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REVIEW

Hosting capacity in distribution grids: A review of definitions, performance indices, determination methodologies, and enhancement techniques

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Abstract

For the past few years, the world has seen a great shift toward renewable energy resources from conventional ones. But the ever-increasing integration of distributed generation (DG) to the electrical network leads to integration limiting constraints like overvoltage, under voltage, harmonics, equipment ampacity violations, and failure of protection schemes. Therefore, an extensive investigation of the methodologies in which DGs can be incorporated into the electrical network is presented in this manuscript. This article provides an extensive review of all the hosting capacity (HC) terms, references, limiting constraints of the studied networks, geographical segregation, and their determination methodologies. Moreover, the factors defining the HCs of various networks and the architectures employed to increase them, are also explained briefly in the conducted review study.

KEYWORDS

distributed generation, distribution grid, hosting capacity, renewable integration

1 | INTRODUCTION

Power grids were started to establish around 1870. At that time there was no concept of the generation of electric energy by an independent consumer, so those grids were only responsible for the unidirectional flow of power, from the grid to the distribution centers. For the past few decades, customers are being encouraged by utilities to integrate distributed generation (DG). However, the network operators must deal with network congestion and power quality standard-abiding problem.[1] Although all renewable resources are being utilized in the electrical grids at one point or another, photovoltaic (PV) energy resources are the most common source that is being utilized by the end-user.[2] Now a day's large number of applications are received by distribution companies for the installation of new PV systems that results in high PV penetration in the low voltage (LV) networks, resulting in the power-quality's standard abidance issue and the operational constraints' violation problems,[3,4] for instance, voltage and ampacity violations of the distribution equipment, protection scheme failure because of the reverse power flow, and so on.[4–6] The system resilience toward the PV penetration in the system requires an extensive study related to the performance indices that might not be met if the PV connections exceed a certain limit. And to define that limit of PVs that will not have an impact on the normal operation of the existing distribution grid, the idea of hosting capacity (HC) of a grid was introduced by Math Bolan.[6] The HC concept later became the key idea in relating the performance indices of the network and power quality constraints' violations that will be directly linked with the amount of DGs that can be integrated into the downstream network. One of the needs for proper studies related to HC is to find a common ground for DG investors and DG system operators. Hence, such studies became an important tool in power system planning and power quality abidance studies for the network operators where the uncertainty of DGs is of utmost importance.[7]

In a traditional power system, the impacts of DGs on the existing equipment operation and protection schemes' coordination can be hazardous. For instance, the voltage regulation equipment such as step voltage regulators (SVRs), on-load tap changers (OLTC's), line drop compensators (LDC), and capacitor banks are set as per the requirement of the unidirectional power flow and have the least information about the schemes to follow in case of reverse flow of power. Therefore, some practice rule of thumb is presented in Shayani and de Oliveira,[8] to select the maximum DG penetration. Moreover, according to the standard specified,[9] DG should not take part in the voltage regulation scheme. They are only added to the existing scheme when there is a mutual agreement between the utility and the customer. As, DGs can cause high voltages when connected in small residential areas and if the transformer's primary voltage is already at its upper limit, the DG can reduce voltage drop through the transformer and secondary conductors. This will cause high voltages which will be experienced by other customers.[10]

Voltage-controlled capacitor banks should not be impacted by the DGs if they operate outside the voltage regulation mode. To avoid the "voltage hunting" between the capacitors and DG, some specific set points should be adjusted, and time delays should be extended. If the capacitor bank is switched on while a DG is operating, resultant voltages could exceed the limits. DG can also affect the capacitor switching in case line current control is being used since the monitored current will not reflect the current profile on the feeder. When operating DG at unity power factor, the reactive power flow will not be much affected, but if the capacitor control senses a reactive power flow toward the load above the threshold value, it can switch the capacitor which is a correct action from the reactive power demand requirement.[11] DG can also impact LDC operations through SVR if a significant amount of apparent power is produced as compared to the load flow through SVR. Due to DG incorporation, current flow through the SVR will get low, which will be assumed as load reduction and tap-down action by the SVR, resulting in low voltage at the far-end customer. The capacitors can also affect the SVR in a similar way.

Traditionally, the protection schemes are designed considering the unidirectional flow of power. But as the power reverses in the periods of high generation of green resources, the protection schemes are bound to malfunction. Due to increased fault current magnitude and the direction of fault current, false tripping will be occurring if the amends will not be made to the existing schemes. Fuses will be operating for the temporary faults; DGs will be disconnected from the system for the faults on the adjacent feeders leading to the unnecessary islanding of a portion of the power system. Moreover, the islanded portion of the system will have overvoltage due to loss of grounding and self-excitation. According to Santos et al.,[12] the DGs connected to radial parts of the system often cause fail-to-trip. The authors in Walling et al.[11] highlighted problems related to the coordination of protective devices and the islanding of a portion of the grid. Sun[13] explained that conventional protection coordination settings need to be revised after a certain level of DGs has been added to the system.

In this review paper, an attempt has been made to present a comprehensive overview of the different aspects of the HC. In Section 2 a brief definition of HC is given along with the definition of HC uncertainty and HC coefficient. There are several references in respect of which HC can be defined rather than one. These criteria differ from network to network and as per the ease of utilities in their choice. Due to this reason, it is not feasible to generalize defining criteria for HC rather it is important to have the knowledge of different defining criteria. Section 3 consists of different criteria mentioned in different studies in respect of which HC can be defined for a particular network. Section 4 comprises limiting constraints that affect the overall HC of a distribution network. Having knowledge of the fact that what kind of KPIs are important for a given network can be effective at the planning stage. Also, having an idea of the possible issues that could be faced by a grid can help the utilities to focus on only those issues and thus enhance their effectiveness. In the literature, there are several techniques mentioned that are used to determine the HC of a network. Selection of these determining methodologies is a trickier task. Consideration of available data and its nature plays a crucial role in selecting the method of determination. So, a detailed explanation of several methodologies is provided in Section 5 to give an overview of all those techniques. Section 6 alludes to different techniques to increase the HC of a distribution network presented in different literature. The selection of enhancement technique greatly depends upon the issue faced by the distribution system and its severeness. There

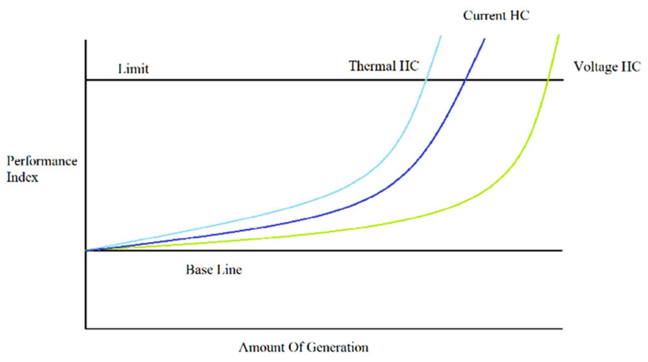

FIGURE 1 Hosting capacity definition with respect to different performance indices

are different schemes mentioned in different research papers, and an attempt has been made to explain all those in detail.

2 | HC

HC is defined as "the total DG capacity that can be accommodated on a given feeder without adversely impacting voltage, protection, and power quality and with no feeder upgrades or modifications."

Figure 1 gives the idea of HC with respect to various limiting constraints. For instance, just considered one constraint, overvoltage, for the HC study. There is a limit to the PV incorporation in the system after which the system's voltage constraint will be violated, and further increment in the PV integration will have an impact on the smooth operation of the system. So, such studies will abstain the network to enter the unacceptable operation region that is above the limit line. Moreover, HC can be measured and evaluated in terms of many parameters in this case we have thermal HC, current HC, and voltage HC. The defined criteria can vary from study to study and grid to grid but most commonly, power quality standards, such as EN50160, are implemented in the studies and are predefined by the network operators. If any of the evaluating constraints exceed their defined limit, the DG attached at that point in time will define the HC of that network. To define the HC limit, certain performance indices of a grid are selected, and then an acceptability limit for those indices is defined. The limiting constraints for a network depend upon the nature of the network and the type of the grid selected, for instance, in rural networks (typically radial and long) voltage level violation is the primary concern while in the urban regions, ampacity violation of the equipment is the HC defining constraint because of large loads.[1]

2.1 | HC uncertainty

HC is a location-sensitive phenomenon[14] that can be greatly impacted by the answer to the following points:

1. Customer location (start or end of the feeder) and type of connection (single or three phases),
2. Energy storage capacity,
3. Type and number of inverters,
4. Intermittent nature of renewables,
5. Equipment limitations, and
6. Standards to be followed.

All mentioned points vary from one customer to another and to know the answer to all these critical points is almost impossible but is essential to calculate the exact HC of a particular network. Accordingly, the resulting HC will not be a single value, but multiple values that will be introduced according to the uncertainty percentage. For instance, in the case of locational uncertainty, mentioned in Ismael et al.,[15] instead of units at a fixed location different localities are considered for the total amount of production to the feeder. Mover, to tackle the uncertainties, Monte-Carlo Techniques can be utilized that will generate several different scenarios, and different performance indices will be used for the HC determination. Hence, this methodology will result in a range of HC values, instead of one value.

2.2 | Hosting capacity coefficient (HCC)

In literature, the HCC has been defined as "the ratio of the curtailed energy and the installed capacity above the initial hosting capacity."

$$\mathrm{HCC} = \frac{\text{Curtailed energy}}{\text{Capacity above HC}}. \tag{1}$$

The concept of HCC is related to the curtailment techniques that are hard and soft curtailments. In Etherden and Bollen[16] a distinction is made between "hard curtailment" where all production is disconnected when overcurrent and overvoltage limits exceed a certain limit and "soft curtailment" where the amount of production to be disconnected is minimized depending upon the conditions. The case studies show concerns about the previously employed rule of thumb of 15% of the peak load, which was implemented by the USA distribution companies. It is a necessity to conduct a proper analysis of the HC studies for every grid, as the HC value will be different depending on the type of grid. Bajaj and Kumar Singh[17] considered the HC as equivalent to instantaneous penetration level and its mathematical expression is given in Equation (2)

$$\mathrm{HC}\,(\%) = \frac{P_d \times 100}{(\mathrm{RatedMVA})_{\mathrm{load}}} = \frac{\sum_{h=1}^{n} |\overline{V_L}(h)|.\ |\overline{I_D}(h)|.\ \cos(\Phi_h)}{\sqrt{(P_L + P_{NL})^2 + (Q_L + Q_{NL})^2}} \times 100, \tag{2}$$

where P_d is injected power, n is harmonic order, P_L and Q_L are active and reactive power of linear load, P_{NL} and Q_{NL} are active and reactive power of nonlinear load, $\overline{V_L}(h)$ is RMS of hth order and $\overline{I_D}(h)$ is hth harmonic component of injected current. Table 1 provides the distribution system operators' (DSO) rule of thumb for the integration of DGs in the LV networks. As for the medium voltage network rules, Czech has a limitation on DGs such that their rating should be less than the accumulation of the high-voltage (HV)/medium-voltage (MV) transformer rating and the minimum substation load. For South Korea, the DG rating should be less than 20% of the HV/MV transformer ratings.[18]

3 | HOSTING CAPACITY DEFINING CRITERIA

As per the literature, the HC definition is relative to the reference that is being utilized in the study and varies between 20% and 200% of the selected reference.[19] The utilized references for the determination of HC are:

1. Transformer rating,
2. Number of customers having PVs,
3. Network loading,
4. Roof space availability,
5. Annual energy share of PVs, and
6. Active power of the load.

3.1 | Transformer rating

HC relative to the transformer rating is the ratio of the total PV integration to the rating of the distribution or feeding transformer. The transformer loading could vary from region to region and network to network, for instance, according to the Brazilian network mentioned in Arshad et al.,[20] if the transformer loading is greater than 187.5% then the violation will be flagged. The further increase in PV penetration will cause the reverse power flow to exceed the transformer rating and thus affecting the net HC of the system. The use of smart inverter control allowed an increase of 19.7% in the HC from 246 kVA to almost 292 kVA. In Rahman et al.[21,22] the effect of zero sequence current on the transformer was discussed, and a voltage control strategy was devised to counter it. With the proposed methodology the network's PV hosting ability improved from 20% (40 kW) to 35% (64 kW) and if we further increase penetration for a decentralized PV system, it will have more impact on voltage (overvoltage). But the proposed methodology can remove the voltage violation and even enhance the HC from 64 to 128 kW and reduce the network losses (kW), and transformer loading (kVA). The network losses were reduced by up to 74% by utilizing OLTC and DG in tandem. Similarly, in Singh

TABLE 1 Different DSOs rule of thumb for DG integration

Limiting constraint	Country	DSO rules for DG ratings
Transformer rating	Portugal	<25% of the MV/LV transformer rating
	Italy	<65% of the MV/LV transformer rating
	Belgium	<MV/LV transformer rating
	Spain	<50% of the MV/LV transformer rating
	South Africa	<50% of the MV/LV transformer rating
CB rating	South Africa	<25% of the feeding CB for shared feeder <75% of the feeding CB for dedicated feeder for DGs
SCC	USA	DG rating should be <10% of the SCC at the PCC
	China	
Feeder load	Canada	<50%–100% of the feeder capacity
	USA	<15% of the annual feeder load
	South Africa	

Abbreviations: CB, circuit breaker; LV, low-voltage; MV, medium voltage; PCC, point of common connection; SCC, short circuit capacity.

et al.,[23] utilization of active and reactive power control strategies has increased the HC of the system by approximately 95%. In Chathurangi et al.[24] authors determined the HC with increasing penetration levels of 50%, 60%, and 75% of the actual transformer rating. The power losses were 6kW, 5kW, and 13kW, respectively, for the above-mentioned penetration levels.

3.2 | Number of customers having PVs

HC in terms of the PV-equipped customers in the feeder is the ratio of the total customers having PVs to the ones that do not have the PV integration in their vicinity. The authors in Navarro-Espinosa and Ochoa[25] defined the HC value by using Monte-Carlo simulations and different penetration levels (houses with PVs) to a real-time LV network of seven feeders and further carried it out for a network of 128 feeders. The network's constraint violations arising due to PV systems, electric heat pumps (EHPS), and electric vehicles EVs were 47%, 53%, and 34%, respectively. Also, feeders having less than 25 customers were having no problem with any of the renewable technology. In Bollen et al.,[1] a test network having a solar penetration level of 30% is shown without any network constraint violations, while for 50% penetration the voltage rise was outside the standard statutory limits. Similarly, in Lamberti et al.[26] an analysis of power quality was performed to analyze the effects of the increased PV penetration on the voltage profile of the network. Authors in Navarro-Espinosa and Ochoa[27] proposed a solution to increase the number of customers by using OLTC-fitted transformers for low-voltage networks. The results showed that the voltage problems were shifted from 40% penetration to 60% penetration and by using remote regulation the values can be increased to 100% PV penetration. Moreover, to cope with the uncertainty of location and the behavior of load, a stochastic approach was utilized.

3.3 | Network loading

Network loading is the most used reference for the quantification of the HC, as most of the researchers utilized it in terms of the peak load of the feeder, that is, the ratio of the maximum feeder loading to the capacity of the PV integration.

In Rahman et al.,[21] a suburban Australian low voltage distribution network was presented, and effects of PV generation and unbalanced loading were observed. The PV HC ability was improved by improving network voltage magnitude and unbalance voltages. The losses were reduced to 78% by using OLTC and demand response in cohesion, rather than using only a demand response solution. Load profiles were collected, and the worst-case hours were extracted from them for the HC investigations. Torquato et al.[28] examined the grid constraints for a specific time interval at noon. A general rule was presented for loading level according to which low voltage networks having high loading will allow more PV penetrations due to higher voltage drop along with low voltage circuits. As per the results when the percentage of customers having PV connections was increased from 20% to 80% the average capacity per generator decreased from 6.88% to 3.58%, but overall HC of the system was increased from 37% to 80%. For the studies conducted by Rusinaru et al.,[29] the voltage profile of a low voltage grid on high network loading and lowest loading with and without generation units and values of HC was determined for each of the cases. The authors presented a criterion according to which for voltage regulation and to mitigate the voltage rise issue, the maximum permissible HC for the test grid was 33.4% and 46.67%, respectively. In Saber et al.,[30] annual time series data for a substation loading was obtained for a 15-min time resolution for five different feeders. The HC for the feeders were 31.5%, 23.2%, 132.2%, 14.5%, and 18.1%, while after Volt-Var control with VAR as a priority the HC improved by 25% and the new HCs were 41.6%, 72%, 168%, 19.8%, and 22.6%. In Ding and Mather,[31] an algorithm was designed to determine the maximum load of the network. The algorithm under the incremental load conditions performed load flow analysis until the violation occurs and once the violation is detected the HC limit was set at that point. According to the performed study, the PV HC was 3.3 MW without the implementation of the OLTC, and the value increased to 12 MW with the OLTC in the network.

However, network loading is a reference that is frequently used in HC studies; the ever-fluctuating load curve will not be able to provide a stable reference point. The authors of Baldenko and Behzadirafi[32] and Nijhus et al.[33] show that the variability of the load will lead to inconsistent HC with the changing network conditions.

3.4 | Roof space availability

The HC relative to the roof space is the ratio of the available space for the PV system installation at the customer vicinity to the total PV capacity integration. Arshad and Lehtonen[19] considered roof space availability as a major defining parameter. According to the study the purely rural region has many empty spaces so HC can be enhanced. HC will be somewhat the same for the intermediate region (with and without roof consideration), and due to the lack of roof space in purely urban areas, the HC value decreased in comparison to the theoretical values that did not consider the roof space as the limiting constraint. Moreover, results indicated the HC of the rural area is affected by OV constraint (long radial networks) with the increase in HC due to OLTC implementation. The HC value without OLTC implementation was 105% but increased to 113% by using it. In Heinrich et al.[34] authors pointed out that to enhance the HC by reactive power control, remotely situated grids are more suitable due to the presence of more rooftop areas. According to Grabner et al.,[35] the authors considered the roof data that includes the actual tilt of the PV panels and roof orientations while randomly allocating PVs in the system. The results showed that the chosen PV-installed power greatly impact the results. The median HC for 10 kW installed PVs is almost 50% more as compared to 15 kW installed PVs. However, some of the research studies that are presented in this paper have added the roof space consideration as one of the limiting constraints, but most of the research only provides the theoretical maximum, without considering the real-world scenario. Therefore, most of the research is overestimating HC values.

3.5 | Annual energy share of PVs

HC in terms of annual energy share is the ratio of the total generation of the integrated PVs to the annual energy usage. The more the PV penetration for a locality, the more its HC will be compromised. Different studies conducted on low voltage networks in Germany having high PV penetrations were presented in Divshali and Soder.[36] The results depicted the decrease in maximum rapid voltage change from 8% to 5% thus enhancing the HC. According to the authors, such a type of grid needs a fast-controlling device to regulate rapid voltage change and to improve the HC. In Weisshaupt et al.,[37] the impacts of high PV penetration in a low voltage network of Zurich, Germany was studied focusing on the placement of PV in such a manner that it is cost-optimal and with a suitable sizing of battery storage. A temperature-based active power curtailment (APC) strategy was utilized, and the yearly energy losses were reduced from 21.5% to 19.8%. However, the technique was more suitable for short-term overloaded transformers. In Ravikumar Pandi et al.[38] the impacts of increasing PV penetration on power quality were studied. The main objective of the study was to quantify the maximum HC of the system within the voltage and harmonic distortion limits. The impacts on the DG penetration levels were also considered by removing the capacitors. The DG penetration level was 24.18%, but it got reduced to 23.16% by removing the bus shunt capacitors. In Hasanpor Divshali and Soder,[39] an extensive study has been carried out to try to increase the PV penetration level and to use some specialized techniques that could even enhance it further like battery storage systems using a quadratic power control to improve HC. The effect of the size of the inverter on HC was also explained having 80 kVA converter improved the HC by 29.2% as compared to a 20 kVA inverter which increased the HC by only 12.3%.

3.6 | Active power of the load

The HC relative to the active power of the load is the ratio of the PV capacity integrated to the cumulative active power of the feeder. In Hashemi and Østergaard[40] a process of voltage droop control was presented to restrain the active MV/LV transformers for high PV penetration. The study has been applied to a low-voltage feeder in Felsberg, Germany. The proposed method allows an extensive range of voltage rise and can also be used to feasibly enhance the HC value. According to the results by using an active MV/LV transformer, the PV HC can be increased to 87% from 45%. This value can further be increased by using V-droop control without even reactive power absorption by PV inverters. Authors in Kikuchi et al.,[41] compared countermeasures for two different systems (6.6 and 22 kV) and first analyzed the HC without any control mechanism. After that, the HC was calculated with a controlled power factor strategy and finally with a distributed control strategy. The HC was improved from 1.2 to 3.2 MW by using a constant power factor strategy and the distributed control enhanced it to 4 MW.

4 | LIMITING CONSTRAINTS

In the previous section, the HC defining criteria are presented that can be calculated based on the violations of one of the two technical categories comprising voltage quality and network equipment's loading limitations. These limiting constraint performance indices (PIs) were introduced in Schwaegerl et al.[42] Based on the literature, these major categories can be further classified into the following PIs:

1. Voltage level violation (under and over voltages),
2. Equipment ampacity violations,
3. Voltage unbalance (VU),
4. Voltage flicker, and
5. Harmonics.

4.1 | Voltage level violation

With the increasing PV penetration downstream of the LV distribution networks, the unbalance in the generation and consumption leads to the reverse power flows in the peak generation periods. The increase in turn gives rise to over voltage issues. However, in the off-peak hours, the low voltage scenario can be the major issue because of the transformer taps setting that is at a lower value to eradicate the overvoltage problem. Therefore, the PI that most of the DSOs must deal with in the determination of HC of a particular network is the voltage level violation issue. In Alalamat[43] the approximated voltage rise at different busses is given as

$$\Delta V_{\text{rise}} \cong \frac{(P \times R) + (Q \times X)}{|V_n|}. \quad (3)$$

Furthermore, the voltage level definition in different regions varies, and different countries are utilizing different voltage level standards. The most widely utilized standards are presented in Table 2. The standard used in Alam et al.[44] and Kitworawut et al.[45] allowed the maximum value for HC to be increased up to 25%. According to the ANSI C84.1 standard mentioned in Bertini et al.,[46] for an Italian LV grid the HC was increased by a margin of 10%. The +5% of U_n criteria mentioned in Navarro and Navarro[47] had the outcome of an increase in 10 MW of HC for a grid system in the Philippines. In Etherden and Bollen[48] the authors concluded that a standard of ±5% of U_n allowed an increase of 30–60 MVA. There was an increase of almost 95% in the HC for remote farm networks in Qatar following the standard of ±6% of U_n.

As per the findings of mentioned literature, each country has its own set of standards, and a single study cannot be implemented in other localities. So before increasing the PV penetration in a particular grid, a detailed study is necessary by accurately modeling the feeder characteristics, feeder length, and worst case hour selection, so that the DSOs can prepare for the issues to be faced in the future.

To mitigate these overvoltages and under voltage, different techniques are used. The most prominent of these is the usage of OLTCs. OLTCs can alter the voltage level depending on the power generated by PV.[57,58] Also, active power curtailment can be used for maintaining the voltage within its defined limits.[58] Implementing voltage regulators can also become useful in regulating voltage levels.[59] Different kinds of literature also presented the idea of optimal placement of battery energy storage system (BESS) to control voltages in a distribution network.[19,60] Usage of these techniques is presented in detail in Section 6.

TABLE 2 Country-dependent voltage level standard

Country	Standard	Values
European[49]	EN-50160	±10% of U_n
German[50]	VDE-AR-N 4105	+3% of U_n
American[51]	ANSI C84.1	±5% of U_n
Australian[44]	-	−6/+10% of U_n
Canadian[52]	CSA	±6% of U_n
UK[45]	BS EN-50160	−15/+10% of U_n
Italy[53]	ANSI C84.1	−4/+10% of U_n
Sri Lanka[54]	-	+6% of U_n
Denmark[55]	-	+5% of U_n
Philippines[47]	-	+5% of U_n
Indonesia[56]	-	+5% of U_n
Sweden[48]	-	±5% of U_n
Switzerland[34]	-	+3% of U_n
Qatar[23]	-	±6% of U_n

4.2 | Equipment ampacity violation

Maximum current limitation through the equipment such as transformers and cables defines the ampacity limit and is used in many of the papers for the HC determination. There is no fixed value for the loadings of the equipment that is utilized as a standard. In Shayani and de Oliveira[8] authors proposed the following mathematical equation for having an estimation of maximum penetrable DG.

$$P_{DG} = 2 \times P_{\text{load}} + (1 - S_{\text{load}}). \quad (4)$$

However, the HC studies that are conducted with respect to the countries and different region-dependent grids define the limits of 100%–190% and 85%–150% of the nominal rating of transformers and cables, respectively. These values are utilized as the limiting values. The details are presented in Table 3.

In the case of balanced and unbalanced PV installations, the largest HC value was observed when the overvoltage limit was +10% of the nominal.[19] The network reinforcement along with the use of OLTC improved the OV tolerance to 60% penetration from 30% (no OLTC employed). Moreover, a large PV system per node can be incorporated with smaller penetration levels, for instance, PV systems of sizes 6.8 and 18 kW can be integrated into 100% and 10% of the system nodes, respectively. According to Torquato et al.,[28] while considering different technical aspects, the voltage unbalance was found to reduce the PV penetration by

TABLE 3 Regional studies considering the ampacity limitation as the performance index

Equipment	Region (grid)	Limitation
Transformer	Finland (rural, suburban, urban)[19,20]	100% of rated
	Zurich (urban)[37]	
	Qatar (rural)[23]	
	Germany (suburban)[50]	150% of rated
	Brazil (urban)[28]	187.5% of rated
Cable	Zurich (urban)[37]	85% of rated
	Qatar (rural)[23]	100% of rated
	Finland (rural, suburban, urban)[19,20]	
	Germany (suburban)[50]	150% of rated
	New Orleans (urban)	105% of rated

TABLE 4 Various voltage unbalance limits in the literature

VU limit	Literature
1% of U_n	[61]
1.3% of U_n	[45]
2% of U_n	[20, 22, 62, 63]
3% of U_n	[14, 28, 63–65]

9.6%. PV penetration was reduced by 27.7% in case of conductor overload. Overvoltage has a clear dominance of nearly 61%, while under voltage affect 1.2% of the systems. In Singh et al.[23] authors explained the role of tap positions on HC and how the inverters operating at wider pf range can affect the HC value. HC of the network was improved from 90 to 175 kVA. In Stetz et al.[50] the economic benefits of various strategies for inverter control to enhance HC were presented. The HC was determined based on the transformer and cable loading. As soon the loading crossed 150% of the rated power, HC is defined there.

In accordance with the above literature, the ratings and loading of the transformer should be analyzed at the planning stage for every region and network because it can greatly impact the HC values. Similar is the case for cable ampacity values. More PV penetration eventually causes more thermal overloading on the equipment especially distribution cables. So, a greater cable ampacity value will allow the DSOs for more PV penetration and in result greater HC value.

4.3 | Voltage unbalance

Negative sequence voltage unbalance is defined as the ratio of the negative sequence voltage to the positive sequence voltage. In literature, VU is observed to be limiting the LV networks where the distribution of single-phase PV in the phases is not symmetric. The IES standard defines the limit of 2% of the nominal voltage on the negative sequence VU.[1] However, its value is not strictly implemented in different distribution regions. Table 4 presents the various VU limitations as per the literature.

The authors in Wang et al.[61] proposed an optimal BESS allocation method to minimize the voltage unbalancing by considering loads, PV generators, and future installations as an uncertainty. The PV capacity was increased from 393.9 to 463.6 kW in phase A. A similar increasing pattern was also observed for phase B (233–578 kW) and phase C (318–495 kW). In Rahman et al.,[22] a method to integrate network OLTC and residential PV systems was presented to effectively improve the voltage unbalancing by using a modified particle swarm optimization (MPSO) based algorithm. Without any enhancement technique and voltage violation the HC of the system was 20% which was improved to 35% by using MPSO. The studies conducted in Kitworawut et al.[45] mentioned the PV unbalance factor (VUF) in the range of 0.03%–0.4% for a PV penetration of 100%. The VUF was 0.8% when PV integration rose to 200% which was in accordance with the standards. In Hu et al.,[65] five different OLTC control options were explained to control the voltage unbalancing to a specified limit. Each of the techniques had its own effects on VUF growth. The adaptation of one-phase OLTC control mitigated the voltage deviation from 17% to 11.8% thus enabling the increase in the limit for HC. In Arshad et al.[20] the increment in HC for balanced PV feed for a prominently rural area was found to be 200% without the usage of OLTC but was enhanced to 240% by using OLTC. Authors in Arshad et al.[62] evaluated and compared the HC of the system for various configurations of BESS. As per the simulated results the base value of 26% HC drops to 20% for case A (BESS on random phase) but for case B (BESS on the same phase as that of single-phase PV) and case C (Load unbalance consideration). In Tang and Chang[63] the photovoltaic hosting capacity (PVHC) was enhanced by using PVs with smart inverters. Different operating modes of inverters were implemented and compared. According to the results, the base value of HC (4325 kW) was increased to (6405 kW) by using Volt Watt control (7920 kW) by using Volt-Var control, and (6720 kW) by using the combination of both methods. In Dubey et al.[64] the effect of change in the voltage (by changing network loading) on HC was observed. In the conducted simulations the HC at 4 MW of load increased from 3000 kW to the value of 9500 kW by increasing the load value to 12 MW.

4.4 | Voltage flicker

As per the IEEE standard 1453-2004, voltage flicker is the high-frequency voltage change that can be seen through the naked eye.[66] These fast fluctuations are related to the intermittency of the load in the traditional grid, but with the DGs integration downstream of the network, production intermittency can also give rise to the voltage flicker. In the flicker studies the main points that are to be considered are:

1. Modeling of the network,
2. Type of network (weak or strong),
3. Resolution of the loading and generation of data, and
4. The standard that is being implemented by the utility.

Modeling plays an important role in the exact analysis for the flicker studies, as in the HC studies the inverter is considered a black box. However, if it is exactly modeled it can be a source of flicker, as in Stewart et al.,[67] maximum power point tracking of the inverter is the main source of flicker. Moreover, the grid that is under study is also of great importance, whether it is a weak grid or a strong one. As in Andreas Spring et al.[68] the voltage flicker value was within limits except for those parts of the grids that were too long and scarcely loaded (weak grid).

Some of the studies take the step changes to model the load and irradiance changes, which is highly unrealistic.[69,70] Moreover, if the load and generation curves are utilized, the resolution of the data is not high enough.[71] Intermittency of the PV generation due to cloud movements alone is not a source of flicker,[67,72] But if all the parameters defined above will be considered at the same time in the studies, the flicker value is bound to breach the standard value.

The flicker measurement method that is frequently utilized in the literature is the standard IEC61000-4-15 which replicates the incandescent light bulb and eye response to fast voltage fluctuations. The flicker indices that are usually defined are:

1. Short-term flicker index (Pst)
2. Long-term flicker index (Plt)

Furthermore, for the long-term flicker index evaluation, a sliding window approach is utilized is defined in IEEE 1453. According to standard EN-50160,[73] the short-term and long-term indices should be less than 1 for 95% of the time for 1 week period. However, some utilities have stricter guidelines, for instance, VDE-AR-N 4105 defines the long-term flicker index to be less than 0.5[68] for the LV networks and even stricter for the MV networks, that is, 0.46.[74]

In Sharma et al.[75] a comparatively new technique of using smart loads was used. The results showed that with the usage of smart loads, the voltage unbalancing decreased at all busses and the severity indexes of voltage flicker were also in range according to the IEC 641000-4-15 standards. Studies in Ferdowsi et al.[76] showed that the flicker measurement of a network is affected greatly by the time resolution of the analysis. The granular nature of data is important to determine the safe penetration level of PV. Authors in Rahman et al.[77] calculated a correlation coefficient between PV output and Voltage flicker. The analysis of the studies concluded that there are multiple reasons responsible for voltage flickers like network topology, PV location, weather, and atmospheric conditions. All these factors play a role in limiting the HC value. The results of Arshad and Lehtonen[78] showed that the unbounded flickers were mostly found in the weaker grids and that too on the end nodes of the feeder. So, a reactive power control was applied to smooth out the flickers.

4.5 | Harmonics

New methods of energy generation, changing the behavior of the consumers in energy utilization and the addition of active power electronics in the system cause the uprising of issues like supra-harmonics, low-frequency subharmonics, and inter-harmonics. The distortion in the normal voltage or current waveform is defined as harmonics. The main cause of harmonics is the nonlinear loads, which have seen a steep rise in their usage at various points in the power system. Some other causes of harmonics according to IEEE standard 141 are high voltage DC transmission stations, magnetic core of transformers, and synchronous motors.

From the literature, it has been observed that these harmonics significantly constrain the HC. These harmonics cause low power quality and energy losses in the system. In Sakar et al.,[79] HC of a typical distribution system was evaluated for various nonlinear loads. The HC decreased to a large extent having harmonics as a major limiting constraint. At 0% penetration of the nonlinear loads, the HC was almost 90%, but as the percentage nonlinearity increased to 25% the HC decreased drastically to 20%. So, the authors employed a C-type filter to maximize the HC value according to the standards of IEEE-519, for voltage and current. After implementing the filter design, the new HC was 55.34%. Similarly, in Harrison[80] the authors performed a time series optimization analysis, and results showed that harmonic limits were violated when active network management freed up the new capacity. So, to overcome the issue a harmonic constrained optimal power flow-based harmonic mitigation technique, like active filters, was proposed. It was observed that by curtailing the wind power by only 5% yearly allowed the HC to increase by 127%. Authors in Ampofo et al.[81] mentioned the study of HC in terms of harmonic distortion limit and a passive harmonic filter to mitigate the harmonics was proposed. The passive filter improved the HC from 44% to 73.33%.

4.6 | Multidirectional power flow

Power reliability and power quality are of great importance in power system operations. Many grids experience multidirectional power flows because of the addition of the DGs which eventually enhances the complexity of grids operation. Since most of the grids comprise equipment that was designed to counter unidirectional issues. Complex fault currents, that is, from the customer's end to the upstream render the functionality of that equipment ineffective. Also, the bidirectional power flow can cause wear and tear on the equipment. This can lead to more frequent replacement of the equipment which is cost utilizing.[82] The mentioned issues are being tackled by utilizing innovative equipment and using controlling and monitoring technologies. Communication between different equipment can also be used to overcome the issue as well. International Electrotechnical Commission introduced some standard protocols known as IEC 61850 which defines communication between different equipment of a network connected to a local area network (LAN). A supervisory software integrates all the Intelligent electronic devices (IEDs) used in the network. The most important component of these supervisory systems are the sensors which generate information for the supervisory system.[83]

5 | HC DETERMINATION METHODOLOGIES

HC determination approaches are greatly influenced by the data availability and its resolution. Traditionally, an analytical approach was utilized that assesses every data point to reach the final HC value. However, there are some points in the data set that does not have any impact on the final value of HC but result in a large computational overhead. Therefore, worst-case hour approaches were introduced that give near-accurate results but with the least latency. There were many different approaches that were utilized by the researchers to conduct the HC studies, which are mentioned as follows:

1. Deterministic approach
2. Stochastic approach
3. Time series approach
4. Worst-case hour approach
5. Stochastic-time series Approach

5.1 | Deterministic approach

This approach utilizes the known fixed data that is inputted to a model, conducting power flow analysis, and determining an HC value as a single output. In Luthander et al.[84] the combined effect of the storage system and PV power curtailment was analyzed along with the substation overloading and feeder currents with different penetration levels. The study was conducted on two medium voltage grids and 338 low voltage grids along with the data of 5174 end users. The deterministic approach was utilized to find the number of customers affected by the overvoltage problem. In Ampofo et al.[81] authors tried to investigate the effect of changing DG penetration level on voltage change and the effects of different loading conditions online thermal limits utilizing a deterministic approach. In Parihar and Malik[85] a direct deterministic approach to solving radial distribution system was presented. The results obtained had faster convergence for both the composite load model and complex power. In Heslop et al.,[86] many load flow simulations for an Australian distribution network system were conducted to derive a relation between maximum PV generation, feeder impedance, and load. The authors utilized a deterministic approach to find out the PV generation limit that can be incorporated into the system to determine the maximum HC of the system. As per the reviewed literature, the computational overheads increase with the increase in the complexity of the network. Moreover, the uncertainties in the variables that are to be incorporated into the methodology are not possible. A flow chart of the deterministic approach is presented in Figure 2.

5.2 | Stochastic approach

As per the detailed review of the deterministic approach, there are a few shortcomings that are:

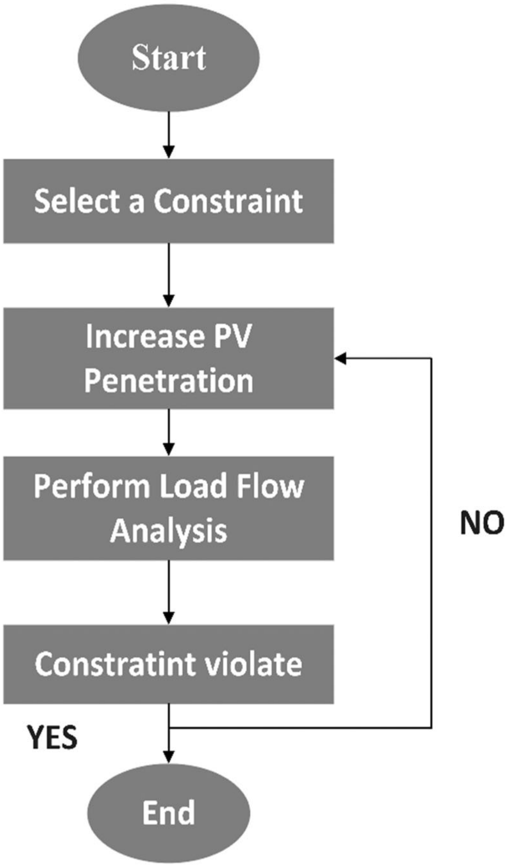

FIGURE 2 Flow chart of deterministic approach

1. Computational overhead.
2. Uncertainties in the generation, loading, connection, and sizing of DGs, and so on not incorporated in the methodology.

Therefore, to cope with the variables that are inherently intermittent probabilistic approach is developed that will deal with the probability distribution functions of such variables, leading toward more realistic studies for the HC studies. For instance, in Torquato et al.,[28] authors have conducted an extensive study to determine the PV HC of 50,000 real LV systems in Brazil. The paper proposed a simple stochastic process to assess PV characteristics for the LV system. In Navarro-Espinosa et al.,[25] a probabilistic assessment methodology for a UK network has been presented which incorporates different uncertainties related to various low carbon technologies (LCTs) using Monte Carlo simulations. In Ding et al.,[31] a probabilistic approach based on MCSs was used to determine the HC of a system. The methodology considered the impact of multiple loading scenarios on HC and uncertainty in the location and size of PV. Similarly, in Rossi et al.[87] the 800,000 simulations of randomly generated DERs' configurations (size and

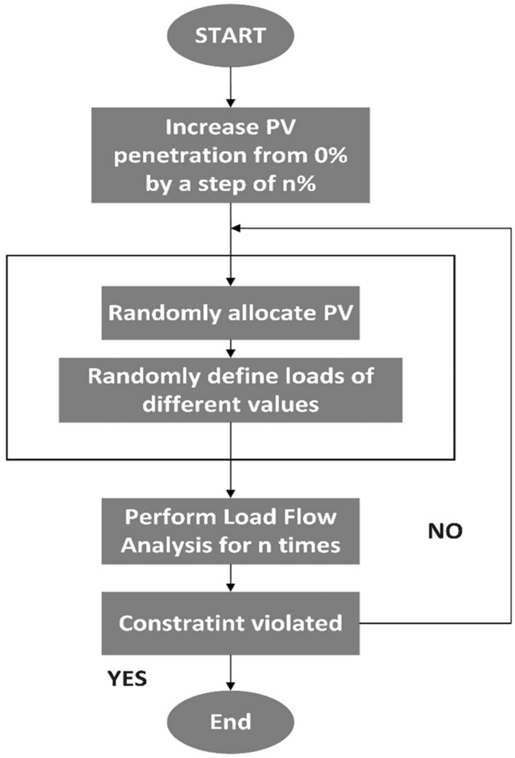

FIGURE 3 Flow chart of stochastic approach

location) were carried out, and later their impact on the network was evaluated. The detailed flow chart of the stochastic approach is presented in Figure 3.

5.3 | Time series approach

The stochastic approach is found to be the most realistic approach in dealing with uncertainties in HC studies. However, the detailed study from the point of the equipment that changes their steps as per the changes in the network constraints, for instance, OLTC, cannot be gauged utilizing the probabilistic approach. This requires the time-series approach that utilizes the actual measurements of the variables from the power system and correlates the generation and loading patterns. For instance, authors in Khoshkbar-Sadigh and Smedley[88] highlighted the importance of the resolution of data used for time series simulations. High variability points have a high impact on the operation of different system components like voltage regulator capacitor banks, and substation tap changers. The following recommendations were given in the paper for time resolution:

1. Energy impacts: hourly.
2. Voltage fluctuations: secs-mins.
3. Steady-state overvoltage: minutes.

According to authors in Behravesh et al.[89] who compared the voltage in 1 and 10-min time resolution. The findings of the study proved that the data of high temporal resolution is more suitable to capture daily voltage fluctuations. In Fan et al.[90] on basis of time series analysis, quantification indices, that is, voltage quality, economics, and HC were established to provide measurement criteria for practical planning and operation purposes. A drawback of the time series approach is the longer time taken if the simulation is to be carried out for several years with a time step of an hour or even less. So according to authors in Pagnetti and Delille,[91] if we simulate some specific representative points, it is possible to reconstruct the whole time series for any output. These specific points were termed the worst-case hours, and this approach will be discussed in the following section. Figure 4 shows a semantic of the time series deterministic approach.

5.4 | WC hour approach

Deterministic, stochastic, and time series methodologies can be made computationally less extensive if only those instances are to be considered where there is a large chance of constraints' violation in the power system. For instance, rather than considering the data set for the whole day, only the hours having maximum generation and minimum loading will be sufficient for the HC determination study.

Therefore, in the WC hour approach, only the critical data values are considered in the study. In Arshad et al.,[20] authors used the barycenter approach to find the worst-case hours using total grid load and load barycenter along the feeder. The procedure also depicts the impact of a number of nodes on worst-case hours. In Chen,[92] it was explained that worst-case hours' analysis was significant for urban distribution systems. In Torquato et al.[28] a risk-based determination approach was presented that randomly chose the hours of critical situations and based on those critical hours, the HC of the whole system was determined. The workflow of the worst-case hours approach is presented in Figure 5.

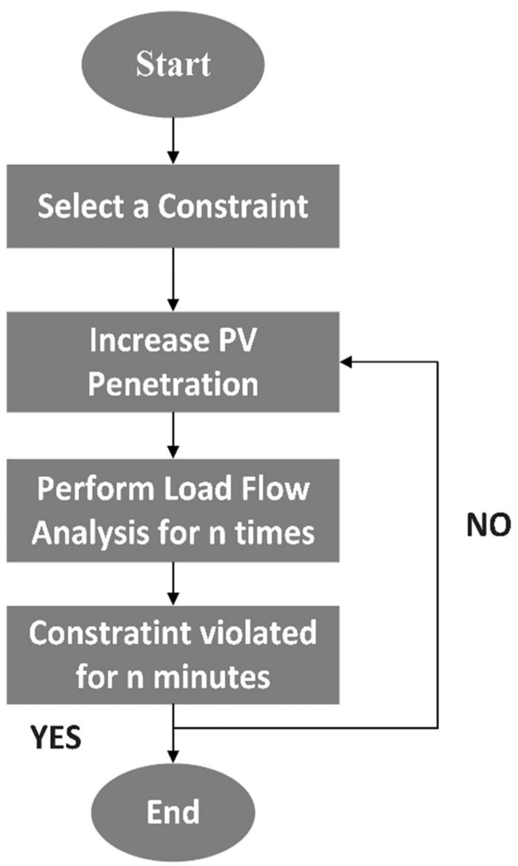

FIGURE 4 Flow chart of time series HC determination approach

5.5 | Stochastic-time series approach

In this methodology, many load profiles, as well as generation profiles, are available, and random profile selection is made from the pool for defining the probabilistic variables. In Navarro-Espinosa and Ochoa[25] MC approach was applied on an electrothermal system to examine the effects of combined heat and power unit (CHP) plant size and location. Multiple snapshots of load and generation were considered. The impacts were quantified by using both probabilistic and time-series approaches.

6 | HOSTING CAPACITY ENHANCEMENT

In recent times, plenty of research is being carried out on finding ways to enhance the HC of distribution networks to avoid high-cost up-gradation. This section deals with different methods and techniques presented in different kinds of literature to increase the HC of the electrical network. In Ismael et al.,[93] a method for the optimal selection of a conductor is proposed using Salp Swarm Optimization (SSO) algorithm. The objective is to reduce the combined annual investment cost and cost of energy while staying within the limits of system voltages and conductors' thermal and mechanical capacities. There are some practical hindrances in the proposed strategy, so in the same article, another method of feeder reinforcement is proposed as well, resulting in enhanced HC values. In Divshali and Soder[36] the focus is to keep in control the dynamic voltage changes in the DG

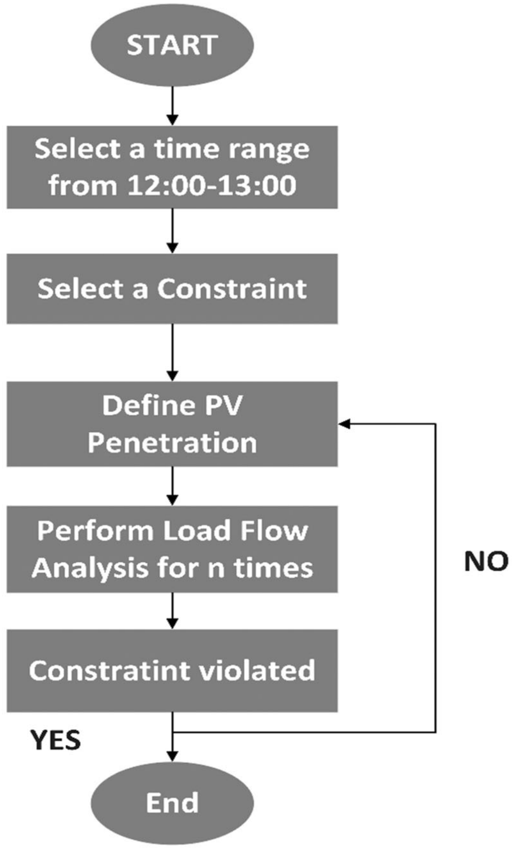

FIGURE 5 Flow chart of worst-case hour approach

integrated systems. For the improvement of voltage regulation in a steady state as well as in a dynamic state, an adaptive controller is proposed for the STATCOMs that are used in LV grids. The controller improves both static and dynamic hosting capacity. In Al-Saadi et al.,[5] a risk assessment technique is used for the evaluation of the HC of active distribution networks (ADNs) while considering different uncertainties of DGs. The probabilistic HC approach was used to consider the system uncertainty. Also, numerous techniques have been developed to increase the network HC such as the demand response of smart grids; in Karimi et al.[4] and Al-Saadi et al.,[5] optimal PV placement in Athari et al.[94] Moreover, Rascon et al.,[95] proposes the two techniques for the reactive power control, that is, cos (φ) and $Q(V)$, and prediction-based active power control with DG were considered. The control strategies were simulated over an existing distribution grid consisting of a single MV feeder and many LV grids. It was observed that as compared to the cos (φ) control strategy HC of an area can be increased by 15% using the $Q(V)$ strategy. In Hashemi and Østergaard,[40] a voltage control strategy for active transformers is presented. According to the literature, after implementing this control limitation for the installation of PV systems is no longer the overvoltage in the network but the ratings of the grid components. As far as all these mentioned techniques are concerned, these are not very generic (dependent on the grid topology and specifications) and have certain limitations that will be discussed in the following section.

6.1 | OLTC transformer employment

Voltage control using OLTCs is one of the most used tools for providing automatic compensation for voltage level violation in the system. In Schwaegerl et al.[42] the impacts of uncontrollable DG units on the system's voltage profiles were presented. The studies conducted in Berizzi et al.[96] proved that voltage control has many positive effects on the improvement of voltage quality, reduction in system losses, and enhancement of HC. The decentralized method of local voltage control by using the local information can be used to increase the HC. The process of local voltage control can be done by power factor control of DG or by OLTC. The studies in Mina Mirbagheri et al.[97] compared the scenarios of no OLTC, five taps on OLTC, and nine taps on OLTC. The results demonstrated HC can be increased from 50% to 100%. OLTCs that use a few local field measurements to control the voltage in the feeders (wide-area control) are effective in only 48% of the feeders. A centralized solution that combines OLTC and DG control produces good results in only 20% of the feeders. In the rest of the cases, as additional generation is added to the system, many feeders become thermally compromised, and this voltage-control solution becomes ineffective. Potentially more expensive solutions like curtailment or classical grid reinforcement are applicable everywhere.[7] Similarly using different techniques in cohesion with the other voltage-controlling techniques can enhance the HC as presented in Table 5.

6.2 | Curtailment of dispersed generation resources

Curtailment of DG sources includes a reduction in the output power of some specific resources at the time of need. Using DG curtailment, HC can be controlled if the performance indices' limits get exceeded, and the remaining energy production will be curtailed.[97] Using the curtailment technique will enable utility systems to install a large capacity of distributed energy resources. But one thing to be kept in mind is that during curtailment the energy is still produced by the sources but only as much permissible by HC limits. If the curtailment of DG units can be acceptable for the larger durations, then more production capacity can be added to the system.[48]

TABLE 5 Increase in HC using different techniques

Country	Centralized voltage control	Increase in HC (%)
Germany	Field measurement based OLTC	67.00
Spain	OLTC + STATCOM control	64.53
Austria	Field measurement-OLTC + DG reactive power control	62.99
Australia	Field measurement-OLTC	53.36
Spain	STATCOM control	20.02

One drawback of the technique is that if we keep on increasing the production capacity the need for additional energy curtailment also increases, eventually a point comes when it is no longer useful to increase the production because that increased production will eventually be curtailed.

6.3 | Optimized PV deployment

In the literature, there are some works that use the optimal PV deployment for the enhancement of HC. Some specific PV locations can have a strong effect on the total amount of PV power that can penetrate a feeder. A locational sensitivity study was conducted in Ding et al.[98] and the hosting capacity of the PV system was determined by selecting PV customers based on the factors like primary impedance, distance from the substation, and phase connection. The results conducted in the study concluded that by integrating PV systems nearer to the substation, HC can be increased. Also, if we select the PV locations based on the primary impedance as compared to selecting them on basis of feeder length, we can achieve better performance. In Bartecka et al.[99] an attempt has been made to mitigate the PV generator's effect by placing them properly using greedy algorithms. These algorithms work by selecting the best choice for the moment and operate by finding a sequence of locally optimal solutions, which usually leads to a globally optimal solution. The algorithm is computationally effective and fast enough to be suitable for effective PV deployment even though the obtained solution is sometimes not so effective.

However, the optimized PV deployment demonstrates enhancements in the HC of the network but cannot be a solution for the small-scale PV integrations that are made by the customers at their houses. They are small-scale systems, and the locations cannot be predefined. Therefore, the optimization problem is to be solved for the cases in which large PV systems are to be incorporated into the system.

6.4 | Active power control

Controlling active power can be meant to increase the HC and can solve the issues of rising voltage in high penetration conditions. In Hashemi and Østergaard,[40] a voltage droop control method is presented to control the active power of the MV/LV transformer. Results showed that without using reactive power absorption by PV inverters, the HC can be increased from 45% to 78%. In Ding and Mather[31] an active distribution network management system is presented to improve the HC value. The approach deals with the optimal control of capacitor banks, and tap changers, reconfiguration of the system, and adjusting the power factor of inverters. The PV capacity was enhanced to 97.3% of the peak load and reduced the system losses by 22.1%. A similar approach is presented to enhance the network's HC. Results showed that HC on a constant power factor of 0.95 lagging increased the HC by 3.96%, whereas the Volt-VAR operation method increased the HC on average by 18.74%. However, there was a 100% HC increase when using the Volt-Watt operation method. In Collins and Ward[100] two different methods for active power control (APC), that is, static maximum (SM) and dynamic maximum (DM) were presented. Results showed that voltage reduction by DM-APC was better than SM-APC. The SM-APC model reduced the overvoltage by 20%–25% whereas the DM-APC reduced the overvoltage by 40%–60%.

However, a significant improvement will be made in HC by the involvement of active power control techniques, but the power curtailment would be large if this technique is the only employed methodology. During the peak hours, when the mismatch between the generation and load is maximum, temporary curtailment is unavoidable, but during the off-peak hours, the cohesion of more than one enhancement technique will bring a fourth better result, with the least curtailment possible.

6.5 | Reactive power control

In Seuss et al.,[101] the authors used the PV inverters for voltage balancing and to study the impact of VAR control on the HC of the network. The results showed that there is an increase in the HC by 50% from 600 to 900 kW. In Collins and Ward,[100] an effective control scheme for inverters was implemented that reduces the amount of curtailment of real power and reduces the overvoltage. The results showed that the inclusion of the reactive power Volt-VAR method has resulted in additional voltage reduction of around 8% and 15% for dynamic maximum and static maximum, respectively. According to Rascon et al.,[95] the capability of a PV inverter to control reactive power or $Q(V)$ control was used to mitigate the voltage rise problem. The reactive power is regulated depending upon voltage on point of common connection (PCC), thus enabling the inverter to operate only when reactive power control is needed. The baseline scenario for HC was taken to be 1357 kW which was increased by 116% to 1694 kW, using the $Q(V)$ control strategy. In Atmaja Sarjiya et al.,[102] the improvement in rooftop PV penetration by using reactive power control was presented. Three different power factors, that is, unity, leading, and lagging, were employed and the HC was determined. HC for unity pf was in the range of 113–479 kW, for lagging pf the range was 233–1967 kW and for leading pf the HC range was the least from all, that is, 53–327 kW because of the voltage rise problem.

However, reactive power control is one of the most utilized enhancement techniques that is employed for voltage regulation as well as increasing a grid's HC. But during the peak generation periods, the Q-reserves are not enough to tackle the OV problem. Either curtailment is to be employed that will incur monetary loss, or an oversized inverter can be used to increase the reactive power capability of the inverter. As in Demirok et al.[103] and AlKaabi et al.,[104] 17.64% and 41.4% oversized inverters are utilized, respectively, to increase the inverter's reactive power reserves. In Hasanpor Divshali and Soder,[39] the voltage regulation was achieved by only applying the RPC, and the curtailment was not employed even in the peak generation periods. Although the oversized inverter is the most feasible methodology to eradicate the voltage violation problem, nevertheless the cost-effectiveness is to be checked as well. As per Su et al.,[105] 60% inverter oversizing is feasible both in terms of cost-effectiveness and voltage regulation. Moreover, in Divan et al.[106] the author described the 15% oversizing of the inverter will significantly increase the reactive power control capability with minimal cost increment. In Divshali and Soder,[36] a method to control the central BESS to improve the HC was presented depending on the size of the inverter. A 20 kVA inverter has an HC of about 12.3% which was increased to 29.2% by using an inverter of 80 kVA.

6.6 | Network reconfiguration

The HC of a distribution system greatly depends upon the characteristics of the feeder. Feeder reconfiguration is generally used to improve voltages and reduce energy losses.[107] It can also be used to improve the DG HC. For the maximum DG power, an optimal topology of the feeder can be determined by solving an optimization problem. As after the system reconfiguration the PV locations and primary impedances change, the reconfiguration problem can be formulated as restricting primary impedances within the limits. The proposed method in Smith et al.[108] first solves the problems in the case of worst-case scenarios, and then the resulting configuration is assessed for the rest of the time periods to check if it is suitable with the given network constraints. The objective function is examined to correct such reconfigurations that cause over or under voltages at the busses and overloading of distribution lines. For a given network configuration, the fitness function can be obtained by considering both the maximum allowed power supplied by DG sources and the exploitation of the lines together with the bus voltage profiles. The purpose of the problem is to reconfigure the network and DG sizing to improve the HC and reduce network power loss. For the solution to this problem, the Particle Swarm Optimization technique is used. In Chittur Ramaswamy et al.[109] and Makarov et al.,[59] a genetic algorithm is proposed to reconfigure the system to maximize the HC at selected nodes. In Ismael et al.[93] an optimized problem was presented to minimize the annual energy losses while satisfying the system voltage limits and thermal capacity of the equipment. Also, a sensitivity index, that is, feeder reinforcement index is also presented in the literature for the feeders that need to be reinforced first. Different penetration levels were used for the base case and reinforced network case. The HC for the reinforced case was improved to 150% considering the voltage constraints.

According to the distribution system operation time frame network reconfiguration can be classified into the following two categories[110]:

1. Static reconfiguration.
2. Dynamic configuration.

The work described in the paper provides an optimized power flow framework to cope with the voltage rise and thermal issues. The proposed method was able to improve the HC by up to 51.8% as compared to the original configuration. In Capitanescu et al.[110] an optimization problem is defined for boosting PV hosting capacity by adjusting taps of voltage regulators, reconfiguring the network, switching capacitor banks, and operating PV inverters. Decision variables for optimization problems include the kVA capacities and power factors of PV inverters, the states of controllable branch switches, tap positions for voltage regulators, and the states of switched capacitors. Thus, the PV hosting capacity maximization problem is finally formulated as a constrained, mixed-integer nonlinear optimization problem. The results showed that the unity PF approach will cause the reduction in HC because of loss increment and the switched operation in branches will have a significant impact on the PVHC value increment. In Xiong et al.,[111] the authors discussed the reconfigurability of a Chinese high voltage distribution network (HVDN). By managing load curtailment and PV shedding, the PVHC was improved from 17.2% to 73.46%. HC depends greatly on the PV location and primary impedance of the PV bus (lower impedance results in higher HC). Thus, keeping in mind, the mentioned fact authors in Ding et al.[98] objectified the reconfiguration of the network to restrict the primary impedances which improved the HC from 30% to 50%. Authors in Jothibasu et al.[112] modified a distribution system by incorporating new distribution lines equipped with tie switches to enhance the HC. According to the results, the HC was increased to 53% by just adding two additional distribution lines. In Capitanescu et al.[110] a method is proposed to improve the HC by implementing static reconfiguration (configuration at the planning stage) and dynamic reconfiguration (reconfiguration using remotely controlled switches) along with active network management (ANM). According to the results, there was a 51.8% gain in HC by using SR while 50.2% for DR.

6.7 | BESS

Another type of technique that is being used to enhance HC is to control the voltage of DGs with feed-in limitation or also known as BESS. Energy storage techniques enable the power system to react to long, medium, and short-term variability and can enhance the HC. Different applications of storage described in different works of literature include smoothing of fluctuations from renewable sources,[109] regulation in frequency,[59] and load leveling.[113] There are different methods that are utilized to increase the BESS involvement in the HC enhancement like stochastic optimization,[114] probabilistic methods,[115] and cost–benefit analysis.[116] The selection of the method depends upon the nature, location, and type of the system being studied. Along with these, some other strategies have also been devised to improve the HC of the systems. In Hashemi and Østergaard[40] using PV generation forecasting, the power injected into the grid and power stored by PV systems is observed, and dynamic operating points were determined for the storage system. The results showed that by using dynamic set points, the maximum active power absorbed by the storage system was reduced to about half. For a 75% penetration, the storage system required to prevent over-voltage was reduced to 5 kWh at dynamic set points, as compared to the 14 kWh at fixed power threshold which in turn can increase the PV penetration to about 50% without encountering the over voltages. In Gupta et al.,[117] a tractable convex optimal power flow technique was presented to estimate and increase the HC by placing and sizing the BESS optimally. In Etherden and Bollen,[48] uses a thermal line model where ambient temperature, aggregated heating, and dissipation in power lines are used to calculate the maximum permissible current through time that is dynamic line loading. In Wang et al.[61] an optimal allocation of BESS to improve the HC of a low voltage distribution network. HC was boosted by a value of 281.45 kW. Authors in Joshi and Gokaraju[52] proposed a four-quadrant operation of BESS to maximize the HC from 25% to 60%. In Hasanpor Divshali and Sodern[39] an optimal method for placement and size of BESS using a quadratic power control was proposed. Placing BESS at a large distance from the substation increased the HC up to 50% which was more than the configurations in which BESS was placed closer. In Arshad et al.[62] results for different BESS locations with respect to PV were compared. A fall of about 23% was observed when PV and BESS were at random phases, but connecting PV and BESS at the same phase caused the HC to rise to a value of 111%. In Hashemi and Østergaard[40] a centralized control methodology of BESS to improve HC was discussed. The process involved estimating PV generation, consumption of load, and estimating reactive power absorbed by the inverter to determine BESS set points (points at which voltage at any point exceeds the allowed value). The PV penetration increased by up to 75% by using a 5 kWh of BESS, and without this BESS the value of HC was 50%.

6.8 | Mitigation of harmonics

The harmonics cause low power quality and energy losses in the system. Therefore, proper protection measures should be taken against these harmonic issues before the designing process of a grid. In Sakar et al.,[79] the HC of a Brazilian two-bus industrial distribution system is determined by considering harmonic constraints. According to the studies, the HC decreases very sharply with the increase in nonlinearity on the load side. So, to mitigate those harmonics a C-type passive filter is proposed to maximize the HC while also providing better voltage regulation, improved power factor, and limiting the harmonics, enhancing the HC up to 55.34%. A generic equation capable of determining the HC at a specific point concerning harmonic distortions in distribution and transmission systems was presented in Santos

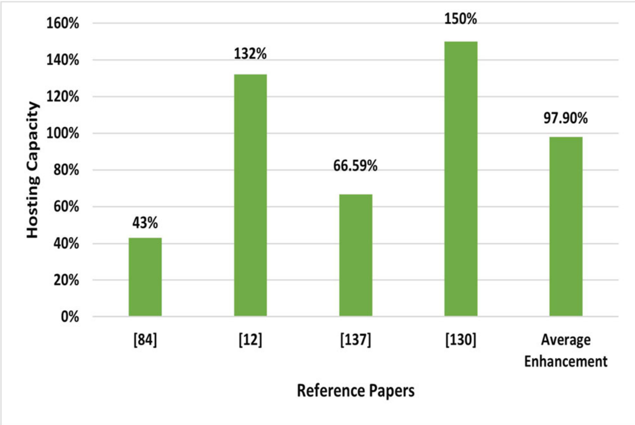

FIGURE 6 Enhanced value using harmonic mitigation

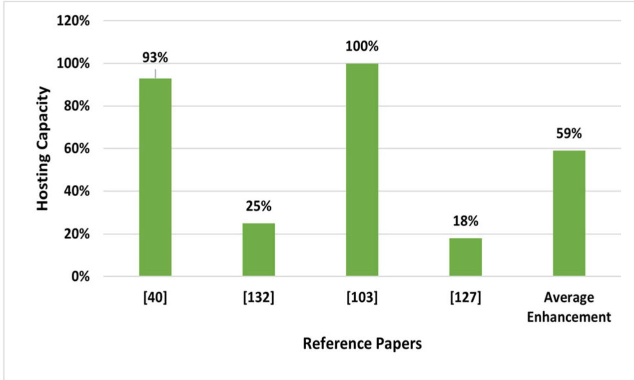

FIGURE 8 Enhanced value using on-load tap changer

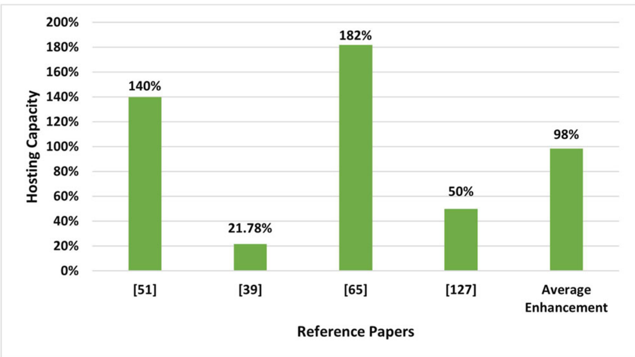

FIGURE 7 Enhanced value using battery energy storage system

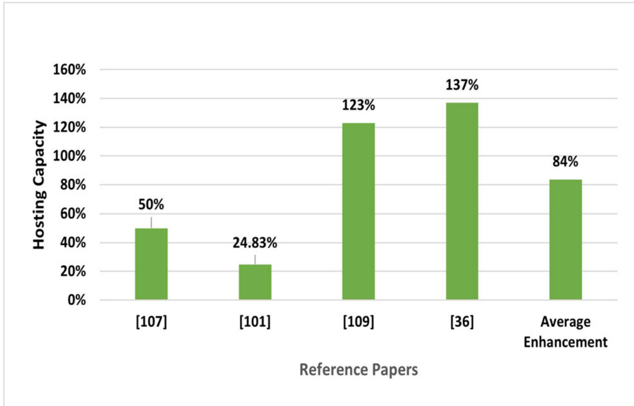

FIGURE 9 Enhanced value using reactive power control

et al.[12] An actual Brazilian power system was tested for HC assessment and a range (worst and best-case scenario) for HC was made. HC for the worst-case scenario was 37 MW, while it was 160 MW for the best-case scenario. In the studies conducted in Sun et al.,[118] an AC optimal power flow technique was used to counter the harmonics that were presented as the main constraint that causes the limiting of HC along with voltage and thermal constraints. The authors of Bhowmik et al.,[119] formulated closed-form equations to determine the allowable limit for the penetration of DGs. The proposed method has been developed in compliance with acceptable harmonic analysis assumptions for every possible condition. The method was justifiable both technically and economically and suitable for conventional radial distribution systems.

Results shown in Figures 6–9 represent the results of enhancement in HC because of using different enhancement techniques.

These results do not articulate the idea of one technique being better than the other one. Rather it shows the average enhancement of different literature using the same techniques. The networks and methodologies used in the literature were totally independent of each other. After carrying out a proper investigation of the feeder and analysis of the factors that influence the HC of the feeder, only then the enhancement technique can be deployed.

7 | DISCUSSION AND CONCLUSIONS

HC is a locational-sensitive phenomenon and depends upon different criteria like characteristics of the grid understudy and defining criteria of HC for a specific case. Therefore, a single generic approach, for defining the HC, cannot be implemented on all the grid systems. Moreover, the DGs' penetration will keep on increasing with the steps taken by the different governments to reduce the carbon footprint. Therefore, before incorporating DGs, specifically PVs into the system, a detailed study should be carried out keeping in mind the limiting constraints, economic and operational feasibility, and the applicable HC determination and enhancement technique. In the presented manuscript an

TABLE 6 Summary of HC limiting constraints, defining criteria, enhancement technique, and enhanced values

Reference	Defining criteria	Limiting constraints	Enhancement technique	HC value	Enhanced HC value
[120]	_	Over voltages, under voltages	C-type filter design	30%	75%
[99]	Number of customers having PV	_	Optimal PV placement	_	30%
[48]	Transformer, cable, and line ampacity	Rise in voltage levels	Curtailment of DGs	130 MW	170 MW
[79]	Current carrying capability of supply lines	Harmonic distortion voltage changes	Passive filters	38.53%	55.34%
[28]	Transformer overloading	Voltage quality	_	37.4%	80.1%
[121]	_	Over voltages	OLTC transformers	89.81%	113.48%
[100]	_	Over voltages	Reactive power absorption	_	_
[95]	Transformer and cable rating	Over voltages	Cos(θ) control and PV storage control	_	101% and 116%
[58]	Transformer rating	Voltage unbalance	Using active MV/LV transformers	38%	45%
[40]	_	Over voltages	Electric energy storage system (EESS)	_	_
[122]	Equipment ampacity	Steady state bus voltage	_	_	_
[101]	Thermal violation of equipment	Transient and steady state voltage violations	Volt-VAR droop control	_	Increased by 533 kVA
[123]	Short circuit capacity, minimum load, and transformer rating	Voltage level violations	Reactive power support	7.9 MW	18.7 MW
[124]	_	Dynamic voltage regulation	Using STATCOMS	_	_
[40]	Transformer rating	Over voltages	Using active transformers	45%	87%
[50]	Transformer rating	Rise in Voltage	PF droop control and grid reinforcement	_	_
[125]	_	Harmonics	Passive filter	44%	73.3%
[111]	Grids equipment ampacity	_	Grid reconfiguration	17.2%	73.46%
[98]	_	Primary Impedance	Grid reinforcement and restricting PV locations	30%	50%
[110]	_	Thermal and voltage constraints	Static and dynamic reconfiguration and active network management	_	51.8% and 50.2%
[39]	Thermal limit of power lines	Reverse active Power	Quadratic power control and optimal battery and converter size	_	50
[52]	_	Voltage Rise	Using BESS	25%	60%
[62]	_	Power Quality and voltage unbalance	Optimal location of BESS	_	111%

(Continues)

TABLE 6 (Continued)

Reference	Defining criteria	Limiting constraints	Enhancement technique	HC value	Enhanced HC value
[79]	Current carrying capability	Harmonic Distortion	Implementing a C type Filter	38.5%	55.34%
[31]	–	Voltage Magnitude and voltage unbalance	Volt-Var control	30%	60%
[53]	Ampacity limit of lines and cables	Rapid voltage changes	Network reconfiguration	–	18%
[40]	Transformer rating and number of customers having PV	Over Voltages	Efficiently controlling active transformers	38%	45% with maximum of 3% of voltage rise
[101]	Number of customers with PV	Transient and steady state Voltage violations	Reactive power control	–	84.4%
[95]	Equipment overloading	Over voltages	Using residential PV storages and reactive power control	–	80% by Cos(θ) control 120% by $Q(V)$ control 70% by forecasting

attempt was made to explain the concept of HC in detail and examine different factors associated with it. Some basic definitions associated with the HC, that is, hosting capacity uncertainty and hosting capacity coefficient were explained briefly. At first different defining criteria for HC were described which included equipment ampacity, number of customers having PVs, roof space availability, the active power of load, and network loading.

It was found that the defining criteria is a DNO-specific term and can vary from region to region. There are no common criteria that can be used to define the HC for different regions based on the same reference value. Later based on the type of network loading data and the standards implemented, limiting constraints were defined that included harmonics, voltage flickers, voltage level violation, voltage unbalance, and equipment ampacity violations. A system can be affected by any of these constraints depending on its characteristics and location. The most common HC limiting criteria was found to be overvoltage due to increased DG penetration downstream of the network. The availability of data in different resolutions greatly impacts the HC study and determination methodology. For instance, high-resolution data is required for the flicker studies, whereas time series data was mandatory to calculate the impact of increasing penetration on regulation equipment like OLTC and voltage regulators.

The main determination techniques found in the literature were deterministic, time series, worst-case hour, stochastic and stochastic-time series approaches with their respective pros and cons. Lastly, HC enhancement techniques were presented which included the usage of OLTC transformers, curtailment of DGs, active and reactive power control, optimized PV deployment, network reconfiguration, and usage of BESS. All these techniques were used independently or in different combinations depending on the operational requirement, and a significant increment was observed in the HC results.

In a nutshell, HC is a terminology that was found to be a constraint, grid, standard, and enhancement methodology-dependent phenomenon that is always different for different regions. Unless there is a standard that is defined for the HC studies and is uniformly implemented throughout the globe, the comparison studies will not be easy to make for different regions' grids. However, there might be a solution in the machine learning techniques that will be used to define the common criteria for different types of grids to have a rough estimate of the HC values. Table 6 presents a summary of limiting constraints, defining criteria, enhancement techniques, and enhanced values observed in different literature.

NOMENCLATURE

ANM	active network management
APC	active power curtailment
BESS	battery energy storage system
DG	distributed generation
DHC	dynamic hosting capacity
DM-APC	dynamic maximum active power control
DSO	distribution system operator
HC	hosting capacity
HCC	hosting capacity coefficient
HV	high voltage
LDC	line drop compensator
LV	low voltage
MCS	Monte Carlo simulations
MV	medium voltage
OLTC	on-load tap changer
OV	over-voltage
PF	power factor
PI	performance indices
PV	photovoltaic
SHC	static hosting capacity
SM-APC	static maximum active power control
SVR	step voltage regulator
VU	voltage unbalance

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REFERENCES

1. Bollen MHJ, Rönnberg SK. Hosting capacity of the power grid for renewable electricity production and new large consumption equipment. *Energies*. 2017;10(9):1325. doi:10.3390/en10091325
2. Liu YJ, Tai YH, Huang CY, Su HJ, Lan PH, Hsieh MK. Assessment of the PV hosting capacity for the medium-voltage 11.4 kV distribution feeder. Proceedings of 4th IEEE International Conference on Applied System Innovation 2018, ICASI 2018; 2018:381-384. doi:10.1109/ICASI.2018.8394262
3. Mohammadi P, Mehraeen S. Challenges of PV integration in low-voltage secondary networks. *IEEE Trans Power Delivery*. 2017;32(1):525-535. doi:10.1109/TPWRD.2016.2556692
4. Karimi M, Mokhlis H, Naidu K, Uddin S, Bakar AHA. Photovoltaic penetration issues and impacts in distribution network—a review. *Renew Sustain Energy Rev*. 2016;53:594-605. doi:10.1016/j.rser.2015.08.042
5. Al-Saadi H, Zivanovic R, Al-Sarawi SF. Probabilistic hosting capacity for active distribution networks. *IEEE Trans Industr Inform*. 2017;13(5):2519-2532. doi:10.1109/TII.2017.2698505
6. Bollen M, Hassan F. Integration of distributed generation in the power system. *Integr Distributed Generation Power Syst*. 2011;80. doi:10.1002/9781118029039
7. Currie B, Abbey C, Ault G, et al. Flexibility is key in New York: new tools and operational solutions for managing distributed energy resources. *IEEE Power Energy Mag*. 2017;15(3):20-29. doi:10.1109/MPE.2017.2660818
8. Shayani RA, de Oliveira MAG. Photovoltaic generation penetration limits in radial distribution systems. *IEEE Trans Power Syst*. 2011;26(3):1625-1631. doi:10.1109/TPWRS.2010.2077656
9. Basso TS, DeBlasio RD. IEEE P1547-series of standards for interconnection. Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference, Vol 2; 2003:556-561. doi:10.1109/tdc.2003.1335335
10. Saint R, Friedman NR. The application guide for distributed generation interconnection the NRECA guide to IEEE 1547. Papers—Rural Electric Power Conference, Vol 5; 2002. doi:10.1109/repcon.2002.1002300
11. Walling RA, Saint R, Dugan RC, Burke J, Kojovic LA. Summary of distributed resources impact on power delivery systems. *IEEE Trans Power Delivery*. 2008;23(3):1636-1644. doi:10.1109/TPWRD.2007.909115
12. Santos IN, Ćuk V, Almeida PM, Bollen MHJ, Ribeiro PF. Considerations on hosting capacity for harmonic distortions on transmission and distribution systems. *Electric Power Syst Res*. 2015;119:199-206. doi:10.1016/j.epsr.2014.09.020
13. Sun W. *Maximising renewable hosting capacity in electricity networks*. Doctor of Philosophy Dissertation, The University of Edinburgh, Edinburgh. 2014.
14. Ding F, Mather B, Ainsworth N, Gotseff P, Baker K. Locational sensitivity investigation on PV hosting capacity and fast track PV screening. Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference. Vol 2016; 2016:3-7. doi:10.1109/TDC.2016.7519878
15. Ismael SM, Abdel Aleem SHE, Abdelaziz AY, Zobaa AF. State-of-the-art of hosting capacity in modern power systems with distributed generation. *Renew Energy*. 2019;130:1002-1020. doi:10.1016/j.renene.2018.07.008
16. Etherden N, Bollen MHJ. Overload and overvoltage in low-voltage and medium-voltage networks due to renewable energy—some illustrative case studies. *Electric Power Syst Res*. 2014;114:39-48. doi:10.1016/j.epsr.2014.03.028
17. Bajaj M, Kumar Singh A. Hosting capacity enhancement of renewable-based distributed generation in harmonically polluted distribution systems using passive harmonic filtering. *Sustain Energy Technol Assess*. 2021;44:101030. doi:10.1016/j.seta.2021.101030
18. Christakou K. A unified control strategy for active distribution networks via demand response and distributed energy storage systems. *Sustain Energy Grids Networks*. 2016;6:1-6. doi:10.1016/J.SEGAN.2016.01.001
19. Arshad A, Lehtonen M. Probabilistic assessment of photovoltaic hosting capacity in Finnish LV networks. Proceedings of 2019 IEEE PES Innovative Smart Grid Technologies Europe, ISGT-Europe 2019; 2019:1-5. doi:10.1109/ISGTEurope.2019.8905450
20. Arshad A, Lindner M, Lehtonen M. An analysis of photo-voltaic hosting capacity in Finnish low voltage distribution networks. *Energies*. 2017;10(11):1702. doi:10.3390/en10111702
21. Rahman MM, Shafiullah AA, Arefi A, Pezeshki H, Hettiwatte S. Improvement of voltage magnitude and unbalance in LV network by implementing residential demand response. IEEE Power and Energy Society General Meeting, Vol 2018; 2018:1-5. doi:10.1109/PESGM.2017.8273831
22. Rahman MM, Arefi A, Shafiullah GM, Hettiwatte S. A new approach to voltage management in unbalanced low voltage networks using demand response and OLTC considering

consumer preference. *Int J Electrical Power Energy Syst*. 2018;99(May 2017):11-27. doi:10.1016/j.ijepes.2017.12.034
23. Singh NK, Wanik MZC, Jabbar AA, Sanfilippo A. Enhancing PV hosting capacity of a qatar remote farm network using inverters ability to regulate reactive power—a case study. Proceedings of 2019 IEEE PES Innovative Smart Grid Technologies Europe, ISGT-Europe 2019; 2019:1-5. doi:10.1109/ISGTEurope.2019.8905545
24. Chathurangi D, Jayatunga U, Rathnayake M, Wickramasinghe A, Agalgaonkar A, Perera S. Potential power quality impacts on LV distribution networks with high penetration levels of solar PV. Proceedings of International Conference on Harmonics and Quality of Power, ICHQP, Vol 2018; 2018:1-6. doi:10.1109/ICHQP.2018.8378890
25. Navarro-Espinosa A, Ochoa LF. Probabilistic impact assessment of low carbon technologies in LV distribution systems. *IEEE Trans Power Syst*. 2016;31(3):2192-2203. doi:10.1109/TPWRS.2015.2448663
26. Lamberti F, Calderaro V, Galdi V, Piccolo A, Graditi G. Impact analysis of distributed PV and energy storage systems in unbalanced LV networks. 2015 IEEE Eindhoven PowerTech, PowerTech 2015; 2015:2-7. doi:10.1109/PTC.2015.7232717
27. Navarro-Espinosa A, Ochoa LF. Increasing the PV hosting capacity of LV networks: OLTC-fitted transformers vs. reinforcements. 2015 IEEE Power and Energy Society Innovative Smart Grid Technologies Conference, ISGT 2015; 2015:2011-2014. doi:10.1109/ISGT.2015.7131856
28. Torquato R, Salles D, Oriente Pereira C, Meira PCM, Freitas W. A comprehensive assessment of PV hosting capacity on low-voltage distribution systems. *IEEE Trans Power Delivery*. 2018;33(2):1002-1012. doi:10.1109/TPWRD.2018.2798707
29. Rusinaru D, Manescu LG, Cojoaca A, Alba M, Bulac C, Rosca D. Grid integration of the small generation units in LV distribution networks. Proceedings of 2018 International Conference on Applied and Theoretical Electricity, ICATE 2018; 2018:1-6. doi:10.1109/ICATE.2018.8551370
30. Saber AY, Khandelwal T, Srivastava AK. Fast feeder PV hosting capacity using swarm based intelligent distribution node selection. IEEE Power and Energy Society General Meeting, Vol 2019; 2019:1-5. doi:10.1109/PESGM40551.2019.8973389
31. Ding F, Mather B. On distributed PV hosting capacity estimation, sensitivity study, and improvement. *IEEE Trans Sustain Energy*. 2017;8(3):1010-1020. doi:10.1109/TSTE.2016.2640239
32. Baldenko N, Behzadirafi S. Determination of photovoltaic hosting capacity on radial electric distribution feeders. 2016 IEEE International Conference on Power System Technology, POWERCON 2016; 2016:3-6. doi:10.1109/POWERCON.2016.7753969.
33. Nijhuis M, Gibescu M, Cobben JFG. Incorporation of on-load tap changer transformers in low-voltage network planning. IEEE PES Innovative Smart Grid Technologies Conference Europe; 2016:1-6. doi:10.1109/ISGTEurope.2016.78562
34. Heinrich C, Fortenbacher P, Fuchs A, Andersson G. PV-integration strategies for low voltage networks. 2016 IEEE International Energy Conference, ENERGYCON 2016, Vol 2, no. 1, 2016. doi:10.1109/ENERGYCON.2016.7514141
35. Grabner M, Souvent A, Suljanović N, Košir A, Blažič B. Probabilistic methodology for calculating PV hosting capacity in LV networks using actual building roof data. *Energies*. 2019;12(21). doi:10.3390/en12214086
36. Divshali PH, Soder L. Improving PV hosting capacity of distribution grids considering dynamic voltage characteristic. 20th Power Systems Computation Conference, PSCC 2018; 2018. doi:10.23919/PSCC.2018.8442517
37. Weisshaupt MJ, Schlatter B, Korba P, Kaffe E, Kienzle F. Evaluation of measures to operate urban low voltage grids considering future PV expansion. *IFAC-PapersOnLine*. 2016;49(27):336-341. doi:10.1016/j.ifacol.2016.10.714
38. Ravikumar Pandi V, Zeineldin HH, Xiao W. Allowable DG penetration level considering harmonic distortions. IECON Proceedings (Industrial Electronics Conference); 2011: 814-818. doi:10.1109/IECON.2011.6119415
39. Hasanpor Divshali P, Soder L. Improving hosting capacity of rooftop PVs by quadratic control of an LV-central BSS. *IEEE Trans Smart Grid*. 2019;10(1):919-927. doi:10.1109/TSG.2017.2754943
40. Hashemi S, Østergaard J. Efficient control of energy storage for increasing the PV hosting capacity of LV grids. *IEEE Trans Smart Grid*. 2018;9(3):2295-2303. doi:10.1109/TSG.2016.2609892
41. Kikuchi S, Machida M, Tamura J, et al. Hosting capacity analysis of many distributed photovoltaic systems in future distribution networks. 2017 IEEE Innovative Smart Grid Technologies—Asia: Smart Grid for Smart Community, ISGT-Asia 2017; 2018:1-5. doi:10.1109/ISGT-Asia.2017.8378408
42. Schwaegerl C, Bollen MHJ, Karoui K, Yagmur A. Voltage control in distribution systems as a limitation of the hosting capacity for distributed energy resources. IEEE Conference Publication, Vol 4; 2005:153-157. doi:10.1049/cp:20051229
43. Alalamat F. Increasing the hosting capacity of radial distribution grids in Jordan. http://www.teknat.uu.se/student
44. Alam MJE, Muttaqi KM, Sutanto D. Community energy storage for neutral voltage rise mitigation in four-wire multigrounded LV feeders with unbalanced solar PV allocation. *IEEE Trans Smart Grid*. 2015;6(6):2845-2855. doi:10.1109/TSG.2015.2427872
45. Kitworawut PB, Azuatalam DT, Unigwe OC, Collin AJ. An investigation into the technical impacts of microgeneration on UK-type LV distribution networks. 2016 IEEE International Conference on Renewable Energy Research and Applications, ICRERA 2016; 2017:124-129. doi:10.1109/ICRERA.2016.7884478
46. Bertini D, Falabretti D, Merlo M, Moneta D, Carneiro JSDA, Silvestri A. Hosting capacity of Italian LV distribution networks. undefined, 2011.
47. Navarro BB, Navarro MM. A comprehensive solar PV hosting capacity in MV and LV radial distribution networks. 2017 IEEE PES Innovative Smart Grid Technologies Conference Europe, ISGT-Europe 2017—Proceedings, Vol 2018; 2017: 1-6. doi:10.1109/ISGTEurope.2017.8260210
48. Etherden N, Bollen MHJ. Increasing the hosting capacity of distribution networks by curtailment of renewable energy resources. 2011 IEEE PES Trondheim PowerTech: The Power of Technology for a Sustainable Society, POWERTECH 2011; 2011:1-7. doi:10.1109/PTC.2011.6019292
49. Ed SEN, Radim Č, Krej P. Undefined parameters and two-limit parameters in; 2015:1-4.

50. Stetz T, Marten F, Braun M. Improved low voltage grid-integration of photovoltaic systems in Germany. *IEEE Trans Sustain Energy*. 2013;4(2):534-542. doi:10.1109/TSTE.2012.2198925
51. Haghi HV, Pecenak Z, Kleissi J, et al. Feeder impact assessment of smart inverter settings to support high PV penetration in California. IEEE Power and Energy Society General Meeting, Vol 2019; 2019:6-10. doi:10.1109/PESGM40551.2019.8974016
52. Joshi K, Gokaraju RR. An iterative approach to improve PV hosting capacity for a remote community. *IEEE Power and Energy Society General Meeting*, Vol 2018; 2018. doi:10.1109/PESGM.2018.8586196
53. Falabretti D, Merlo M, Delfanti M. Network reconfiguration and storage systems for the hosting capacity improvement. 22nd International Conference on Electricity Distribution Paper 1504; 2013:10-13.
54. Pukhrem S, Basu M, Conlon MF, Sunderland K. Enhanced network voltage management techniques under the proliferation of rooftop solar PV installation in low-voltage distribution network. *IEEE J Emerging Selected Topics Power Electron*. 2017;5(2):681-694. doi:10.1109/JESTPE.2016.2614986
55. Hashemi S, Ostergaard J, Yang G. Effect of reactive power management of PV inverters on need for energy storage. Conference Record of the IEEE Photovoltaic Specialists Conference; 2016:2304-2308. doi:10.1109/PVSC.2013.6744938
56. Rahman FFS, Adi Sarjiya KW, Putranto LM. Study on photovoltaic hosting in yogyakarta electric distribution network. Proceedings—2018 5th International Conference on Information Technology, Computer and Electrical Engineering, ICITACEE 2018; 2018:240-244. doi:10.1109/ICITACEE.2018.8576961
57. Schwaegerl C, Bollen M, Karoui K, Yagmur A, Nc PS. Voltage control in distribution systems as a limitation of the hosting capacity for distributed energy resources. 18th International Conference on Electricity Distribution, CIRED 2005; 2005.
58. Hashemi S, Østergaard J. Methods and strategies for overvoltage prevention in low voltage distribution systems with PV. *IET Renew Power Gen*. 2017;11(2):205-214. doi:10.1049/iet-rpg.2016.0277
59. Makarov Yv, Du P, Kintner-Meyer MCW, Jin C, Illian HF. Sizing energy storage to accommodate high penetration of variable energy resources. *IEEE Trans Sustain Energy*. 2012;3(1):34-40. doi:10.1109/TSTE.2011.2164101
60. Ramaswamy, PC. Reconfiguring distribution grids for more integration of distributed generation. 22nd International Conference on Electricity Distribution. CIRED 2013; 2013.
61. Wang B, Zhang C, Dong ZY, Li X. Improving hosting capacity of unbalanced distribution networks via robust allocation of battery energy storage systems. *IEEE Trans Power Syst*. 2021;36(3):2174-2185. doi:10.1109/TPWRS.2020.3029532
62. Arshad A, Püvi V, Lehtonen M. Monte Carlo-based comprehensive assessment of PV hosting capacity and energy storage impact in realistic Finnish low-voltage networks. *Energies*. 2018;11(6):121693718. doi:10.3390/en11061467
63. Tang NC, Chang GW. A stochastic approach for determining PV hosting capacity of a distribution feeder considering voltage quality constraints. Proceedings of International Conference on Harmonics and Quality of Power, ICHQP, Vol 2018; 2018:1-5. doi:10.1109/ICHQP.2018.8378864
64. Dubey A, Santoso S, Maitra A. Understanding photovoltaic hosting capacity of distribution circuits. IEEE Power and Energy Society General Meeting, Vol 2015; 2015. doi:10.1109/PESGM.2015.7286510
65. Hu J, Marinelli M, Coppo M, Zecchino A, Bindner HW. Coordinated voltage control of a decoupled three-phase on-load tap changer transformer and photovoltaic inverters for managing unbalanced networks. *Electric Power Syst Res*. 2016;131:264-274. doi:10.1016/j.epsr.2015.10.025
66. Buren RF. IEEE 1453—how well does it work in the real world. 2006 IEEE Power Engineering Society General Meeting, PES; 2006:1-2. doi:10.1109/pes.2006.1709223
67. Stewart EM, Aukai TP, MacPherson SDJ, Quach BP, Nakafuji D, Davis R. A realistic irradiance-based voltage flicker analysis of PV applied to Hawaii distribution feeders. IEEE Power and Energy Society General Meeting; 2012:1-7. doi:10.1109/PESGM.2012.6344978
68. Andreas Spring S, Wirth G, Becker G, Pardatscher R, Witzmann R. Effects of flicker in a distribution grid with high PV penetration. *J Energy Power Eng*. 2014;8(12). doi:10.17265/1934-8975/2014.12.003
69. Morsi WG, El-Hawary ME. Effect of distributed generation on voltage flicker in distributed systems: a case study. Canadian Conference on Electrical and Computer Engineering; 2008:65-70. doi:10.1109/CCECE.2008.4564497
70. Woyte A, Van Thong V, Purchala K, Belmans R, Nijs J. Quantifying the occurrence and duration of power fluctuations introduced by photovoltaic systems. 2003 IEEE Bologna PowerTech—Conference Proceedings, Vol 3; 2003:7-13. doi:10.1109/PTC.2003.1304368
71. Katiraei F, Mauch K, Dignard-Bailey L. Integration of photovoltaic power systems in high-penetration clusters for distribution networks and mini-grids. *Int J Distributed Energy Resources*. 2007;3(3):207-223.
72. Pakonen P, Hilden A, Suntio T, Verho P. Grid-connected PV power plant induced power quality problems—experimental evidence. 2016 18th European Conference on Power Electronics and Applications, EPE 2016 ECCE Europe, Vol 2017; 2016. doi:10.1109/EPE.2016.7695656
73. Masetti C. Revision of European Standard EN 50160 on power quality: reasons and solutions. ICHQP 2010—14th International Conference on Harmonics and Quality of Power, Vol 2006; 2010. doi:10.1109/ICHQP.2010.5625472
74. Viotto M. Present status of DG in Germany: national codes, standards, requirements and rules for grid-interconnection and operation; 2002:1-27.
75. Sharma SK, Chandra A, Saad M, Lefebvre S, Asber D, Lenoir L. Voltage flicker mitigation employing smart loads with high penetration of renewable energy in distribution systems. *IEEE Trans Sustain Energy*. 2017;8(1):414-424. doi:10.1109/TSTE.2016.2603512
76. Ferdowsi F, Mehraeen S, Upton GB. Assessing distribution network sensitivity to voltage rise and flicker under high penetration of behind-the-meter solar. *Renew Energy*. 2020;152:1227-1240. doi:10.1016/j.renene.2019.12.124
77. Rahman S, Moghaddami M, Sarwat AI, Olowu T, Jafaritalarposhti M. Flicker estimation associated with PV

integrated distribution network. conference proceedings—IEEE Southeastcon, Vol 2018, no. 1553494; 2018:1-6. doi:10.1109/SECON.2018.8479058
78. Arshad A, Lehtonen M. Instantaneous active/reactive power control strategy for flicker mitigation under high PV penetration. Proceedings 2018 IEEE PES Innovative Smart Grid Technologies Conference Europe, ISGT-Europe 2018; 2018. doi:10.1109/ISGTEurope.2018.8571855
79. Sakar S, Balci ME, Aleem SHEA, Zobaa AF. Hosting capacity assessment and improvement for photovoltaic-based distributed generation in distorted distribution networks. EEEIC 2016–International Conference on Environment and Electrical Engineering; 2016:2-7. doi:10.1109/EEEIC.2016.7555515
80. Harrison GP. Incorporating harmonic limits in to assessment of the hosting capacity of active net works. Proceedings of CIRED 2012 Workshop: Integration of Renewables into the Distribution Grid, Vol 5; 2012:3-6.
81. Ampofo DO, Otchere IK, Frimpong EA. An investigative study on penetration limits of distributed generation on distribution networks. Proceedings—2017 IEEE PES-IAS PowerAfrica Conference: Harnessing Energy, Information and Communications Technology (ICT) for Affordable Electrification of Africa, PowerAfrica 2017; 2017:573-576. doi:10.1109/PowerAfrica.2017.7991289
82. Li Z, Shahidehpour M, Alabdulwahab A, Al-Turki Y. Valuation of distributed energy resources in active distribution networks. *Electricity J*. 2019;32(4):27-36. doi:10.1016/j.tej.2019.03.001
83. Waleed A, Virk US, Riaz MT, et al. Effectiveness and comparison of digital substations over conventional substations. *Adv Sci Technol Eng Syst J*. 2019;4(4):431-439. doi:10.25046/aj040452
84. Luthander R, Lingfors D, Widén J. Large-scale integration of photovoltaic power in a distribution grid using power curtailment and energy storage. *Sol Energy*. 2017;155:1319-1325. doi:10.1016/j.solener.2017.07.083
85. Parihar SS, Malik N. Interval arithmetic power flow analysis of radial distribution system with probabilistic load model and distributed generation. *Process Integr Optim Sustain*. 2022;6:3-15. https://doi.org/10.1007/s41660-021-00200-8
86. Heslop S, Macgill I, Fletcher J, Lewis S. Method for determining a PV generation limit on low voltage feeders for evenly distributed PV and load. *Energy Proc*. 2014;57:207-216. doi:10.1016/j.egypro.2014.10.025
87. Rossi M, Viganò G, Moneta D. Hosting capacity of distribution networks: evaluation of the network congestion risk due to distributed generation. 2015 International Conference on Clean Electrical Power (ICCEP), 2015:716-722. doi:10.1109/ICCEP.2015.7177570
88. Khoshkbar-Sadigh A, Smedley KM. The necessity of time-series simulation for investigation of large-scale solar energy penetration. 2015 IEEE Power and Energy Society Innovative Smart Grid Technologies Conference, ISGT 2015; 2015. doi:10.1109/ISGT.2015.7131803
89. Behravesh V, Keypour R, Foroud AA. Stochastic analysis of solar and wind hybrid rooftop generation systems and their impact on voltage behavior in low voltage distribution systems. *Sol Energy*. 2018;166(2017):317-333. doi:10.1016/j.solener.2018.03.063
90. Fan S, Pu T, Li L, Yu T, Yang Z, Gao B. Evaluation of impact of integrated distributed generation on distribution network based on time-series analysis. China International Conference on Electricity Distribution, CICED, Vol 2016, CICED; 2016:10-13. doi:10.1109/CICED.2016.7576171
91. Pagnetti A, Delille G. A simple and efficient method for fast analysis of renewable generation connection to active distribution networks. *Electric Power Syst Res*. 2015;125:133-140. doi:10.1016/j.epsr.2015.03.025
92. Chen P, Salcedo R, Zhu Q, et al. Analysis of voltage pro file problems due to the penetration of distributed generation in low-voltage. *IEEE Trans Power Delivery*. 2020;27(4):2020-2028.
93. Ismael SM, Abdel Aleem SHE, Abdelaziz AY, Zobaa AF. Practical considerations for optimal conductor reinforcement and hosting capacity enhancement in radial distribution systems. *IEEE Access*. 2018;6:27268-27277. doi:10.1109/ACCESS.2018.2835165
94. Athari MH, Wang Z, Eylas SH. Time-series analysis of photovoltaic distributed generation impacts on a local distributed network. 2017 IEEE Manchester PowerTech, Powertech 2017; 2017. doi:10.1109/PTC.2017.7980908
95. Rascon OC, Schachler B, Buhler J, Resch M, Sumper A. Increasing the hosting capacity of distribution grids by implementing residential PV storage systems and reactive power control. International Conference on the European Energy Market, EEM, Vol 2016; 2016. doi:10.1109/EEM.2016.7521338
96. Berizzi A, Bovo C, Ilea V, et al. Advanced functions for DSOs control centre. 2013 IEEE Grenoble Conference PowerTech, POWERTECH 2013; 2013. doi:10.1109/PTC.2013.6652343
97. Mina Mirbagheri S, Falabretti D, Ilea V, Merlo M. Hosting capacity analysis: a review and a new evaluation method in case of parameters uncertainty and multi-generator. Proceedings of 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2018; 2018. doi:10.1109/EEEIC.2018.8494572
98. Ding F, Mather B, Gotseff P. Technologies to increase PV hosting capacity in distribution feeders. IEEE Power and Energy Society General Meeting, Vol 2016; 2016:1-5. doi:10.1109/PESGM.2016.7741575
99. Bartecka M, Barchi G, Paska J. Time-series PV hosting capacity assessment with storage deployment. *Energies*. 2020;13(10):1-20. doi:10.3390/en13102524
100. Collins L, Ward JK. Real and reactive power control of distributed PV inverters for overvoltage prevention and increased renewable generation hosting capacity. *Renew Energy*. 2015;81:464-471. doi:10.1016/j.renene.2015.03.012
101. Seuss J, Reno MJ, Broderick RJ, Grijalva S. Improving distribution network PV hosting capacity via smart inverter reactive power support. IEEE Power and Energy Society General Meeting, Vol 2015; 2015:1-4. doi:10.1109/PESGM.2015.7286523
102. Atmaja Sarjiya WY, Lesnanto MP, Pramono EY. Hosting capacity improvement using reactive power control strategy of rooftop PV inverters. Proceedings of 2019 the 7th International Conference on Smart Energy Grid Engineering, SEGE 2019; 2019:213-217. doi:10.1109/SEGE.2019.8859888
103. Demirok, E, Sera, D, Teodorescu, R, Rodriguez, P, Borup, U. Clustered PV inverters in LV networks: an overview of impacts and comparison of voltage control strategies. 2009 IEEE Electrical Power and Energy Conference, EPEC 2009; 2009:1-6. doi:10.1109/EPEC.2009.5420366

104. AlKaabi SS, Khadkikar V, Zeineldin HH. Incorporating PV inverter control schemes for planning active distribution networks. *IEEE Trans Sustain Energy*. 2015;6(4):1224-1233. doi:10.1109/TSTE.2015.2422305
105. Su X, Masoum MAS, Wolfs PJ. Optimal PV inverter reactive power control and real power curtailment to improve performance of unbalanced four-wire LV distribution networks. *IEEE Trans Sustain Energy*. 2014;5(3):967-977. doi:10.1109/TSTE.2014.2313862
106. Divan D, Moghe R, Chun H. Managing distribution feeder voltage issues caused by high PV penetration. 2016 IEEE 7th International Symposium on Power Electronics for Distributed Generation Systems, PEDG 2016; 2016. doi:10.1109/PEDG.2016.7527047
107. Ding F, Loparo KA. Feeder reconfiguration for unbalanced distribution systems with distributed generation: a hierarchical decentralized approach. *IEEE Trans Power Syst*. 2016;31(2):1633-1642. doi:10.1109/TPWRS.2015.2430275
108. Smith J, Rylander M, Rogers L, Dugan R. It's all in the plans: maximizing the benefits and minimizing the impacts of DERs in an integrated grid. *IEEE Power Energy Mag*. 2015;13(2):20-29. doi:10.1109/MPE.2014.2379855
109. Chittur Ramaswamy P, Vingerhoets P, Deconinck G. Reconfiguring distribution grids for more integration of distributed generation. IET Conference Publications, Vol 2013; 2013. doi:10.1049/CP.2013.0713/CITE/REFWORKS
110. Capitanescu F, Ochoa LF, Margossian H, Hatziargyriou ND. Assessing the potential of network reconfiguration to improve distributed generation hosting capacity in active distribution systems. *IEEE Trans Power Syst*. 2015;30(1):346-356. doi:10.1109/TPWRS.2014.2320895
111. Xiong Q, Liu F, Lv L, Liu Y, Li Y, Zhu C. Urban power grids dynamic control model with photovoltaic and electric vehicles. China International Conference on Electricity Distribution, CICED, Vol 3; 2018:2462-2466. doi:10.1109/CICED.2018.8592506
112. Jothibasu S, Dubey A, Santoso S. Two-Stage distribution circuit design framework for high levels of photovoltaic generation. *IEEE Trans Power Syst*. 2019;34(6):5217-5226. doi:10.1109/TPWRS.2018.2871640
113. Oudalov A, Chartouni D, Ohler C. Optimizing a battery energy storage system for primary frequency control. *IEEE Trans Power Syst*. 2007;22(3):1259-1266. doi:10.1109/TPWRS.2007.901459
114. Lo CH, Anderson MD. Economic dispatch and optimal sizing of battery energy storage systems in utility load-leveling operations. *IEEE Trans Energy Convers*. 1999;14(3):824-829. doi:10.1109/60.790960
115. Abbey C, Joos G. A stochastic optimization approach to rating of energy storage systems in wind-diesel isolated grids. *IEEE Trans Power Syst*. 2009;24(1):418-426. doi:10.1109/TPWRS.2008.2004840
116. Barton JP, Infield DG. Intermittent renewable energy. *IEEE Trans Energy Convers*. 2004;19(2):441-448.
117. Gupta R, Sossan F, Paolone M. Countrywide PV hosting capacity and energy storage requirements for distribution networks: the case of Switzerland. *Appl Energy*. 2021;281(2020):116010. doi:10.1016/j.apenergy.2020.116010
118. Sun W, Harrison GP, Djokic SZ. Distribution network capacity assessment: incorporating harmonic distortion limits. IEEE Power and Energy Society General Meeting; 2012:1-7. doi:10.1109/PESGM.2012.6344764
119. Bhowmik A, Maitra A, Halpin SM, Schatz JE. Determination of allowable penetration levels of distributed generation resources based on harmonic limit considerations. *IEEE Trans Power Delivery*. 2003;18(2):619-624. doi:10.1109/TPWRD.2003.810494
120. Sakar S, Balci ME, Abdel Aleem SHE, Zobaa AF. Increasing PV hosting capacity in distorted distribution systems using passive harmonic filtering. *Electric Power Syst Res*. 2017;148:74-86. doi:10.1016/j.epsr.2017.03.020
121. Arshad A, Lehtonen M. A stochastic assessment of PV hosting capacity enhancement in distribution network utilizing voltage support techniques. *IEEE Access*. 2019;7:46461-46471. doi:10.1109/ACCESS.2019.2908725
122. Rabiee A, Mohseni-Bonab SM. Maximizing hosting capacity of renewable energy sources in distribution networks: a multi-objective and scenario-based approach. *Energy*. 2017;120:417-430. doi:10.1016/j.energy.2016.11.095
123. Padullaparti HV, Jothibasu S, Santoso S, Todeschini G. Increasing feeder PV hosting capacity by regulating secondary circuit voltages. IEEE Power and Energy Society General Meeting, Vol 2018; 2018. doi:10.1109/PESGM.2018.8586615
124. Divshali PH, Soder L. Improving PV dynamic hosting capacity using adaptive controller for STATCOMs. *IEEE Trans Energy Convers*. 2019;34(1):415-425. doi:10.1109/TEC.2018.2873057
125. Sakar S, Balci ME, Abdel Aleem SHE, Zobaa AF. Integration of large-scale PV plants in non-sinusoidal environments: considerations on hosting capacity and harmonic distortion limits. *Renew Sustain Energy Rev*. 2018;82(2017):176-186. doi:10.1016/j.rser.2017.09.028

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