the optimal economic HC of a network is impacted by the cost of the curtailed energy. Altin et al. [76] presented a method for HC calculation in MV distribution networks. The authors demonstrated the importance of the HC concept for Turkish DSOs. Klonari et al. [77] analyzed the overvoltage problems raised due to the higher PV penetration at LV distribution systems. The authors utilized probabilistic approaches based on real SM measurements to overcome the uncertainty problem of intermittent PV generation and varying load profile. The MC simulation approach was selected to simulate the uncertainty of PV generation and its impact on the voltage profile. Rossi et al. [78] proposed a novel solution to evaluate the HC based on the risk of network congestion. The proposed approach considered stochastic DG allocation and examined DG location impact on the HC results. The authors concluded that the HC cannot be identified by a single value, but by means of a probability density function. Jothibasu et al. [79] presented a detailed sensitivity analysis for the system HC due to higher PV penetration considering many varying parameters such as voltage class of the feeder, PV location and voltage regulation devices. The authors concluded that the HC of a distribution system depends on the feeding transformer rating, voltage level at the PCC, characteristics of the voltage regulation devices, and PV inverters.

The efforts exerted by EPRI to assist network planners in evaluating DER penetrations into their networks were explored in Refs. [80,81]. EPRI developed a module that evaluates the system HC based on the SLHC method. The proposed method was examined on an actual distribution system and was shown to be efficient and time-saving. Dubey et al. [82] introduced a sensitivity analysis for HC assessment of distribution networks that considered the effect of changing the distribution system parameters and the simulation parameters. Chen et al. [85] proposed a robust optimization technique to determine the maximum DG penetration level for ADNs while considering the uncertainty in DG ratings, location and load variations. Navarro et al. [86] introduced a probabilistic impact assessment to determine the impact of the low carbon DG sources such as PV, EVs and CHP.

Table 3 presents an executive summary for some international real case studies for HC assessment and enhancement techniques that were introduced.

5. Hosting capacity: enhancement techniques

Nowadays, enhancing the system HC is considered one of the important goals for DSOs, which is clearly shown in the American and Australian distribution company studies in Refs. [87,88]. In Ref. [89], the technical solutions that can be utilized to enhance the system's HC have been categorized into three categories: DSO solutions, prosumer solutions and interactive solutions. This section reviews the various HC enhancement techniques, keeping in mind that the effectiveness of these solutions depends on various factors such as investment costs, technology readiness, impact on congestion and compliance with the applied codes.

The increase in HC that may result from adding a soft open point (SOP) to link two distribution networks as addressed in Ref. [90]. In Ref. [91], a risk assessment tool is presented to evaluate the HC of ADNs while considering various DG uncertainties. The PHC approach was proposed to consider the uncertainty in system modeling. Recently, different techniques have been utilized to increase the network HC such as the demand response of smart grids in Refs. [92,93], ADN management in Ref. [94], load balancing in Ref. [95], optimal PV placement in Ref. [96] and advanced smart grid technologies in Ref. [97]. Ebe et al. [98] evaluated the system HC while comparing different approaches for PV allocation, such as deterministic and probabilistic approaches. Quintero et al. [99] studied the relationship between the DG location and the relevant HC and proposed a new index to assess the optimum DG location based on the studied relationship. In Ref. [100], results of experimental studies and practical experiences of integrating solar PV systems into remote Australian electrical networks were analyzed and presented.

5.1. Reactive power control

Voltage rise problems are considered as the most significant factor for high DG penetration. Reactive power control techniques are believed to be the most effective methods for relieving over voltage problems with DSOs and end-users. Various reactive power control techniques can be utilized such as shunt and series capacitor banks, SVC, STATCOM and DG units controlled by smart inverters.

Stochastic mathematical models that aim to maximize system HC were presented in Refs. [101,102]. The authors highlighted that the utilization of reactive power control and storage systems allow for increased DG penetration and reduced system losses. The authors concluded that their proposed model could be utilized in smart grids where integration of large-scale DG sources is preferable. Meuser et al. [103] discussed the effect of reactive power control and improved transformer tapping control on HC enhancements. The authors pointed out that reactive power control in rural areas may lead to an imbalance in reactive power flows during high DG penetration. Accordingly, it was advised to allocate DG sources near substations to balance reactive power needs. Mende [104] presented different reactive power control methods and examined its effect on HC enhancement. The authors examined different control techniques such as fixed power factor (PF) control method, real power control as a function of PF and reactive power control as a function of voltage. Seuss et al. [105] discussed HC enhancement using reactive power control through smart PV inverters. The authors studied the effect of local Volt/VAR control on feeders HC. It was concluded that smart inverter capabilities have enhanced the feeder HC. Soroudi et al. [106] examined the demand response effect on HC maximization using reactive power control of wind turbines. Simulation results revealed that the demand response and controlled switching of capacitor banks are effective methods for HC maximization. Ding et al. [107] introduced stochastic analysis for PV penetration. PF and Volt/VAR optimizations were proposed as mitigation solutions for the overvoltage problems. The authors highlighted that controlling the PV inverter's PF have a positive impact on the HC maximization.

5.2. Voltage control using OLTC

OLTCs are one of the most practical tools providing automatic compensation for the voltage profile in the network. Schwaegerl et al. [108] addressed the impacts of uncontrollable DER units on the system's voltage profiles. The authors examined different case studies and highlighted that system overvoltage depends on both the generated power and the loading conditions. Berizzi et al. [109] presented the results of the INGRID-2 project. This project introduced new approaches for reactive power control of DG sources. The authors concluded that the coordinated voltage control has many beneficial impacts such as improving voltage quality, reducing network losses and increasing HC of the system. Sáiz-Marín et al. [110] proposed a methodology for voltage control of wind farms that aimed to increase the system's HC. The authors pointed out that steady-state bus voltage constraint is one of the most important factors in the HC assessment of the Spanish electrical systems. Bletterie et al. [111] highlighted that the optimum operation of OLTC equipment and appropriate reactive power control lead to an extended operating voltage band, which in-turn enhances the HC. The authors proposed the concept of the feeder's critical length. The feeder critical length is the length at which the performance constraints start to exceed its limits. Navarro et al. [112] introduced a techno-economic assessment of using OLTC as a solution for overvoltage problems encountered in the UK due to high PV penetration. Local and remote voltage control approaches were examined and compared with conventional network reinforcement solutions. It was found that suitable OLTC control leads to a noticeable increase in the system HC. Rauma et al. [113,114] examined the advanced control of OLTC transformers and its role in HC enhancement. A simulation model was built based on actual voltage measurements obtained from advanced metering tools. Presented simulations covered a set of 631 real LV electrical networks in France. It is concluded that the OLTC control can enhance the HC. Bletterie et al. [115] provided an in-depth analysis for different reactive power control and active power curtailment control concepts. Many techniques were presented and their impact on reducing the system overvoltage, reducing system losses and increasing system's HC were analyzed. Long et al. [116] studied the overvoltage problem of LV networks in the presence of high PV

Table 3
Executive summary for some international real case studies for HC assessment and enhancement.

Ref.	Year	Country	Real studied system	Performance index considered	HC enhancement considered?		Used HC enhancement technique	Notes
					Yes	No		
[42]	2011	Italy	Examples of Italian urban and rural LV networks.	- Overvoltage - Thermal overloading - Rapid voltage changes		✓		- It was concluded that the HC reduces as the DG location moves far away from the main MV/LV distribution transformer. - Also, rural networks are characterized by small transformers and small-size overhead conductors, which means that the HC is mainly limited by voltage limit violations. - On the contrary, urban networks are characterized by large transformers and large-size underground conductors.
[119]	2011	Sweden	Existing 130/50/10 kV network	- Overvoltage - Thermal overloading	✓		Active power curtailment	- It was highlighted that advanced communication technologies between DSOs and DG units may help in achieving optimal power curtailment. - Also, the DG curtailment should be evaluated while considering both technical and economic aspects.
[20]	2012	Sweden	Various real test systems were investigated for city grid in Stockholm, Suburban grid and rural grid.	- Overvoltage - Thermal overloading	✓		- Reactive power control - OLTC	- It was concluded that the overvoltage is the main performance limit for HC calculations. - Also, it was found that reactive power control and adjustments of transformer tap changers can be useful techniques for increasing the HC and overcoming the overvoltage problems. - Examined Swedish grids were found to have high possibility of PV connection (high HC)
[16]	2013	Germany	Real LV grid was examined containing 122 household.	- Overvoltage - Thermal overloading	✓		- Reactive power control - OLTC - Feeder reinforcement	- Both technical and economic assessments were investigated for the examined HC enhancement techniques. - It was concluded that reactive power provision is an effective tool for HC enhancement.
[136]	2013	Denmark	LV network in Bornholm, Denmark.	- Overvoltage - Thermal overloading	✓		Energy storage technologies (EVs)	- It was concluded that energy storage technologies and EVs are beneficial tools for HC enhancement.
[25]	2015	Jordan	A real distribution network of Al-Qatraneh town.	- Overvoltage - Thermal overloading	✓		- Inverter power factor control - Capacitor banks for reactive power compensation - Feeder reinforcement	- It was concluded that the overvoltage is the main performance limit that governs the selection of the optimum HC enhancement technique. - In addition, it was concluded that reactive power support allows for effective HC enhancement.
[30]	2015	USA	16 real main feeders were examined	- Overvoltage - Thermal overloading - Power quality		✓		- The presented results aimed to provide California utilities with precise methods to determine the available HC of some examined existing distribution feeders. - EPRI found that the HC method is more practical compared to the conservative 15% rule previously applied in the USA. - It was concluded that the main factors affect a system from high PV penetration are feeder voltage class, PV integration location, and feeder resistance.
[36]	2016	USA	216 real MV feeders were examined	- Overvoltage - Thermal overloading		✓		- Overvoltage problems were found to be the most adverse impact encountered due to high PV penetrations followed by the feeder thermal overloading problems. - It was also found that the feeder HC is highly dependent on its voltage class and its loading profile.

(*continued on next page*)

Table 3 (*continued*)

Ref.	Year	Country	Real studied system	Performance index considered	HC enhancement considered?		Used HC enhancement technique	Notes
					Yes	No		
[63]	2016	Brazil	Brazilian university electrical system	- Power system harmonics		✓		- It was concluded that the HC is affected by the amount of background harmonic distortion.
[90]	2016	UK	UK Generic Distribution System (UKGDS) with 61 buses	- Overvoltage	✓		By using back-to-back voltage source converters known as soft open points (SOP)	- SOPs are new power electronic-based control types of equipment that are used to transfer power between normally separate parts of the network. Voltage source converter of the back-to-back configuration is one of the common SOPs. - It was concluded that using SOPs has a beneficial effect on increasing the system HC.
[138]	2016	Japan	Japanese standard model of a distribution network containing 36 feeder with 235 switches	- Overvoltage - Thermal overloading	✓		Network reconfiguration	- Optimum network reconfiguration techniques proved its efficiency in enhancing the network HC.
[83]	2017	Cyprus	Existing networks at north Cyprus	- Overvoltage - Thermal overloading	✓		Reactive power support	- Various loading conditions were examined. - It has been found that transformer thermal loading is the main HC limitation against more PV connections. - Reactive power compensation proved its efficiency in enhancing the network HC.
[84]	2017	Finland	Test systems were examined for urban, intermediate, and rural grid systems.	- Overvoltage - Thermal overloading	✓		OLTC control	- Both balanced and unbalanced test cases were examined - OLTC control techniques proved efficiency in enhancing the system's HC in case of balanced PV connections. - However, OLTC had minor effect in unbalanced system with excessive single phase PV connections.

penetration. OLTC control and reactive power control were introduced as mitigation solution to the overvoltage problem. The authors concluded that OLTC transformer control and decentralized capacitor banks have a beneficial role in increasing the system HC and reducing overvoltage issues. Further detailed studies on HC enhancement via the efficient control OLTC and advanced active transformers are presented in Refs. [117,118].

5.3. Active power curtailment

Active power curtailment occurs when DGs are asked to decrease their output power to match consumption requirements in order to maintain the operational limits of the grid. Active power curtailment techniques are known to be useful in centralized DG stations where the DSOs can access these DG stations and control their output powers. Etherden at al [119]. explained the active power curtailment techniques and its role in HC enhancement, taking into account the overvoltage and thermal overloading as the performance indices for evaluating the HC. It was highlighted that advanced communication technologies between DSOs and DG units may help in achieving optimal power curtailment. Also, the DG curtailment should be evaluated while considering both technical and economic aspects because it may not be feasible to invest in adding new DG units and then curtailing its added power for long durations.

In Refs. [120,121], some case studies that explain the role of active power curtailments and dynamic line rating in enhancing the system's HC are provided in both LV and MV distribution networks. The authors categorized power curtailment into hard and soft curtailments. Hard curtailment indicates that all the DG output power will be curtailed once the performance index limit is violated, while soft curtailment indicates that a partial amount of DG output power will be curtailed. Both curtailment categories have a beneficial role in enhancing the system's HC. The fixed power curtailment and voltage-dependent Volt/Watt control techniques were investigated in Ref. [122]. Fixed curtailment proved its efficiency over the Volt/Watt control approach for the simulations under the worst-case operating scenarios. However, it should be noticed that the uncertainties in DG penetration and load profile make the optimum curtailment decision a difficult task for DSO planners.

5.4. Energy storage technologies

Energy storage systems help in overcoming the overvoltage resulting from high DG penetration, thus allowing the increase of the system's HC. BESS allows the demand and generation of electricity to be mutually decoupled. Even though energy storage is still expensive, it offers unique benefits that cannot be achieved using other means. Proper sizing and allocation of the BESS may postpone DSO's plans for network reinforcements. Customer-owned and DSO-owned energy storage systems and their role in increasing the allowed DG penetration were investigated in Refs. [123–136].

In Ref. [127], a methodology for sizing BESS was presented and validated by Etherden et al. using analytical simulation studies. The results revealed that BESS increased the HC of the electrical systems. However, economic assessments are required to validate the feasibility of applying BESS in real electrical networks. The utilization of BESSs to enhance the HC was discussed in Ref. [128], where a systematic methodology for deciding when-to-use storage systems was proposed. Due to the fact that BESSs are expensive, the authors compared them to other competing solutions for HC enhancement. Proper sizing and location of the battery storage systems may postpone DSO's plans for network reinforcements. In this regard, Poulios [129] examined the optimal size, location and economic aspects of BESSs to increase the system's HC for a low voltage network in Zurich. It was concluded that BESS prices need to be greatly reduced in order to be economically competitive with other HC enhancement solutions. Jayasekara et al. [130] introduced a cost-based multi-objective optimization tool that evaluates the optimal BESS capacity. The role of BESS was examined for three objectives: voltage regulation, network loss reduction and peak load reduction. MATLAB simulations were included in both MV and LV distribution systems in Western Australia. It was found that the benefits achieved from the BESS depend on the system configuration, generation profile and loading profile. The efficient control of BESS and its utilization for HC enhancement are analyzed and presented in Refs. [131–133]. The number of EVs is getting increased due to its technical and environmental benefits. Nowadays, more than two million EV are now running around the world [134]. The impacts of EVs on electrical distribution networks and its role in HC enhancement are discussed in Refs. [135,136].

5.5. Network reconfiguration and reinforcement

Network reconfiguration and reinforcement are efficient techniques for HC enhancement. The roles of network reinforcement solutions and OLTC control techniques in increasing the system HC were investigated in Ref. [112]. The presented simulations revealed that for low penetration levels, network reinforcement solutions are cost-effective.

Capitanescu et al. [137] explored the role of network reconfigurations in increasing the system HC of ADNs. The authors categorized the network reconfigurations into two categories, static and dynamic reconfigurations. In the static one, all the required reconfiguration requirements are considered during the planning stage of the project. In the dynamic reconfiguration, reconfigurations are performed using remotely controlled switches employed in ADNs management schemes. The authors concluded that static reconfiguration has many benefits in HC enhancement, but the dynamic reconfiguration can support the HC's enhancement only if a sufficient number of remotely controlled switches were available. The main disadvantages of dynamic reconfigurations are the wear and tear costs of the switching events and the increased risk of failure of the switches. The network reconfiguration is a complicated optimization problem, especially in practical networks with a huge number of switches. Thus, Takenobu et al. [138] proposed an efficient methodology for network reconfiguration to increase the HC by formulating small sub-problems that represent the overall reconfiguration problem. The authors implemented their proposed method on a practical distribution network that consists of 235 switches in Japan, and they were successful in reaching the global optimum solution in 49 h. Fu et al. [139] explored the multi-period reconfiguration of electrical distribution networks as a tool to enhance the network's HC using minimal number of switching events. Ismael et al. [140] investigated the problem of selecting the optimal conductor for a real radial distribution system in Egypt. The authors proposed a novel feeder reinforcement index (*FRI*) to assist the DSOs and network planners to determine the feeders that first need to be reinforced. Besides, Gensollen et al. [141] presented the cheapest procedure for system upgrades to reach a predefined HC. Promising techniques were explored using adaptations to traditional shortest path algorithms. These approaches are foreseen to be used by utilities to reduce the costs of system upgrades.

5.6. Harmonic mitigation techniques

Extensive employment of nonlinear loads and large-scale grid-connected DG units has led to greatly distorted voltages and currents due to their aggregated harmonic distortions. These distorted bus voltages and line currents may result in excessive losses and poor energy transfer efficiency. Therefore, the maximum allowable values for individual and total harmonic distortion of PCC voltages and currents should be strictly adhered to. Many studies investigated the impact of the harmonic distortion generated by the DG units on the HC of distribution systems [62,142–147].

Sakar et al. [62] explored the harmonic-constrained HC assessment and enhancement of distribution systems. The authors concluded that harmonic distortion constraints greatly impact the system's HC, especially in highly distorted systems. It was obvious from the performed studies that under non-sinusoidal conditions, total and individual harmonic distortion percentages are the performance indices that may be violated first; hence, suitable harmonic mitigation solutions should be considered to allow for more DG penetration. Incorporating the harmonic constraints as performance indices for HC evaluation were performed in Refs. [142,143] and it was concluded that harmonic distortion has remarkable impacts on HC assessment. Sakar et al. [144] evaluated the HC of a distorted distribution system with PV units while considering various performance limits such as over-voltage, under-voltage, feeder thermal capacity and harmonic distortions. A comprehensive overview of the harmonic-constrained HC was analyzed and discussed in Ref. [145]. The authors concluded that the system's HC decreases with increase in the load side's nonlinearity values and the utility side's background voltage distortion. The background voltage distortions of the non-sinusoidal system and the nonlinearity degree of the load impact the HC noticeably. Thus, HPR index was proposed to reflect the impact of harmonics on the system's HC. The HPR is given in Eq. (6).

$$HPR = \frac{P_{DG}^{nl}}{P_{DG}^{l}} \leq 1 \tag{6}$$

The HPR ranges from 0 to 1, where zero indicates that no DG penetration is allowed due to high harmonic pollution level, while one indicates that either the system is pure sinusoidal or the harmonic pollution level is too low to affect the hosted DG. HC assessment was discussed in Ref. [146] considering over and under voltage performance limits. The authors investigated the various harmonic types and its relation to the HC assessment such as inter-harmonics and supra-harmonics. It was concluded that the consideration of supra-harmonics in HC calculations is not achievable due to the unavailability of standard limits for the harmonic distortions in this high-frequency range. Tiago et al. [147] validated the role of considering background harmonic distortions on the assessment of network's HC. the authors proposed an index to calculate the voltage rise and harmonic voltage distortion considering background distortions at the PCC.

Finally, Fig. 6 shows an illustrative representation of the various techniques that can be considered in the HC enhancement.

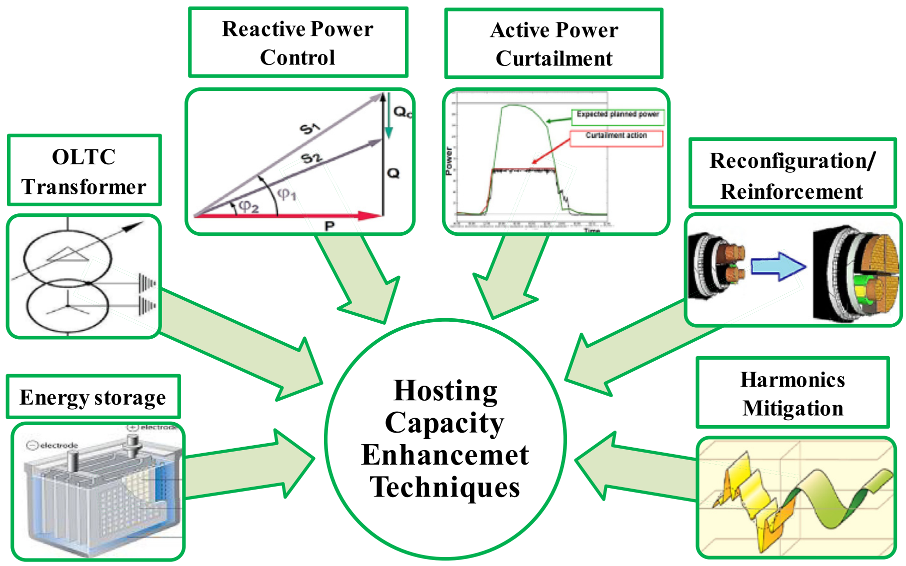


Fig. 6. HC enhancement techniques.

6. Discussion

HC research is a key enabler for affordable, reliable and renewable energy sources so it is possible to transition away from traditional high-carbon energy sources. Therefore, it is imperative that novel solutions be sought to enable networks to cope with future developments to realize resilient distribution networks that can host the pushy DG penetration while enhancing the system reliability of power supplies and controlling the over-hosted areas.

In the near past, quick but conservative methods like the 15% rule were used to limit integrated DG capacities. Nowadays, the HC concept has been developed to define the maximum amount of DG that can be integrated into the electrical network accurately, without exceeding any operational performance limits. However, the HC is a recently-developed concept and a misconception was noticed between penetration and HC in different publications. In this regard, penetration can be considered a DG-oriented concept such that higher DG penetration means that more DGs can be connected to the system. On the other hand, the HC can be considered a system-oriented concept that is portrayed from the system's viewpoint. Higher HC means that more DGs can be hosted by the system satisfactorily. In addition, the HC is a specific, measurable, practical and fair concept that facilitates the ease of use of clear performance limits as evaluation criteria for DG penetration.

Based on the experience gained during preparation of this study, the HC calculation is not a single value that can be calculated once. It should be regularly calculated for various performance indices such as voltage and frequency variations, power quality and so on. Furthermore, the minimum value of the HC should be determined at each node to estimate the overall system's HC.

Uncertainty in the assessment of HC calculations may arise due to many factors such as unknown DG locations and ratings, the intermittent nature of the DGs' output powers, alterations of loads and lack of data when performing power system calculations. Accordingly, the HC should not be a deterministic approach in which no randomness is involved. Instead, it should be viewed as a probabilistic method, whereby account accuracy and uncertainty levels are considered.

The HC is also a location-dependent concept. For example, the minimum HC (worst-case scenario) occurs at the maximum generation and minimum loading conditions, whereas the maximum HC (best-case scenario) occurs at the minimum generation and maximum loading condition. In this regard, HC maps represent an illustrative application of the locational HC approach. These maps can be produced on the geographical feeder routing layout or with network single line diagrams.

As we have shown, different HC enhancement techniques have been developed and each of them has its pros and cons. A detailed network study should be performed to determine whether a solution offers promising benefits or not. It will then be possible to ascertain the most appropriate techniques for coping with the acceptable limits of network operators in relation to technical, economic, operability and maintainability aspects.

7. Conclusions

If not properly assessed, excessive DG penetration may lead to various problems such as overvoltage, thermal overloading, power quality problems and system protection problems. Furthermore, overvoltage can be considered the main problem for high DG penetration.

In this paper, an extensive literature review of the HC concept was provided and explored HC basics and historical developments. The five most common criteria that are of interest for distribution system operators (DSOs) in calculating the HC are based on analyzing the overvoltage, thermal overloading, electrical power loss, power quality and protection problems. All of them are discussed in the manuscript. In addition, different HC enhancement techniques such as reactive power control, voltage control, active power curtailment, energy storage technologies, network reconfiguration and reinforcement and harmonics mitigation techniques are discussed. This research can be beneficial to DSOs and researchers in this field as it presents the past, present and future of HC research. It is expected that the HC will play a significant role in future power systems and smart grids.

Using HC approach to drive network requirements could steer DG toward areas of the network where it could have the greatest positive impact on network reliability and win-win benefits with DG owners. Finally, smarter DG integration into future electrical systems can be met if utilities have a clear forecast of their potential network HC.

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References

[1] P.N. Vovos, A.E. Kiprakis, A.R. Wallace, G.P. Harrison, Centralized and distributed voltage control: impact on distributed generation penetration, IEEE Trans. Power Syst. 22 (2007) 476–483, https://doi.org/10.1109/TPWRS.2006.888982.

[2] J.A.P. Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, N. Jenkins, Integrating distributed generation into electric power systems: a review of drivers, challenges and opportunities, Elec. Power Syst. Res. 77 (2007) 1189–1203, https://doi.org/10.1016/j.epsr.2006.08.016.

[3] S. Stanfield, et al., Optimizing the Grid a Regulator's Guide to Hosting Capacity Analyses for Distributed Energy Resources, IREC, USA, 2017. https://irecusa.org/publications. (Accessed 6 March 2018).

[4] H. Pezeshki, P.J. Wolfs, G. Ledwich, Impact of high PV penetration on distribution transformer insulation life, IEEE Trans. Power Deliv. 29 (2014) 1212–1220, https://doi.org/10.1109/TPWRD.2013.2287002.

[5] D. Chattopadhyay, T. Alpcan, Capacity and energy-only markets under high renewable penetration, IEEE Trans. Power Syst. 31 (2016) 1692–1702, https://doi.org/10.1109/TPWRS.2015.2461675.

[6] N. Hatziargyriou, E. Karfopoulos, A. Tsitsimelis, D. Koukoula, M. Rossi, V. Giacomo, On the DER hosting capacity of distribution feeders, in: 23rd Int. Conf. Electr. Distrib, CIRED, Lyon, Paris, 2015.

[7] M. Ebad, W.M. Grady, An approach for assessing high-penetration PV impact on distribution feeders, Elec. Power Syst. Res. 133 (2016) 347–354, https://doi.org/10.1016/j.epsr.2015.12.026.

[8] T. Adefarati, R.C. Bansal, Integration of renewable distributed generators into the distribution system: a review, IET Renew. Power Gener. 10 (2016) 873–884, https://doi.org/10.1049/iet-rpg.2015.0378.

[9] M. Karimi, H. Mokhlis, K. Naidu, S. Uddin, A.H.A. Bakar, Photovoltaic penetration issues and impacts in distribution network - a review, Renew. Sustain. Energy Rev. 53 (2016) 594–605, https://doi.org/10.1016/j.rser.2015.08.042.

[10] V. Silva, M. Lopez-Botet-Zulueta, Y. Wang, Impact of high penetration of variable renewable generation on frequency dynamics in the continental Europe interconnected system, IET Renew. Power Gener. 10 (2016) 10–16, https://doi.org/10.1049/iet-rpg.2015.0141.

[11] P. Mohammadi, S. Mehraeen, Challenges of PV integration in low-voltage secondary networks, IEEE Trans. Power Deliv. 32 (2017) 525–535, https://doi.org/10.1109/TPWRD.2016.2556692.

[12] C.T. Gaunt, E. Namanya, R. Herman, Voltage modelling of LV feeders with dispersed generation: limits of penetration of randomly connected photovoltaic generation, Elec. Power Syst. Res. 143 (2017) 1–6, https://doi.org/10.1016/j.epsr.2016.08.042.

[13] Power Surge Ahead; How Distribution Utilities Can Get Smart with Distributed Generation, Accenture consulting, 2017. https://www.accenture.com/us-en/insight-smart-integration-distributed-generation-utilities. (Accessed 8 March 2018).

[14] M. Bollen, F. Hassan, Integration of Distributed Generation in the Power System, Wiley- IEEE Press, Hoboken, USA, 2011, https://doi.org/10.1002/9781118029039.

[15] T. Stetz, W. Yan, M. Braun, Voltage control in distribution systems with high level PV-penetration-improving absorption capacity for PV systems by reactive power supply, The 25th European Photovoltaic Solar Energy Conference and Exhibition 49 (2010) 1–7.

[16] T. Stetz, F. Marten, M. Braun, Improved low voltage grid-integration of photovoltaic systems in Germany, IEEE Trans. Sustain. Energy. 4 (2013) 534–542, https://doi.org/10.1109/TSTE.2012.2198925.

[17] J. von Appen, M. Braun, T. Stetz, K. Diwold, D. Geibel, Time in the sun, IEEE Power Energy Mag. 11 (2013) 55–64, https://doi.org/10.1109/MPE.2012.2234407.

[18] M.H.J. Bollen, M. Häger, Power quality: interactions between distributed energy resources, the grid, and other customers and with distributed energy, Electr. Power Qual. Util. Mag. I (2005) 51–61.

[19] J. Deuse, D. Benintendi, Power system and market integration of DER, the eu-deep approach, 18th Int. Conf. Electr. Distrib. (2005) 6–9.

[20] T. Walla, Hosting Capacity for Photovoltaics in Swedish Distribution Grids, Uppsala University, Uppsala, Sweden, 2012. M.Sc. thesis.

[21] S. Papathanassiou, N. Hatziargyriou, P. Anagnostopoulos, L. Aleixo, B. Buchholz, C. Carter-Brown, et al., Capacity of Distribution Feeders for Hosting DER, vol. 24, 2014. Working Group C6.

[22] N. Etherden, Increasing the Hosting Capacity of Distributed Energy Resources Using Storage and Communication, Lulea University of Technology, Lulea, Sweden, 2014. Ph.D. thesis.

[23] W. Sun, Maximizing Renewable Hosting Capacity in Electricity Networks, The University of Edinburgh, Edinburgh, Scotland, 2015. Ph.D. thesis.

[24] M.H.J. Bollen, F. Sollerkvist, A. Larsson, M. Lundmark, Limits to the hosting capacity of the grid for equipment emitting high-frequency distortion, Proc. Nord. Distrib. Asset. Manag. Conf. Nord. (2006).

[25] F. AlAlamat, Increasing the Hosting Capacity of Radial Distribution Grids in Jordan, Uppsala University, Uppsala, Sweden, 2015. B.Sc. thesis.

[26] N. Etherden, M.H.J. Bollen, S. Ackeby, O. Lennerhag, The transparant hosting-capacity approach – overview, applications and developments, in: 23 Rd Int. Conf. Electr. Distrib., 2015, pp. 1–5.

[27] B. Palmintier, R. Broderick, B. Mather, M. Coddington, K. Baker, F. Ding, M. Reno, M. Lave, A. Bharatkumar, On the Path to SunShot: Emerging Issues and Challenges in Integrating Solar with the Distribution System, 2016. NREL/TP-5D00-6533, SAND2016-2524 R, NREL/TP-5D00-65331; SAND2016-2524R.

[28] A. Rabiee, S.M. Mohseni-Bonab, Maximizing hosting capacity of renewable energy sources in distribution networks: a multi-objective and scenario-based approach, Energy 120 (2017) 417–430, https://doi.org/10.1016/j.energy.2016.11.095.

[29] M. Rylander, J. Smith, Stochastic analysis to determine feeder hosting capacity for distributed solar PV, EPRI Tech. Updat. 1026640 (2012) 1–50, 1026640.

[30] Alternatives to the 15% Rule: Modeling and Hosting Capacity Analysis of 16 Feeders, EPRI, Palo Alto, CA, 2015, 3002005812.

[31] S. Stanfield, IREC Insight Series: Key Lessons from the California Integrated Capacity Analysis, Interstate renewable energy council (IREC), 2017. http://www.irecusa.org/2017/03/irec-insight-series-key-lessons-from-the-california-integrated-capacity-analysis/. (Accessed 10 October 2017).

[32] A. Dubey, S. Santoso, A. Maitra, Understanding photovoltaic hosting capacity of distribution circuits, in: IEEE Power Energy Soc. Gen. Meet., 2015, https://doi.org/10.1109/PESGM.2015.7286510.

[33] J. Le Baut, P. Zehetbauer, S. Kadam, B. Bletterie, N. Hatziargyriou, J. Smith, M. Rylander, Probabilistic evaluation of the hosting capacity in distribution networks, in: IEEE PES Innov. Smart Grid Technol. Conf. Eur., 2017, https://doi.org/10.1109/ISGTEurope.2016.7856213.

[34] E.J. Palacios-Garcia, A. Moreno-Muñoz, I. Santiago, I.M. Moreno-Garcia, M.I. Milanés-Montero, PV hosting capacity analysis and enhancement using high resolution stochastic modeling, Energies 10 (2017), https://doi.org/10.3390/en10101488.

[35] M. Rylander, J. Smith, W. Sunderman, Streamlined method for determining distribution system hosting capacity, IEEE Trans. Ind. Appl. 52 (2016) 105–111, https://doi.org/10.1109/TIA.2015.2472357.

[36] M.J. Reno, R.J. Broderick, Statistical analysis of feeder and locational PV hosting capacity for 216 feeders, in: IEEE Power Energy Soc. Gen. Meet., 2016, https://doi.org/10.1109/PESGM.2016.7741269.

[37] J. Reno Matthew, Streamlined Interconnection Analysis of Distributed PV Using Advanced Simulation Methods, Ph.D. Thesis, Georgia Institute of Technology, 2015.

[38] R.A. Shayani, M.A.G. De Oliveira, Photovoltaic generation penetration limits in radial distribution systems, IEEE Trans. Power Syst. 26 (2011) 1625–1631, https://doi.org/10.1109/TPWRS.2010.2077656.

[39] P. Hauffe, C. Wendel, M. Arnold, W. Wellssow, Techno-Economic assessment of planning principles for low voltage grids in the presence of massive distributed PV generation, in: 23rd Int. Conf. Exhib. Electr. Distrib., 2015.

[40] P. Westacott, C. Candelise, Assessing the impacts of photovoltaic penetration across an entire low-voltage distribution network containing 1.5 million customers, IET Renew. Power Gener. 10 (2016) 460–466, https://doi.org/10.1049/iet-rpg.2015.0535.

[41] M.K. Gray, W.G. Morsi, On the role of prosumers owning rooftop solar photovoltaic in reducing the impact on transformer's aging due to plug-in electric vehicles charging, Elec. Power Syst. Res. 143 (2017) 563–572, https://doi.org/10.1016/j.epsr.2016.10.060.

[42] D. Bertini, D. Falabretti, M. Merlo, D. Moneta, J. Carneiro, Hosting capacity of Italian LV distribution networks, in: 21st Int. Conf. Exhib. Electr. Distrib., 2011.

[43] M. Emmanuel, R. Rayudu, Evolution of dispatchable photovoltaic system integration with the electric power network for smart grid applications: a review, Renew. Sustain. Energy Rev. 67 (2017) 207–224, https://doi.org/10.1016/j.rser.2016.09.010.

[44] Y. Yang, M.H.J. Bollen, Power Quality and Reliability in Distribution Networks with Increased Levels of Distributed Generation, Elforsk, 2008.

[45] T. Degner, G. Arnold, T. Reimann, B. Engel, M. Breede, P. Strauss, Increasing the photovoltaic-system hosting capacity of low voltage distribution networks, in: 21st Int. Conf. Exhib. Electr. Distrib., 2011.

[46] D. Moneta, P. Mora, M. Gallanti, G. Monfredini, M. Merlo, V. Olivieri, MV network with dispersed generation: voltage regulation based on local controllers, in: 21st Int. Conf. Exhib. Electr. Distrib., 2011.

[47] E. De Jaeger, A. Du Bois, B. Martin, Hosting Capacity of LV distribution grids for small distributed generation units, referring to voltage level and unbalance, in: 22nd Int. Conf. Exhib. Electr. Distrib., 2012.

[48] D. Schwanz, S.K. Ronnberg, M. Bollen, Hosting capacity for photovoltaic inverters considering voltage unbalance, in: IEEE Manchester PowerTech, Powertech 2017, 2017, https://doi.org/10.1109/PTC.2017.7981274.

[49] D. Schwanz, F. Moller, S.K. Ronnberg, J. Meyer, M.H.J. Bollen, Stochastic assessment of voltage unbalance due to single-phase-connected solar power, IEEE Trans. Power Deliv. 32 (2017) 852–861, https://doi.org/10.1109/TPWRD.2016.2579680.

[50] L. Collins, J.K. Ward, Real and reactive power control of distributed PV inverters for overvoltage prevention and increased renewable generation hosting capacity, Renew. Energy 81 (2015) 464–471, https://doi.org/10.1016/j.renene.2015.03.012.

[51] R. Seguin, J. Woyak, D. Costyk, J. Hambrick, B. Mather, High-penetration PV Integration Handbook for Distribution Engineers, National Renewable Energy Laboratory, Golden, CO, 2016. NREL/TP-5D00-63114.

[52] S.K. Sharma, A. Chandra, M. Saad, S. Lefebvre, D. Asber, L. Lenoir, Voltage flicker mitigation employing smart loads with high penetration of renewable energy in distribution systems, IEEE Trans. Sustain. Energy. 8 (2017) 414–424, https://doi.org/10.1109/TSTE.2016.2603512.

[53] Wei Sun, G.P. Harrison, S.Z. Djokic, Incorporating harmonic limits into assessment of the hosting capacity of active networks, in: CIRED 2012 Work. Integr. Renewables into Distrib. Grid, 2012, https://doi.org/10.1049/cp.2012.0869, 325–325.

[54] I.N. Santos, M.H.J. Bollen, P.F. Ribeiro, Methodology for estimation of harmonic hosting, in: Proc. Int. Conf. Harmon. Qual. Power, ICHQP, 2014, pp. 708–712, https://doi.org/10.1109/ICHQP.2014.6842849.

[55] M.H.J. Bollen, S. Bahramirad, A. Khodaei, Is there a place for power quality in the smart grid?, in: Proc. Int. Conf. Harmon. Qual. Power ICHQP, 2014, pp. 713–717, https://doi.org/10.1109/ICHQP.2014.6842865.

[56] I.N. Santos, V. Ćuk, P.M. Almeida, M.H.J. Bollen, P.F. Ribeiro, Considerations on hosting capacity for harmonic distortions on transmission and distribution systems, Elec. Power Syst. Res. 119 (2015) 199–206, https://doi.org/10.1016/j.epsr.2014.09.020.

[57] A. Molina-García, A. Honrubia-Escribano, T. García-Sánchez, E. Gómez-Lázaro, E. Muljadi, Power quality surveys of photovoltaic power plants: characterisation and analysis of grid-code requirements, IET Renew. Power Gener. 9 (2015) 466–473, https://doi.org/10.1049/iet-rpg.2014.0215.

[58] X. Liang, Emerging power quality challenges due to integration of renewable energy sources, IEEE Trans. Ind. Appl. 53 (2017) 855–866, https://doi.org/10.1109/TIA.2016.2626253.

[59] N. Mithulananthan, T. Kumar Saha, A. Chidurala, Harmonic impact of high penetration photovoltaic system on unbalanced distribution networks – learning from an urban photovoltaic network, IET Renew. Power Gener. 10 (2016) 485–494, https://doi.org/10.1049/iet-rpg.2015.0188.

[60] H. Sharma, M. Rylander, D. Dorr, Grid impacts due to increased penetration of newer harmonic sources, IEEE Trans. Ind. Appl. 52 (2016) 99–104, https://doi.org/10.1109/TIA.2015.2464175.

[61] P.K. Ray, S.R. Mohanty, N. Kishor, Classification of power quality disturbances due to environmental characteristics in distributed generation system, IEEE Trans. Sustain. Energy. 4 (2013) 302–313, https://doi.org/10.1109/TSTE.2012.2224678.

[62] S. Sakar, M.E. Balci, S.H.E.A. Aleem, A.F. Zobaa, Hosting capacity assessment and improvement for photovoltaic-based distributed generation in distorted distribution networks, in: EEEIC 2016 - Int. Conf. Environ. Electr. Eng., 2016, https://doi.org/10.1109/EEEIC.2016.7555515.

[63] L.D. Campello, P.M. Duarte, P.F. Ribeiro, T.E. De Oliveira, Hosting capacity of a university electrical grid considering the inclusion of wind-turbines for different background distortions, in: Proc. Int. Conf. Harmon. Qual. Power, ICHQP, 2016, pp. 1026–1031, https://doi.org/10.1109/ICHQP.2016.7783335.

[64] T.E.C. De Oliveira, P.F. Ribeiro, I.N. Santos, Determining the harmonic hosting capacity of PV sources for a university campus, in: Proc. Int. Conf. Harmon. Qual. Power, ICHQP, 2016, pp. 836–841, https://doi.org/10.1109/ICHQP.2016.7783371.

[65] J. Deuse, S. Grenard, M.H.J. Bollen, M. Häger, F. Sollerkvist, Effective impact of DER on distribution system protection, Conf. Proc. 19th Int. Conf. Exhib. Electr. Distrib. (2007).

[66] R.A. Walling, R. Saint, R.C. Dugan, J. Burke, L.A. Kojovic, Summary of distributed resources impact on power delivery systems, IEEE Trans. Power Deliv. 23 (2008) 1636–1644, https://doi.org/10.1109/TPWRD.2007.909115.

[67] H. Zhan, C. Wang, Y. Wang, X. Yang, X. Zhang, C. Wu, Y. Chen, Relay protection coordination integrated optimal placement and sizing of distributed generation sources in distribution networks, IEEE Trans. Smart Grid. 7 (2016) 55–65, https://doi.org/10.1109/TSG.2015.2420667.

[68] E. Haesen, F. Minne, J. Driesen, M. Bollen, Hosting capacity for motor starting in weak grids, Int. Conf. Futur. Power Syst. (2005) 1–6, https://doi.org/10.1109/FPS.2005.204291.

[69] V. Van Thong, J. Driesen, R. Belmans, DG interconnection standards and technical requirements comparisons and gaps, 19th Int. Conf. Exhib. Electr. Distrib. (2007).

[70] D. Menniti, M. Merlo, N. Scordino, F. Zanellini, Distribution network analysis: a comparison between hosting and loading capacities, in: SPEEDAM 2012 - 21st Int. Symp. Power Electron. Electr. Drives, Autom. Motion, 2012, pp. 926–933, https://doi.org/10.1109/SPEEDAM.2012.6264635.

[71] L. Consiglio, D. Stein, J. Stromsather, Enel's large scale demonstration project inside GRID4EU: the challenge of RES integration in the MV network, in: 22nd Int. Conf. Exhib. Electr. Distrib. (CIRED 2013), 2013, https://doi.org/10.1049/cp.2013.1085, 1127–1127.

[72] J. Varela, N. Hatziargyriou, L.J. Puglisi, M. Rossi, A. Abart, B. Bletterie, The IGREENGrid project: increasing hosting capacity in distribution grids, IEEE Power Energy Mag. 15 (2017) 30–40, https://doi.org/10.1109/MPE.2017.2662338.

[73] M. Delfanti, M. Merlo, G. Monfredini, V. Olivieri, M. Pozzi, A. Silvestri, Hosting dispersed generation on Italian MV networks: towards smart grids, in: ICHQP 2010 - 14th Int. Conf. Harmon. Qual. Power, 2010, https://doi.org/10.1109/ICHQP.2010.5625442.

[74] M. Alturki, A. Khodaei, A. Paaso, S. Bahramirad, Optimization-based distribution grid hosting capacity calculations, Appl. Energy 219 (2018) 350–360, https://doi.org/10.1016/j.apenergy.2017.10.127.

[75] S.N. Salih, P. Chen, O. Carlson, L.B. Tjernberg, Optimizing wind power hosting capacity of distribution systems using cost benefit analysis, IEEE Trans. Power Deliv. 29 (2014) 1436–1445, https://doi.org/10.1109/TPWRD.2014.2303204.

[76] M. Altin, E.U. Oguz, E. Bizkevelci, B. Simsek, Distributed generation hosting capacity calculation of MV distribution feeders in Turkey, in: IEEE PES Innov. Smart Grid Technol. Conf. Eur., 2015, https://doi.org/10.1109/ISGTEurope.2014.7028776.

[77] V. Klonari, J.F. Toubeau, Z. De Grève, O. Durieux, J. Lobry, F. Vallée, Probabilistic analysis tool of the voltage profile in low voltage grids, in: 23rd Int. Conf. Exhib. Electr. Distrib., 2015.

[78] M. Rossi, G. Viganò, D. Moneta, Hosting capacity of distribution networks: evaluation of the network congestion risk due to distributed generation, in: 5th Int. Conf. Clean Electr. Power Renew. Energy Resour. Impact, ICCEP, 2015, pp. 716–722, https://doi.org/10.1109/ICCEP.2015.7177570.

[79] S. Jothibasu, S. Santoso, Sensitivity analysis of photovoltaic hosting capacity of distribution circuits, in: IEEE Power Energy Soc. Gen. Meet., 2016, pp. 1–5, https://doi.org/10.1109/PESGM.2016.7741861.

[80] J. Smith, M. Rylander, L. Rogers, Integration of Hosting Capacity Analysis into Distribution Planning Tools, EPRI, Palo Alto, CA, 2015. Tech. Report no. 3002005793.

[81] M. Rylander, J. Smith, W. Sunderman, D. Smith, J. Glass, Application of new method for distribution-wide assessment of Distributed Energy Resources, IEEE/PES Transm. Distrib. Conf. Expo. (2016) 1–5, https://doi.org/10.1109/TDC.2016.7519994.

[82] A. Dubey, S. Santoso, On estimation and sensitivity analysis of distribution Circuit's photovoltaic hosting capacity, IEEE Trans. Power Syst. 32 (2017) 2779–2789, https://doi.org/10.1109/TPWRS.2016.2622286.

[83] R. Celiloglu, Integration of Large Capacity PV Power and Measuring PV Hosting Capacity of North Cyprus MV Grid, Aalborg University, Denmark, 2017. M.Sc. thesis.

[84] A. Arshad, M. Lindner, M. Lehtonen, An analysis of photo-voltaic hosting capacity in Finnish low voltage distribution networks, Energies 10 (2017), https://doi.org/10.3390/en10111702.

[85] X. Chen, W. Wu, B. Zhang, C. Lin, Data-driven DG capacity assessment method for active distribution networks, IEEE Trans. Power Syst. 32 (2017) 3946–3957, https://doi.org/10.1109/TPWRS.2016.2633299.

[86] A. Navarro-Espinosa, L.F. Ochoa, Probabilistic impact assessment of low carbon technologies in LV distribution systems, IEEE Trans. Power Syst. 31 (2016) 2192–2203, https://doi.org/10.1109/TPWRS.2015.2448663.

[87] B. Currie, C. Abbey, G. Ault, J. Ballard, B. Conroy, R. Sims, C. Williams, Flexibility is key in New York: new tools and operational solutions for managing distributed energy resources, IEEE Power Energy Mag. 15 (2017) 20–29, https://doi.org/10.1109/MPE.2017.2660818.

[88] Horizon Power, Renewable Energy: Available Hosting Capacity, Australia, 2017. https://www.horizonpower.com.au/media/1592/hosting-capacities-fact-sheet-030317.pdf. (Accessed 10 October 2017).

[89] M. Vandenbergh, R. Hermes, V. Helmbrecht, H. Loew, D. Craciun, Technical solutions supporting the large scale integration of photovoltaic systems in the future distribution grids, in: 22nd Int. Conf. Exhib. Electr. Distrib., 2013, https://doi.org/10.1049/cp.2013.0699.

[90] N. Jenkins, Assessing distribution network hosting capacity with the addition of soft open points, IET Conf Proc 32 (6) (2016).

[91] H. Al-Saadi, R. Zivanovic, S.F. Al-Sarawi, Probabilistic hosting capacity for active distribution networks, IEEE Trans. Ind. Informatics. 13 (2017) 2519–2532, https://doi.org/10.1109/TII.2017.2698505.

[92] A. Soroudi, A. Rabiee, A. Keane, Distribution networks' energy losses versus hosting capacity of wind power in the presence of demand flexibility, Renew. Energy 102 (2017) 316–325, https://doi.org/10.1016/j.renene.2016.10.051.

[93] M.H.J. Bollen, The smart grid: adapting the power system to new challenges, Synth. Lect. Power Electron. 2 (2011) 1–180, https://doi.org/10.2200/S00385ED1V01Y201109PEL003. Smart Grid Handbook; Wiley: Hoboken, NJ, USA, 2016.

[94] F. Ding, B. Mather, On distributed PV hosting capacity estimation, sensitivity study, and improvement, IEEE Trans. Sustain. Energy. 8 (2017) 1010–1020, https://doi.org/10.1109/TSTE.2016.2640239.

[95] P.K.C. Wong, A. Kalam, R. Barr, Modelling and analysis of practical options to improve the hosting capacity of low voltage networks for embedded photovoltaic generation, IET Renew. Power Gener. 11 (2017) 625–632, https://doi.org/10.1049/iet-rpg.2016.0770.

[96] M.H. Athari, Z. Wang, S.H. Eylas, Time-series analysis of photovoltaic distributed generation impacts on a local distributed network, IEEE Manchester PowerTech, 2017, pp. 1–6, https://doi.org/10.1109/PTC.2017.7980908.

[97] A. Christos, Investigation of the Distribution Grid Hosting Capacity for Distributed Generation and Possible Improvements by SmartGrid

Technologies, ETH Zurich University, 2016. M.Sc. Thesis.

[98] F. Ebe, B. Idlbi, J. Morris, G. Heilscher, F. Meier, Evaluation of PV hosting capacity of distribuion grids considering a solar roof potential analysis - comparison of different algorithms, in: 2017 IEEE Manchester PowerTech, Powertech, 2017, https://doi.org/10.1109/PTC.2017.7981017.

[99] V. Quintero-Molina, M. Romero-L, A. Pavas, Assessment of the hosting capacity in distribution networks with different DG location, IEEE Manchester PowerTech, 2017, https://doi.org/10.1109/PTC.2017.7981243. Powertech 2017.

[100] T. Jamal, T. Urmee, M. Calais, G.M. Shafiullah, C. Carter, Technical challenges of PV deployment into remote Australian electricity networks: a review, Renew. Sustain. Energy Rev. 77 (2017) 1309–1325, https://doi.org/10.1016/j.rser.2017.02.080.

[101] S.F. Santos, D.Z. Fitiwi, M. Shafie-Khah, A.W. Bizuayehu, C.M.P. Cabrita, J.P.S. Catalão, New multi-stage and stochastic mathematical model for maximizing RES hosting capacity - Part I: problem formulation, IEEE Trans. Sustain. Energy. 8 (2017) 304–319, https://doi.org/10.1109/TSTE.2016.2598400.

[102] S.F. Santos, D.Z. Fitiwi, M. Shafie-Khah, A.W. Bizuayehu, C.M.P. Cabrita, J.P.S. Catalão, New multi-stage and stochastic mathematical model for maximizing RES hosting capacity - Part II: numerical results, IEEE Trans. Sustain. Energy. 8 (2017) 320–330, https://doi.org/10.1109/TSTE.2016.2584122.

[103] M. Meuser, H. Vennegeerts, P. Schäfer, Impact of voltage control by distributed generation on hosting capacity and reactive power balance in distribution grids, IET Conf. Proc. (2012).

[104] D. Mende, Increasing the hosting capacity of distribution networks for distributed generation using reactive power control-potentials and limits, in: 2nd Int. Work Integr. Sol. Power into Power Syst., 2012, pp. 153–159.

[105] J. Seuss, M.J. Reno, R.J. Broderick, S. Grijalva, Improving distribution network PV hosting capacity via smart inverter reactive power support, in: IEEE Power Energy Soc. Gen. Meet., 2015, https://doi.org/10.1109/PESGM.2015.7286523.

[106] A. soroudi, A. rabiee, A. keane, Distribution network hosting capacity maximization using demand response, in: 23rd Int. Conf. Exhib. Electr. Distrib., 2015, pp. 1–5.

[107] F. Ding, B. Mather, P. Gotseff, Technologies to increase PV hosting capacity in distribution feeders, in: IEEE Power Energy Soc. Gen. Meet., 2016, https://doi.org/10.1109/PESGM.2016.7741575.

[108] C. Schwaegerl, M.H.J. Bollen, K. Karoui, A. Yagmur, Voltage control in distribution systems as a limitation of the hosting capacity for distributed energy resources, in: 18th Int. Conf. Exhib. Electr. Distrib., 2005.

[109] A. Berizzi, C. Bovo, V. Ilea, M. Merlo, G. Monfredini, M. Subasic, C. Arrigoni, F. Zanellini, F. Corti, I. Rochira, Advanced functions for DSOs control center, in: 2013 IEEE Grenoble Conf., PowerTech, 2013, https://doi.org/10.1109/PTC.2013.6652343. POWERTECH 2013.

[110] E. Sáiz-Marín, E. Lobato, I. Egido, Local hosting capacity increase by means of wind farm voltage control provision, IEEE Trans. Power Syst. 29 (2014) 1731–1738, https://doi.org/10.1109/TPWRS.2014.2299290.

[111] B. Bletterie, J. Le Baut, S. Kadam, R. Bolgaryn, A. Abart, Hosting capacity of LV networks with extended voltage band, in: Proc. - 2015 Int. Symp. Smart Electr. Distrib. Syst. Technol., EDST, 2015, pp. 531–536, https://doi.org/10.1109/SEDST.2015.7315265.

[112] A. Navarro-Espinosa, L.F. Ochoa, Increasing the PV hosting capacity of Lv networks: OLTC-fitted transformers vs. reinforcements, in: 2015 IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf., ISGT, 2015, https://doi.org/10.1109/ISGT.2015.7131856, 2015.

[113] K. Rauma, F. Cadoux, N. Hadj-SaïD, A. Dufournet, C. Baudot, G. Roupioz, Assessment of the MV/LV on-load tap changer technology as a way to increase LV hosting capacity for photovoltaic power generators, IET Conf. Proc. (2016), https://doi.org/10.1049/cp.2016.0644.

[114] R. Kalle, Industrial Aspects of Voltage Management and Hosting Capacity of Photovoltaic Power Generation in Low Voltage Networks, Université Grenoble Alpes, 2016. Ph.D. Thesis.

[115] B. Bletterie, S. Kadam, R. Bolgaryn, A. Zegers, Voltage control with PV inverters in low voltage networks-in depth analysis of different concepts and parameterization criteria, IEEE Trans. Power Syst. 32 (2017) 177–185, https://doi.org/10.1109/TPWRS.2016.2554099.

[116] C. Long, L.F. Ochoa, Voltage control of PV-rich LV networks: OLTC-fitted transformer and capacitor banks, IEEE Trans. Power Syst. 31 (2016) 4016–4025, https://doi.org/10.1109/TPWRS.2015.2494627.

[117] D. Erhan, Control of Grid Interactive PV Inverters for High Penetration in Low Voltage Distribution Networks, Aalborg University, Department of Energy Technology, Aalborg, Denmark, 2012. Ph.D. Thesis.

[118] S. Hashemi, J. Østergaard, Efficient control of energy storage for increasing the PV hosting capacity of LV grids, IEEE Trans. Smart Grid. 9 (2018) 2295–2303, https://doi.org/10.1109/TSG.2016.2609892.

[119] N. Etherden, M.H.J. Bollen, Increasing the hosting capacity of distribution networks by curtailment of renewable energy resources, in: 2011 IEEE PES Trondheim PowerTech Power Technol. A Sustain. Soc., POWERTECH, 2011, https://doi.org/10.1109/PTC.2011.6019292, 2011.

[120] N. Etherden, M.H.J. Bollen, Overload and overvoltage in low-voltage and medium-voltage networks due to renewable energy - some illustrative case studies, Elec. Power Syst. Res. 114 (2014) 39–48, https://doi.org/10.1016/j.epsr.2014.03.028.

[121] J.T. Nicholas, Etherden, Math Bollen, Increasing hosting capacity through dynamic line rating – risk aspects, in: Cigré Int. Symp. - across Borders - HVDC Syst. Mark. Integr., 2015.

[122] J. Le Baut, Increased hosting capacity by means of active power curtailment, IET Conf. Proc. 194 (4) (2016), https://doi.org/10.1049/cp.2016.0794, 194 (4 .)(1).

[123] IEC, Electrical Energy Storage, 2011, https://doi.org/10.1002/bse.3280020501 white paper.

[124] IEC, Grid Integration of Large-capacity Renewable Energy Sources and Use of Large-capacity Electrical Energy Storage, 2012, p. 102, https://doi.org/10.1016/j.icrp.2009.12.007 white paper.

[125] A.K. Srivastava, A.A. Kumar, N.N. Schulz, Impact of distributed generations with energy storage devices on the electric grid, IEEE Syst. J. 6 (2012) 110–117, https://doi.org/10.1109/JSYST.2011.2163013.

[126] H. Sugihara, K. Yokoyama, O. Saeki, K. Tsuji, T. Funaki, Economic and efficient voltage management using customer-owned energy storage systems in a distribution network with high penetration of photovoltaic systems, IEEE Trans. Power Syst. 28 (2013) 102–111, https://doi.org/10.1109/TPWRS.2012.2196529.

[127] N. Etherden, M.H.J. Bollen, Dimensioning of energy storage for increased integration of wind power, IEEE Trans. Sustain. Energy. 4 (2013) 546–553, https://doi.org/10.1109/TSTE.2012.2228244.

[128] N. Etherden, M. Bollen, The use of battery storage for increasing the hosting capacity of the grid for renewable electricity production, in: Int. Conf. On Innovation for Secure and Efficient Trans. Grids, CIGRÉ, Belgium, 2014.

[129] V. Poulios, Optimal Placement and Sizing of Battery Storage to Increase the PV Hosting Capacity of Low Voltage Grids, ETH Zurich University, Zürich, Switzerland, 2014. M.Sc. thesis.

[130] N. Jayasekara, M.A.S. Masoum, P.J. Wolfs, Optimal operation of distributed energy storage systems to improve distribution network load and generation hosting capability, IEEE Trans. Sustain. Energy. 7 (2016) 250–261, https://doi.org/10.1109/TSTE.2015.2487360.

[131] O.C. Rascon, B. Schachler, J. Buhler, M. Resch, A. Sumper, Increasing the hosting capacity of distribution grids by implementing residential PV storage systems and reactive power control, in: Int. Conf. Eur. Energy Mark. EEM, 2016, https://doi.org/10.1109/EEM.2016.7521338.

[132] S. Hashemi, J. Østergaard, Methods and strategies for overvoltage prevention in low voltage distribution systems with PV, IET Renew. Power Gener. 11 (2017) 205–214, https://doi.org/10.1049/iet-rpg.2016.0277.

[133] S. Shao, F. Jahanbakhsh, J.R. Aguero, L. Xu, Integration of PEVs and PV-dg in Power Distribution Systems Using Distributed Energy Storage—Dynamic Analyses, Innov. Smart Grid Technol. (ISGT), IEEE PES, 2013, pp. 1–6, 107.

[134] International Energy Agency, Global EV Outlook 2017: Two Million and Counting, IEA Publ, 2017, pp. 1–71, https://doi.org/10.1787/9789264278882-en.

[135] J. Zhao, J. Wang, Z. Xu, C. Wang, C. Wan, C. Chen, Distribution network electric vehicle hosting capacity maximization: a chargeable region optimization model, IEEE Trans. Power Syst. 32 (2017) 4119–4130, https://doi.org/10.1109/TPWRS.2017.2652485.

[136] R. González, Assessment of Hosting Capacity of Low Voltage Networks for Electric Vehicles, Comillas University, Madrid, Spain, 2013. M.Sc. Thesis.

[137] F. Capitanescu, L.F. Ochoa, H. Margossian, N.D. Hatziargyriou, Assessing the potential of network reconfiguration to improve distributed generation hosting capacity in active distribution systems, IEEE Trans. Power Syst. 30 (2015) 346–356, https://doi.org/10.1109/TPWRS.2014.2320895.

[138] Y. Takenobu, S. Kawano, Y. Hayashi, N. Yasuda, S.I. Minato, Maximizing hosting capacity of distributed generation by network reconfiguration in distribution system, in: 19th Power Syst. Comput. Conf. PSCC 2016, 2016, https://doi.org/10.1109/PSCC.2016.7540965.

[139] Y.Y. Fu, H.D. Chiang, Toward optimal multi-period network reconfiguration for increasing the hosting capacity of distribution networks, in: IEEE Power Energy Soc. Gen. Meet., 2018, pp. 1–5, https://doi.org/10.1109/PESGM.2017.8274614.

[140] S.M. Ismael, S.H.E. Aleem, A.Y. Abdelaziz, A.F. Zobaa, Practical considerations for optimal conductor reinforcement and hosting capacity enhancement in radial distribution systems, IEEE Access 6 (2018) 27268–27277, https://doi.org/10.1109/access.2018.2835165.

[141] N. Gensollen, K. Horowitz, B. Palmintier, F. Ding, B. Mather, Beyond Hosting Capacity: Using Shortest Path Methods to Minimize Upgrade Cost Pathways, Preprint, National Renewable Energy Laboratory, Golden, CO, May 2018, 80401,USA.

[142] G.P. Harrison, S.Z. Djokic, Distribution network capacity assessment: incorporating harmonic distortion limits, in: 2012 IEEE Power Energy Soc. Gen. Meet., 2012, pp. 1–7, https://doi.org/10.1109/PESGM.2012.6344764.

[143] D. Schwanz, Hosting capacity of the grid for wind generators set by voltage magnitude and distortion levels, IET Conf. Proc. (2016) 73–79, https://doi.org/10.1049/cp.2016.1062.

[144] S. Sakar, M.E. Balci, S.H.E. Abdel Aleem, A.F. Zobaa, Increasing PV hosting capacity in distorted distribution systems using passive harmonic filtering, Elec. Power Syst. Res. 148 (2017) 74–86, https://doi.org/10.1016/j.epsr.2017.03.020.

[145] S. Sakar, M.E. Balci, S.H.E. Abdel Aleem, A.F. Zobaa, Integration of large- scale PV plants in non-sinusoidal environments: considerations on hosting capacity and harmonic distortion limits, Renew. Sustain. Energy Rev. 82 (2018) 176–186, https://doi.org/10.1016/j.rser.2017.09.028.

[146] M.H.J. Bollen, S.K. Rönnberg, Hosting capacity of the power grid for renewable electricity production and new large consumption equipment, Energies 10 (2017), https://doi.org/10.3390/en10091325.
[147] T.E.C. de Oliveira, P.M.S. Carvalho, P.F. Ribeiro, B.D. Bonatto, PV hosting capacity dependence on harmonic voltage distortion in low-voltage grids: model validation with experimental data, Energies 11 (2018), https://doi.org/10.3390/en11020465.