Research Article

Hosting Capacity In Smart Distribution Network – Definitions, Calculation, Constraints And Improvement

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Abstract. *Renewable sources offer benefits including more efficient power system operation and management and reduction of CO2. Recent increases in distributed generation cause operational and technical challenges such as voltage rise. Hosting capacity aims to estimate how much additional generation can be integrated into the existing network without breaching prescribed technical and operational constraints. The aim of this paper is to explore in the recent literature answers to questions: how HC can be calculated, what factors influence it and how it can be improved. The most common HC improvement methods are photovoltaic inverter reactive power control, voltage control, network reconfiguration and soft open points usage, conductor reinforcement and classical reconstruction of the network, active operational strategies based on control of the active and reactive power, active power curtailment, battery energy storage systems, power quality improvement and electrical vehicles. To achieve advantages like reducing calculation time and improving accuracy, state-of-the-art research enhancements are built on a unique combination of techniques from earlier studies. They take into account both technological and economical constraints, in comparison to earlier approaches where only technological constraints were considered. It also aims to present what are the major contributions in the field, what are the existing research gaps, opportunities and possible future directions. This paper contributes as it presents the state of art in this field and gathers information that can be used as a foundation for future research. It can be concluded that this remains an important area of research with numerous research opportunities*

Keywords

Distributed generation, hosting capacity, photovoltaic, renewable energy sources, smart grid.

1. Introduction

Current environmental issues, electrical energy sector deregulation, renewable energy policies and more recently global energy crises caused by pandemic paved a path to increase in the use of renewable energy sources (RES). With solar and wind resources being at the vanguard of historical energy generating technology shifts, this increase will probably continue. It is predicted that solar photovoltaic (PV) will be the most extensively used renewable generation technology by 2024, almost 60% (around 697 GW) out of 33% predicted world's electricity share from renewable energy sources [1]. Rooftop PV solar systems significantly contribute to the increase in distributed generation (DG) penetration because of relatively lower cost, quick and easy installation, technical merits, and supportive global energy policies. DG systems in general provide numerous technical, operational and economic advantages such as voltage profile support, loss reduction and cost optimization [2]. Recent global energy concerns additionally highlight the need for energy independence, which together with exposure to energy price volatility, provided an additional swing for investment in rooftop PV solar systems. However, the unprecedented increase in DG penetration [3] causes serious concerns and operational challenges as extensively documented in previous research [4]. One such challenge is the question of power system hosting capacity (HC). Power networks around the world are approaching their hosting limits and accommodation.

In order to continue expansion of DG in an efficient way, the network-planning process should be revisited to include modern and innovative techniques. HC analysis is one example that was up to recently omitted from power system studies. Historically, power system planners were concerned with generation capacity and load consumption capabilities of the network. Nowadays, planning interests are extended to distribution systems and include the need to assess, plan and improve HC of the network. HC is also a fair parameter that can be used to steer investments into the appropriate parts of the network. This could improve the efficiency, transparency of the connection process and reduce inappropriate DG allocation.

HC analysis seeks to answer the following question: how much additional generation can be connected to the grid without reinforcement while maintaining prescribed technical limits. Further, how this amount can be calculated or estimated, what factors influence this number and once calculated, how it can be improved? Answers to these questions are a crucial part of modern power system analysis and are a necessary tool for promotion of RES integration. The objective of this paper is to investigate how these questions are answered in recent literature. It also aims to present what are the major contributions in the field, what are the existing research gaps, opportunities and possible future directions.

It presents the state of the art of the HC analysis including the definition, estimation methods, constraints and possible ways to improve HC. This paper is hopefully a part of broader research on HC, and material collected and analyzed here can be used as the base for further research in this field. The review is based on the collection of more than 100 papers, extracted from databases Scopus, IEEEXplore, ScienceDirect and Google Scholar. The materials include recent work published in some of the leading journals and selected quality conferences. Each paper is carefully analyzed and data is used to assess the existing worldwide experience and practices, and finally to draw conclusions on the current state of the field.

The remainder of the paper is structured as follows: section 2. provides basic definitions of HC, followed by detailed discussion of HC estimation methods. Then, HC limitations are presented, as one of the most important factors that influence results, followed by the tools and methods for HC improvement, where they are explicitly compared and discussed. Each of these sections is analyzed through the prism of existing work in the area. Finally, section 6. lists the most important conclusions drawn, together with comparison and prospects of future research directions.

2. HC Definition

HC definitions are numerous. In general, HC is a maximum amount of DG that can be connected to the network in its current form, while observing technical limits of the power system. It is not a single valued number and it depends on the aims and constraints defined in the decision making framework. HC is defined relative to a particular power system parameter. It is not correct to think of HC only in absolute terms (total MW). This approach hinders comparison among various networks and diminishes the importance of the uniqueness and individual qualities of each system. There are many ways to express HC relative to parameters, including percentage of peak load (47%), power transformer rating (20%), share of customers with PV (20%), total energy consumption of the considered area (7%), active power (5%) and PV roof space (2%) [5]. HC value is also influenced by network topologies and the required level of accuracy. Human judgment is inherently tolerant to imprecision and in some cases a very accurate value of HC is not required. This is beneficial because tolerance to imprecation can reduce calculation complexity. HC is directly proportional to the risk distribution system operators (DSOs) are willing to take. It is largely affected by DG allocation which plays an important role in HC calculation and improvement [6]. It was demonstrated that parameters related to HC calculation tend to increase at medium DG penetration and high DG dispersion level and decrease in the case of low dispersion and high penetration scenarios (in range of up to 20%).

HC also depends on the type of DG technology. Photovoltaic hosting capacity (PVHC) refers to the value of PV production that a power grid is able to absorb without violating grid limitations [7]. Diverse factors affect maximum PV penetration limit such as connection arrangement (single or three-phase), intensity of irradiance, network layout and topology and load types [5]. HC is not a single valued quantity and is expressed in relation to a predefined set of objectives and constraints. For example, according to [5] HC can be defined as:

- The proportion of the PV installation's maximum capacity to the feeder's maximum load.

- The proportion of total PV output to the rated capacity of the transformer.
- The proportion of homes in the particular area under consideration that have PVs to all of the homes there.
- The proportion of the PV system's annual energy output to total energy usage.
- The roof space of the homes with feeder connections, which may allow the installation and connection of solar PV panels.
- The PV output to active power of the load ratio.

HC definitions from this section provide a framework for future analysis and demonstrate that HC analysis is an umbrella term, covering various aspects of power system characteristics. Choosing the right definition for particular tasks is important because it steers complete analysis in the chosen direction.

3. HC Estimation Methods

HC calculation methodology ranges from simple to very complex. This depends on numerous things such as topology, dispersion level, limits, tolerance to uncertainty, aims, objectives and perspective. Calculation methods can be observed from customer perspective, DSO perspective, or can be based on regulator oriented goals. HC calculation methods are classified as deterministic, stochastic, optimization and streamline methods. All methods are based on load flow calculations to determine voltage and current values in distribution networks. General HC calculation methodology is represented in Figure 1.

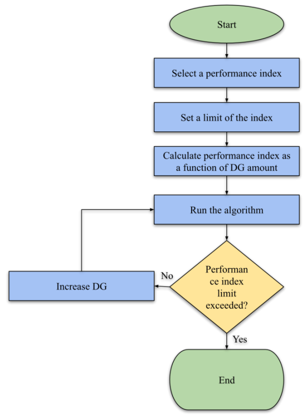

Fig. 1: Graphical representation of general HC calculation procedure

Reference [9] classifies HC calculation methods as steady state inherent advantages and disadvantages. Figure 2 represents highlights of the HC calculation methods. Summary of HC calculation methods in the distribution network are presented in [10]. In the following sections, the most important methods are discussed.

3.1. Deterministic Method

The deterministic method is HC estimation based on known values of distributed energy resources (DER) generation, load consumption and relevant location data before the beginning of HC calculation. It is divided into two methods: the constant generation method and the time series method.

Utilizing a deterministic approach from [11] a solar PVHC assessment tool based on nomograms was created in [12]. It can be used to assess the solar PVHC at a specific location on a low voltage (LV) feeder. Authors suggested using a generalized approach based on a nomogram representation to assess solar PVHC that has been subjected to over-voltage reduction. The nomogram technique appears to capture all influencing elements on solar PVHC.

Deterministic method can DSOs that, in comparison to others, provide a straightforward and reliable indicator of the PVHC and the need for grid reinforcement [13].

1) Constant Generation Method

Constant generation method is based on traditional power system snapchats. It provides the worst-case scenario solutions. This is not a realistic representation of the power system behavior due to low probability of occurrence, specially in PV dominated systems. This approach frames the natural behavior of the system to only one scenario. The deterministic constant generation model completely fails to address the inherent variability of RES. Notwithstanding this, deterministic models continue to be used as they deliver useful results from a DSO perspective. Deterministic approach for evaluation of solar PVHC subjected to overvoltage curtailment in LV networks is presented in [12].

The value of the DER output does not change during the calculation time when using the constant generation method, in this method generally output of the DER is assumed to be maximum. In [14–18] it is based on raising incrementally DER units until size/number of limiting constraints are violated. In [15,16,19] worst-case scenarios are used where DER units output is presumed to be greatest while it is considered that the load power requirement is minimal. Studies of Electric Power Research Institute (EPRI) showed that peak load has low correlation with the HC of a feeder [20].

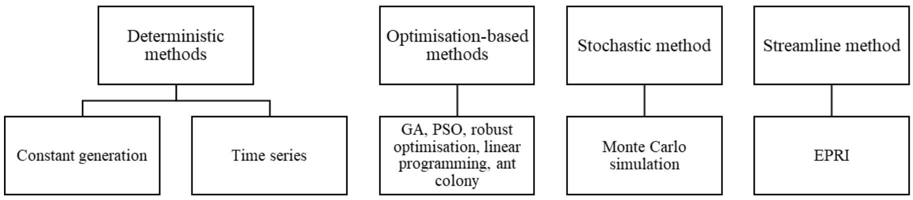

Fig. 2: Graphical representation of general HC calculation procedure

2) Time Series Method

Time series method is an extension of the deterministic constant generation method and it introduces significant improvements. Load and generation output are represented using 24-hour profiles for a chosen scenario, such as winter, summer, spring or autumn. DG location is not a priori known and can be changed. Time series method accounts for the varying loads of power systems and generations, providing results that are more accurate. These improvements increase calculation procedure and require large data to accurately model load and generation. With the increase in computational capacity and availability of power system modeling tools, the benefits of accuracy far exceed the shortcomings of this approach. Reference [21] presents a time series PVHC assessment method with storage deployment.

In this method all dynamic network components are given generation profiles, and load flow calculations are carried out at the smallest time step feasible for the data set. [22–25]. DERs may vary in size, placement, or quantity until one of the limiting constraints is violated [22, 25–27].

3.2. Stochastic Method

Even though time series is an improvement when compared with a constant generation model, it does not entirely address the load and generation uncertainties. Further modeling is required in order to obtain results that are more accurate. Stochastic methods provide appropriate resources for this. The stochastic method is based on DER unit integration into the distribution network with unknowable factors like the number of customers using DERs, location, technology and sizes. Consumption profiles and the output of DERs are also intermittent. Traditionally, this is the most frequently applied method in problems containing uncertainty in power systems, and HC calculation is not an exception.

The stochastic method uses randomicity of some of these variables. Probabilistic power flow (PFF) is used to account for these unknown variables. The creation of random scenarios (number, location, and/or size of DER), the simulation of networks, the examination of network variables (voltage, current, losses, etc.) against the performance limits, and the determination of the HC based on the predefined performance limits are all examples of how these load flow calculations are carried out in PFF with various values of unknown variables to produce a wide range of output results [28].

Testing towards convergence on different feeders reveals that a 1,000-scenario Monte Carlo simulation (MCS) is generally precise, within a tolerance of 2%. By voltage limits, thermal capacity, and unbalance the performance of radial distribution feeders can vary within certain bounds. It is concluded that their stochastic-analytic approach to HC increases feeder performance evaluation across a variety of DG penetration scenarios, and it is suitable for design and operational analysis when compared to different formulations [29].

Similarly, evaluation of PVHC in a small electrical power distribution systems (EPDS) using a better stochastic analysis technique is presented in [30]. Reference [31] presents a stochastic method for evaluating LV networks' solar PVHC. In [32], a dynamic HC analysis for distributed PV resources is presented. It identified the gap of conventional static techniques, which are incapable of capturing grid effects or evaluating the effectiveness of smart inverter-based control schemes.

In [33] is proposed an innovative stochastic method for increasing the HC of PVs in distribution systems. It was built on a coordinated management strategy for various distribution system control components, such as the inverters' reactive power and transformer taps. Electric vehicles have been included in the PV planning model with their stochastic character and detailed model. To precisely solve that model based on grey wolf optimization for maximizing the HC of PV while coordinating the various control devices in distribution systems and addressing all constraints, a double-layer optimizer has been proposed. Scenarios were performed on IEEE 69-bus distribution system.

An analytical strategy to calculate the voltage change probability distribution as a consequence of unpredictable behaviors of several distributed PVs that are spread out at random locations is presented in [34]. This approach was founded on spatio-temporal probabilistic voltage sensitivity analysis, which considers the temporal and spatial uncertainty connected to PV injections. Without having to look into a lot of different scenarios, the calculated distribution is utilized to assess voltage violations for different PV penetration levels and then figure out the system's HC. Results are validated on the IEEE 123 and IEEE 37 node test systems using a standard load flow-based simulation methodology.

1) Monte Carlo Simulation

MCS simulation is by far one of frequently used stochastic method, for generating random scenarios. [35] proposed a Monte Carlo-based technique to evaluate the effect considering various PV penetrations on LV networks to determine the appropriate hosting capacities of such networks. [36] performed Monte Carlo method-based analysis to quantify the HC of the Finland networks in PV systems with balanced and unbalanced feeds and their limiting criteria were assessed. In [37] was discovered that the number of nodes had a significant impact on the feeder's HC. The HC grew in line with the node number. By using Monte Carlo simulations to address the uncertainties and unpredictable loading behavior as well as the unpredictability of PV's placement and size.

[29] proposed methodology for determining the DG's technical effects and the HC of radial distribution feeders. They used a stochastic analytic-probabilistic method that incorporates a polynomial smoothing methodology and an analytic-probabilistic load flow (PLF) transform into an MCS of DG allocation to increase computing efficiency. This allows a huger number of MCS DG allocation scenarios, which supports sufficient HC precision. Utilizing the beta probability density function, HC was statistically quantified, reflecting the composite risk resulting from the many uncertainties.

Various methods were compared in [13] at the distribution system level, to distribute the upcoming PV capacity based on analysis of solar roof potential. For the allocation of PV power to grid nodes, rule-based approaches are created and compared with a probabilistic approach using a Monte Carlo analysis.

A technique for assessing risk that estimates network HC while taking PV-related uncertainty into account, wind turbine (WT) and loads was proposed in [38]. A likelihood approximation approach was used for evaluation. In this paper is proposed the PV localized solar irradiance prediction using the clearness index. They proposed using the sparse grid technique (SGT) as an efficient method for calculating uncertainty, while using the Monte Carlo technique (MCT) for comparative purposes. Usefulness of the proposed tool was demonstrated on two real distribution networks (11-buses and South Australian large feeder).

A residential LV distribution grid's integrated photovoltaic - electric vehicle (PV-EV) grid deployment and HC evaluation under four different energy management system (EMS) scenarios, including (1) no EMS, (2) only electric vehicle (EV) smart charging, (3) only PV reduction, and (4) EV smart charging and PV reduction, was presented in [39]. A graphical approach was used to present the combined PV–EV HC so that both PV and EV HC can be examined using the same method. Authors used stochastic time series for generation and consumption, since it allows introducing different scenarios. To produce user mobility patterns, they used the Monte Carlo method.

Usage of deterministic load flow models and complex stochastic techniques can be bypassed with nomogram, which provides a rough reference to assess the solar PVHC at a specific LV feeders point. As a result of these findings, the minimum level of PVHC (the solar PV hosting capacity's safe limit) and the maximum level of PVHC have been adopted as the foundation for connection requirements for new solar PV connections. The nomogram tool created in [12] is the basis for the solar PV connection criteria, it simplifies reasonable modeling perceptions for HC evaluation in LV networks.

3.3. Optimization-Based Method

In the optimization-based method the aim is to maximize the active power injection of DER into the distribution network with respect to limiting constraints. Optimization methods for HC calculation are popular because they provide the most accurate results, efficiency and speed. They include genetic algorithm (GA), particle swarm optimization, robust optimization, linear programming, ant colony and improved gray wolf method (IGWO). Optimization designs a picture of power systems that operate at their optimum point and can readily be applied to complex and nonlinear systems. However, they are complex, sometimes unstable and could converge prematurely if not properly guided [40]. GA based methods do not need the objective function to be continuous. One of the few references of HC calculation based on the optimization using GA is presented in [41]. Also, an optimization-based distribution grid HC calculations with liberalized power flow is presented in [42]. Reference [2] recognized shortcomings of the existing methods such as lack of theoretical guarantees, time inefficiency, and non-convex problem model and proposed a bottom-up analysis, generalizing the geometric intuition to find optimal HC adapting the analytical solution with respect to different operational constraints and applying parallel computing in order to enhance the computational speed. Finally, HC assessment in EPDS is solved as an optimization problem using metaheuristics greedy randomized adaptive search and tabu search algorithm [43]. Bus voltages, line currents, node power injection, and other restrictions are defined. To identify the HC that minimizes distribution losses or costs while increasing DER integration in [44–46] a multi-objective function is established, while in order to maximize the HC a single objective function is defined in [42, 47–50]. Some of the frequently used approaches to solve the optimization problem are artificial bee colony (ABC) [51] because of its fast convergence, GA [52] because it gives fast results but instead of global optimal solutions with a probability of finding near-optimal solutions, particle swarm optimization (PSO) [45, 53] as it is easy to implement and robust optimization [54–56] as it takes into account the calculation's uncertainty regarding the DG's output, size, and placement. Ref [57] formulated an optimization problem involving the placement, size, azimuth, and tilt of every panel throughout a residential area in order to maximize PV production over the course of a year while taking into account the power grid voltage and line ampacity limits. They considered the Swiss distribution network and artificial irradiance data produced by a clear-sky model for the area under consideration, as a case study.

In [58] an optimization technique is applied for calculation of maximum HC. Authors approximated the PVHC throughout a distribution network with network voltage and power line loading as a constraint. For a selected CIGRE network different buses' simultaneous PV outputs and load variations were taken into account. Power hardware-in-loop methods for testing were used to evaluate the effect of high PV penetration.

Recently, [59] formulated a nonlinear optimization model for EV charging parking lots with the goal of enhancing the smart distribution system's electrical characteristics and raising the wind DG power output of the distribution system (PODS). The objective function encompassed decreasing losses, decreasing voltage fluctuations, and increasing the smart system's power output while taking financial and technological limitations into account. The uncertainties of wind speed, smart grid usage, and charging parking lots were modeled by integrating k-means and Monte Carlo methods to obtain robust optimal solutions. To solve the optimization problem, IGWO was used. The effectiveness of the method was studied on the IEEE 33-bus standard smart system. Results showed high efficiency of the suggested solution.

Since robust optimization and classic stochastic optimization have conservative issues when it comes to managing the uncertainty of distributed PV, [60] presented a two-stage distributionally robust optimization method for evaluating the distributed PV hosting capacity of the flexible distribution network. The historical PV output data was clustered using the weighted k-means clustering algorithm. The algorithm's efficacy is confirmed on a 70-bus system, concluding that the flexible distribution network's distributed PV hosting capability can be enhanced by combining various regulating mechanisms. The flexible distribution network's distributed PV hosting capacity rises progressively as the number of access nodes rises, but it tends to become saturated after a certain number of access nodes is reached. Within a particular range, an increase in branch current upper limit, node voltage upper limit, and energy storage system (ESS) capacity also results in an increase in the flexible distribution network's distributed PV hosting capacity. But since the result depends on the confidence set that was created, the distributionally robust optimization needs to be less conservative.

3.4. Streamlined Method

Streamline is a relatively new heuristic method based on sensitivity analysis. It is developed by EPRI [61] and is only commercially available. For this reason, it is the least frequently used HC calculation method. In this method HC of a given feeder is estimated to simulate a small number of scenarios, as an improvement of the stochastic method where a large number of scenarios are simulated. Detailed stochastic studies were performed on a wide range of distributed feeders and identification of trends that are common to the integration of PV systems into those feeders in order to develop this method [62]. The streamline method provides realistic, optimistic and conservative values of HC through performing a series of sensitivity analyses. Results of HC are based on inclusion or exclusion of different branches in the feeder and extreme or probable DER position. It relies on the information regarding trends of PV systems deployment from previous researches. Since the streamlined approach frequently yields inaccurate HC value calculations in cases where the feeder has high branch diversity or where the actual HC is high [62], the improvement of this method can be seen in computation time and resources. Since the algorithm is offered for purchase as a tool under the name "Distribution Resource Integration and Value Estimation (DRIVE)" it is used in few studies [62, 63].

In addition to EPRI DRIVE module [64] other commercial tools are DigSilent Power Factory [65], NEPLAN [66], PSS Sincal Integrated Capacity Analysis Module [67], Synergi Electric [68] and open source software solutions (OpenDSS) [69] offer readily available HC calculation capabilities. It is crucial to conduct case-by-case validation of HC value due to complexity and inherent variability of EPDS characteristics.

The DIgSILENT PowerFactory platform was used for modeling of smart inverters with differing Volt-Watt and Volt-VAr control functions [70], to evaluate HC of the distribution network, and the effect of the PV integration throughout the distribution network were then analyzed using the digital real-time simulator (DRTS) and power hardware-in-loop (PHIL) simulation approaches [58]. In [35] OpenDSS is used to solve the time-series three-phase four-wire power flow.

State-of-the-art articles according to the HC estimation method applied are summarized in Table 1. Where one can observe that some methods were used more than a decade ago and still applied in today's research. Novel research improvements are based on a unique combination of methods from previous researches, thus contributing to the field with improved results.

Tab. 1: Summarized HC Estimation Methods

Method	References	Publication Year
Deterministic Method (Constant Generation Method)	[12, 14–19]	2016-2019, 2022
Deterministic Method (Time Series Method)	[21–27]	2016-2020, 2023
Stochastic Method	[29–34]	2020-2022
Stochastic Method (Monte Carlo Simulation)	[35–37]	2013,2017, 2024
Optimization-Based Method	[41, 42], [57–60]	2016,2018, 2021,2024

4. HC Calculations Limits

Integration of DERs affects properties of the distribution network, limiting factors are needed to be set in order to estimate acceptable HC. Different limiting factors result in different HC values, so setting the combination of limiting factors in the studies can be seen in the literature. HC calculation constraints (limits) include voltage value (48%), thermal limit (26%), voltage unbalance (19%), harmonics (4%) and flickers (3%) [5]. In [57] it was shown that there are installation requirements other than conventional that enable better net PV production without violating distribution network restrictions, when considering distribution networks with a lot of PV plants. Even though there are numerous issues related to HC, voltage variation remains the main problem. In the following, the most important limits which are represented in Figure 3 are discussed.

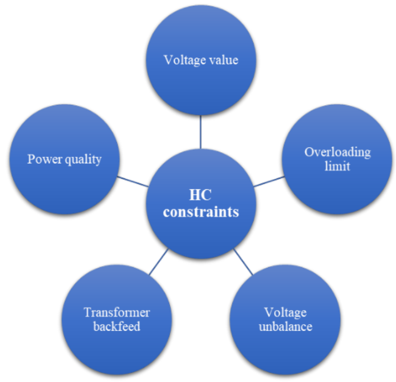

Fig. 3: Summary of the most commonly used HC constraints

4.1. Voltage Variation Limits

Huge PV integration in the distribution network results in the reverse power flow causing overvoltage. It is generally well-accepted fact that reverse power flow causes voltage increase in the network. However, it was experimentally demonstrated and explained by magnitude of power flow, impedance and power factor that voltage reduction can occur in distribution feeders with PV systems [71]. Voltage rise is a main HC constraint in rural area networks with lower short circuit power, while urban networks face issues of component overload. Voltage limits are defined by international standards (such as European standard EN50160) and national grid codes. The adopted limits vary throughout the world, ranging from 1,03 p.u. in China and Germany to 1.05 in USA and Denmark and, finally, 1.1 in Australia and Italy [5]. Voltage limitation studies investigate an absolute value of voltage variation in the systems defined by grid codes or a maximum allowable DG contribution to voltage rise.

Study presented in [12, 34] used only voltage as a constraint, while [33] used voltage constraint in combination with other constraints. In [35, 36] European Standard EN-50160 [72] is used. During normal conditions in accordance with EN-50160 allowable voltage deviation is 10% from nominal voltage (Un) at the customer connection. [35] showed that 40% of PV penetration can cause voltage problems for longer or heavily loaded feeders.

[13] used German Standard VDE-AR-N 4105 [73] which allows +3% deviation from Un. Interval overvoltage risk based PVHC evaluation considering generation and uncertainties of load is presented in [74], which used three-phase bus voltage constraint in accordance with American Standard ANSI-C84.1 [75], where allowable voltage deviation is limited to 5% of the nominal value. Three-phase bus voltage limit in this work is used together with dynamic three-phase power flow and branch transmission capacity constraint.

In addition to voltage constraint [13] used the line loading limit defined in German Standard VDE-AR-N 4105 [73] of 1.0 p.u.. [58] estimated PVHC through two scenarios, one used only voltage as a constraint, while another one used voltage and loading. It is concluded that combination of voltage and line loading limits can reduce PVHC by 50%, in comparison to only voltage as a limit.

Results in [35] indicated that lower PV penetration level causes voltage issues on feeders of bigger lengths and a huger amount of customers. Small feeders with length less than 1 km and number of customers less than 35 showed no problems for any of the examined penetration levels. A novel approach for HC analysis using spatio-temporal probabilistic voltage sensitivity analysis is presented in [34]. It outperforms conventional load flow-based methods in accuracy and computational requirements. Importance of data granularity was pointed out in [35], they presented that hourly and analyses of half hourly resolution underrate the voltage impact of residences PV.

[76] studied how much voltage magnitude before connection impacts the HC, since PVs in electricity distribution networks are mostly limited by the increased voltage magnitude. Representative probability distribution functions were obtained from the measured background voltage during the sunny hours from the measurements of two years. In this paper a guide for selecting the time-of-day (ToD) used was presented. They showed that for HC estimation, a general understanding of the pre-connection voltage's range is necessary. It was concluded that data of one year is enough to estimate the HC. The HC considering the 10 AM – 2 PM sunny hours underestimate the entire day by 11

4.2. Overloading Limit

Network lines have limits of the amount of the current that can carry and transformers have overload limits, if their limits are exceeded they tend to overheat. The risk of overloading and losses is directly related to the current delivered by DG. While losses do not represent a strict criterion in DG connection approval, overloading is a hard limit that cannot be exceeded. Calculation of overloading limits in HC is more complex than voltage, due to non-linearity of the current magnitude.

Transformer overloading limits ranges from 100% [77], [78] to 187.5% [79], while more strict cable overloading limits ranges from 85% [77] to 150% [80]. Regarding the lines that go towards the grid connection point in [56] as the primary constraint is used upper of the current ampacity limitations, whose violation indicates backfeeding surplus power for the main grid. In [36] limiting factors such as thermal limits of transformers and lines are used as a supplement to voltage fluctuations for a Finnish LV network's HC estimate.

Two HC scenarios regarding overloading that require appropriate action are identified in [81]: when the maximum generation exceeds the sum of maximum load and minimum load and when the sum of generation and minimum load exceeds the ampacity (current carrying capacity) of the feeder section. A sensitivity-based decomposition method for rapid HC analysis for thermal loading constraint is presented [82]. Further, during periods of minimum load, there are following HC issues: transformer back feed that causes equipment failure due to increased voltage regulation, the necessity to modify protective mechanisms and transient overvoltage situations [83].

4.3. Voltage Unbalance

The negative sequence unbalance can be decreased by attaching the PV inverter to the phase having the lowest phase voltage [84]. Unbalance in the combination with voltage limits and thermal capacity are used as constraints in [29] to identify acceptable variations of radial distribution feeder performance. Voltage unbalance limits range from 1% Un [85] to 3% Un [79].

4.4. Transformer Back Feed

Transformer back feed can cause an increase in the inrush current, voltage drop and loss of controllability, problems with neutral, increase in fault current, temperature and insulation stress. Protection coordination can also become a problem as discussed in [86]. In addition, there is an increase in power losses and power delivery to transmission systems, which is generally unwelcomed by both DSO and TSO as discussed in [87], [88]. There is no explicit standard that prohibits transformer back feed as long as grid parameters are maintained within limits, but it remains an unwelcome phenomenon. Situation varies throughout the world with Japan in principle forbidding and Germany permitting reverse power flow [89]. However, Germany has restrictions on the feed-in power of residential PV installations as a part of LV system planning strategy [90].

4.5. Power Quality

Finally, power quality constraints present serious HC limitations in PV dominated networks. Main power quality phenomena associated with HC calculation include the ratio of negative to positive sequence voltage (known as voltage unbalance), harmonics and flickers. Temporary voltage variations are in practical situations governed by technical recommendations and standards that range from 2% to 4% in medium networks and 2% to 5% in LV EPDS. A stochastic approach for PVHC assessment considering voltage quality constraints (overvoltage, deviation, imbalance, fast variations) on a distribution feeder is reported in [91], considering PV generation uncertainties and randomly allocating sizes and locations of PV. The limit for voltage imbalance is set at 3% and for fast voltage variations at 4%. HC values in this work range from 116,4% to 213.2% of the peak load. HC considering voltage unbalance is estimated using a stochastic approach by calculating the negative-sequence voltage unbalance for each node in the network in [92]. It was reported that single-phase PV inverters contribute to voltage unbalance, likely more than 1%, but remain within 2% of voltage unbalance limit. Reference [93] analyzes HC harmonic current emission limits in accordance with IEEE Std. 519 (1) with IEC 61000-3-6 in MV systems. HC assessment improvement for a PV dominated system using a hardware in loop approach is proposed in [94], with voltage levels, ampacity and total harmonic distortion as the limiting criteria.

5. Methods for HC Improvement

HC is not a fixed parameter. It can usually be improved using various tools and methods such as reactive power control [95], voltage control [96], network reconfiguration [8]. [98] proposes network reconstruction for HC improvement, while active operational methods based on the control of active and reactive power are presented in [98]. Additional HC improvement methods include active power curtailment [99], battery energy storage systems (BESS) [7] and power quality improvement [100]. While, [101] recently proposed the renewable energy carrying capacity assessment approach for distribution grids while taking into consideration demand-side management (DSM) and network reconfiguration (NR). The aim of the study was maximizing the carrying capacity of distributed renewable energy. The second-order cone relaxation method was applied to solve it in a trans convex way. The simulation example used the upgraded IEEE33-node distribution network (DN). According to the simulation results, it is advantageous to take DSM and NR into account in order to increase the distributed renewable energy's carrying capacity. Overview of HC improvement techniques is represented in Figure 4.

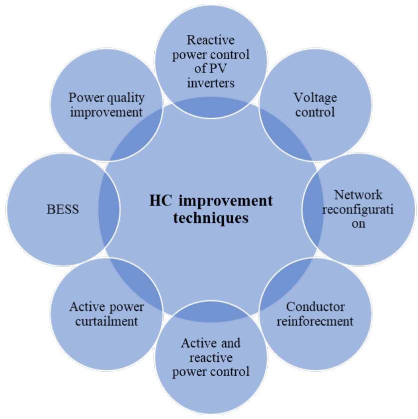

Fig. 4: Summary of the important HC improvement techniquess

5.1. PV Inverter Reactive Power Control

[95] studied improvement of HC using rooftop PV inverters' reactive power control strategy. The effect of power factor configurations of the PV inverters is examined considering three power factors: the unity, lagging, and leading power factors.

The impact of rooftop PV penetration on substation power factors results in active power decrease, if rooftop PV penetration increases. The increase in rooftop PV systems penetration is followed by decrement in substation power factor. Results of the study showed that the power factor of substation decreases slower with (lagging power factor setting) PFlag setting, than with (unity power factor setting) PFuni setting. As a result, the PVHC is increased when using the PFlag setting on rooftop PV inverters. Contrary, the leading power factor setting reduces the PVHC.

5.2. Voltage Control

The study presented by [70] examined the effects on technology and the features of smart inverters as described in Hawaiian Electric Rule 14, California Electric Rule 21, AS/NZS 4777 and IEEE 1547e2018 in order to comprehend the prosperous utilization and a smart PV inverter's configuration to reduce overvoltage violations. The research reported in this study helps to clarify how HC can be increased by utilizing sophisticated inverter control functions, where such gains are subject to locational considerations of inverters in low voltage distribution networks.

[96] compared effectiveness of multiple voltage control methods in justifying high PV penetration rates' effects on distribution system voltages. For the given test feeder, the effects of PV integration are evaluated using a stochastic analysis approach based on Monte

Carlo. Eight case studies were simulated by regulating either (1) only legacy devices, (2) only smart inverters, or (3) both legacy devices and smart inverters, their efficiency in reducing the effects of PV is measured using a variety of customer and system-level metrics based on both snapshot and time-series analysis.

With the exception of Case 3, the feeder can support a PV penetration of 100% for all voltage control scenarios. In Case 3 accommodation is 100% when the smart inverter is operating only at PF = -0.995, in comparison to 40% without voltage control. Study showed that controlling either smart inverters or legacy devices helps in mitigating overvoltage concerns and increase PVHC of the feeder.

Voltage variation from 9% to 4% can be reduced by PV power conditioning devices which involves reactive power vs voltage droop control. Line loading can be lowered by 20% in a PV integrated electrical energy network if the network is configured from radial to mesh type [58].

5.3. Network Reconfiguration and Soft Open Points Usage

Power electronic devices, soft open points (SOPs) in active distribution systems replace the typical open points. With them the resiliency is provided, in terms of delivering the benefits of mesh networks and transferring electrical power between nearby feeders, in active distribution systems sharing active and reactive power amongst nearby feeders [102]. In this work out of SOPs integration technologies such as the unified power flow controller (UPFC), back-to-back voltage source converter (VSC) and static series synchronous compensator (SSSC) [103], the back-to-back VSC integration technologies is employed because it can raise operational and power quality indices [104].

In order to maximize the HCs [8] proposed a bi-level multi-objective optimization approach using simultaneous distribution system reconfiguration (DSR) and SOP allocation on real distribution systems, through two case studies using deterministic and probabilistic approaches. Results showed that the use of DSR with SOPs improves the indices of the systems and minimizes the estimated total annual expenses for the 59- and 83-node distribution systems by more than 75.51% and 57.60% of the original yearly cost, respectively, at the highest DGs penetration and taking into account load uncertainties.

5.4. Conductor Reinforcement and Classical Reconstruction of the Network

In [97], salp swarm optimization (SSO), a meta-heuristic algorithm is used to explore the difficulty of choosing the best conductor for an actual radial distribution system in Egypt. Optimization problem is investigated to reduce the annual cost of energy losses and the conductor investment cost while complying with system voltage restrictions and thermal capacities of the conductors.

They have concluded that the algorithm is effective in fulfilling objective function and constraints. Due to the variations in loading scenarios, load growth and the possibility of connecting DG units with uncertain locations and penetration levels, size reduction of some existing conductors is not allowed by the utilities, but the results of optimization also suggest that the size of some existing conductors needs to be reduced. While considering these uncertainties in order to uphold the limitations, a practical feeder reinforcement approach is proposed. A feeder reinforcement index (FRI) is proposed as a sensitivity index to help the distribution system planners and operators to determine the feeders that need to be reinforced first. Proposed reinforcement approach achieves higher HC from the traditional method of selecting conductors under identical testing circumstances.

5.5. Active Operational Strategies Based on Control of the Active and Reactive Power

[98] explored independent voltage control techniques based on the on-load tap changer (OLTC) and PV systems' active and reactive power control capabilities of transformers. Involvement of OLTC impacts significantly HC, when balanced feed-in is taken into the consideration. Where, for single phase PV installations, the increase was quite minor [36]. [98] observed effects of previously mentioned control strategies on the PVHC considering the voltage control capabilities in LV distribution feeders, modular optimization-based framework is proposed and examined on 128 LV UK feeder.

Results showed that in mode of active power curtailment the most effective control schemes for increase of minimum photovoltaic hosting capacity (MPVHC) are Volt-Watt operation mode (VWOM) and Volt-Var operation mode (VVOM) resulting in increase to 100% and 18.74% (in average), respectively.

Usage of control strategies based on active power, i.e. VWOM and limitation of active power feed-in mode

(LAPFM) results in the least amount of total energy lost for every 1% increase in MPVHC.

The MPVHC is decreased, if OLTC controls the voltage at the end of a feeder. While MPVHC can be increased on average by 51.08% if the goal is to keep the voltage of all the locations in the feeder within allowable limits.

Reactive power based schemes are a lot dependable on the R/X ratio of feeders. Results presented that for VVOM control scheme when the average of R/X ratio is 10.34 MPVHC increases on average by 18.74%, while MPVHC is increased on average by 38.9% with X/R average ratio equals to 5.17. To increase MPVHC the reactive power based control schemes are less cost effective than active power based control schemes, for feeders with R/X ratio greater than 5.

5.6. Active Power Curtailment

In [99] probabilistic approach is used to study the influence of increase of the capacity of integrated DER on the HC and the adaptability of an operator to raise the HC by curtailing PV. Sensitivity analyses were performed in order to determine the impact of the interconnection location and PV penetration level. Multiple PV integration scenarios were considered, in a way that DER penetration level is raised roughly from 20% to 200% in 5 stages.

Results give insight of the largest amount of DER that can be integrated without going over operational constraints and the anticipated amount of PV curtailment needed to reduce the risk of constraint violation at various parts of a distribution circuit.

5.7. Battery Energy Storage Systems

[7] proposed HC estimation method of medium voltage (MV) distribution systems and extended it by energy storage systems. As a result, this study proposed a method to derive cost-optimal plans for countrywide integration of energy storage systems and PV generation taking into account the MV power distribution infrastructure's technical constraints. Therefore, factors of "cost-efficiency" notion are that it is greater when installing PV plants where their capacity factor is bigger and second is that it is more cost effective to install distributed energy storage in highly isolated distribution grids then installing PV plants with low capacity factor.

In [105] it is concluded that battery storage could increase HC by 58% on average. From a distribution system operator perspective BESSs are a more cost efficient alternative to increase HC then the reinforcement of the network.

5.8. Power Quality Improvement

In [100] HC is estimated taking into account the over- and undervoltage restrictions on buses, the lines' capacity to carry current, and the limitations on harmonic distortion as restrictions. In the study it is demonstrated that increment in the harmonic distortion decreases the HC of the system. The study proposed a C-type passive filter in order to maximize the harmonic-constrained HC of the examined system while satisfying the constraints. It is concluded that lower HC can be achieved with conventional filter design approaches such as line loss minimization, voltage total harmonic distortion minimization and power factor maximization, in comparison to the proposed filter design approach.

The outcome is restricted to the maximum instantaneous penetration and its effects on the system's power quality.

5.9. Electrical Vehicles

[105] studied the effect of charging EV and battery energy storage systems on the PVHC of low voltage distribution grids. Results showed that EV alone (taken as reference case) do not improve the HC except when they are connected to the network during sunshine hours. Since in most cases vehicles are used during the day for traveling to and from jobs, so EVs are not plugged in. Sans cars during noon makes impossible absorption of solar maximum generation, so in this case HC is directly proportional to load of the network. Controlled EV charging has no positive impact on availability, obtaining a 12% HC increase on average in comparison to reference cases.

Controlled charging of EV and BESS in a way that PV peak generation is shaved by the BESS, then during the night BESS is discharged by EV, leaving the state of charge the following day regardless of customer's heating type, giving an exceptional increase of HC with 170%. Usage of plug-in electric vehicles (PEV), PV and vehicle-to-grid (V2G) may have a favorable impact on electricity distribution networks since it reduces peak load [106].

Smart charging for EVs can dramatically increase HC for EVs and modestly increase it for PV. Even though PV curtailment considerably increases PVHC it will have no effect on improvement of EV HC. They concluded from the graphical analysis, that in the case of residential areas, there is a minor positive association between PV and EV HC [39].

The use of AI technologies in predicting and improving the EV hosting capacities in distribution networks in comparison to traditional techniques is systematically evaluated in [107]. They outlined a number of potential ways to improve EV HC, including demand response, adjustable operating restrictions, active network management, optimal placement techniques, and network reconfiguration. When using data-driven AI technologies in conjunction with conventional methods for HC calculations, the computation time is decreased while accuracy is increased. While usage of advanced techniques surely increases computational efficiency in terms of execution time and accuracy, the challenge is to meet the data needed for HC calculations (battery storage systems, residential loads, household renewables and different EV profiles).

Tab. 2: Summarized HC improvement methods

Method	References	Publication Year
PV Inverter Reactive Power Control	[95]	2019
Voltage Control	[70, 96]	2017,2021
Network Reconfiguration and Soft Open Points Usage	[8]	2020
Voltage Control Conductor Reinforcement and Classical Reconstruction of the Network	[97]	2018
Active Operational Strategies Based on Control of the Active and Reactive Power	[98]	2021
Active Power Curtailment	[99],	2020
Battery Energy Storage Systems	[7, 105]	2021, 2022
Power Quality Improvement	[100]	2017
Electrical Vehicles	[39, 105, 107]	2021, 2022, 2024

5.10. Comparison of Methods

Every method inevitably contains its own set of advantages and disadvantages. State-of-the-art articles for HC improvement are summarized in Table 2, with reference to the publication years, in order to present method presence through years. Voltage control via power factor seems to be a method of choice but is not always viable in LV networks and it comes at the expense of increased switching frequency, reactive power demand [96] and overloading. Local voltage control can temporarily mitigate overvoltage issues, but it is a source of conflict between local and system level voltage control. Reference [39] shows that PV curtailment achieves an increase in HC. However, it is not cost effective for some investors and appropriate compensation schemes are required. Traditional power system components such as tap changers, voltage regulators and capacitor banks continue to play an important role in HC improvement. However, they have inherent shortcomings when compared with smart automatic voltage control, robust allocation of BESS [85] and demand response. Simultaneous DG and EV HC assessment reported an increase of 9% in HC using the appropriate EV power charging control [43]. PV with BESS optimal smart inverter control to enhance HC using slime mould algorithm is presented in [108]. HC enhancement using passive harmonic filtering in harmonically polluted systems is presented in [109]. Power protection upgrade based HC improvement is not very frequently discussed. One of the few works investigated the relationship between protection setting and the access current of PV as reported in [110].

6. Conclusion

Based on the review of the most recent and relevant literature in this field it can be concluded that this remains an important area of research. The increased number of DG units in the distribution network affects properties of the distribution network. Estimation of the PVHC of the distribution network imposes as necessity, since mostly extensively used renewable generation in future is predicted to be PV.

There are numerous methods for HC calculation from simple to complex. Their selection depends on numerous aspects such as the structure of the network aims and objects of the planner. HC calculation is used to serve customers, investors, DSO and regulators.

Integration of DERs affects properties of the distribution network. Therefore, limiting factors are required to estimate acceptable HC. Different limiting factors result in different HC values, so setting the combination of limiting factors in the studies can be seen in the literature. The most used limiting factors in the literature are voltage value, thermal limit and voltage unbalance. In addition to technological limitations, state-of-the art literature considers financial limitations.

HC value can be increased. Recent studies most frequently include reactive and voltage control, reconfiguration, reinforcement and reconstruction, active power curtailment, BESS and power quality improvement. Each method inevitably has its own set of positives and negatives.

Through the insight and comparison of the recent literature and their results, significant gaps and research opportunities have been identified regarding HC calculations. These gaps identified are related to methods, tools and load generation modeling. Novel research advancements are based on a unique combination of methods from previous researches, which results in field contributions with enhanced results, such as calculation time reduction and accuracy improvement. Therefore, it is proposed to develop additional models and methods for HC calculations. It is especially required to pay attention to more accurate generation and load modeling during the load flow analysis.

Therefore, there is a need to use load and generation modeling curves with data with less than half hourly resolution, since data granularity is important for adequate estimation of the voltage impact.

Author Contributions

M.Š., Z.Dž. and F.M. conceptualized the research. Then, F.M. investigated hosting capacity in smart distribution networks. According to the findings and implemented research, F.M. took the lead in writing and wrote the initial draft. M.Š. and F.M. designed the figures. M.Š. and Z.Dž. reviewed the manuscript and validated the final draft.

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