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Hosting Capacity: A Tool to Modernize the Grid and to Contribute to the Integration of Distributed Energy Resources in Colombia

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In this way, it is intended to evaluate in a general way, the optimization of existing resources, the visibility, and transparency of information associated with them, and finally the need for a regulatory change, which ensures the improvement in the technical processes for determining the hosting capacity, to ensure the quality, continuity, and reliability in the provision of electricity service by integrating renewable energies to the grid.

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Hosting Capacity: A Tool to Modernize the Grid and to Contribute to the Integration of Distributed Energy Resources in Colombia

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Abstract- This document contains a review of various research articles on the topic of hosting capacity for connection of Distributed Energy Resources - DER. The above, to establish a common thread between the multiple possibilities that exist to determine the Hosting Capacity - HC and the criteria that have been established in Colombia to achieve a purpose close to this determination.

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I. Introduction

In the last decade, the growth of electricity generation through renewable resources has been exponential and Colombia is no stranger to this condition. For this reason, public policies have arisen that in turn give way to regulation to establish the conditions for connection and promotion of the connection of DER [37], [43].

Taking into account the novelty of the aforementioned topic and the speed with which it is advancing, it is necessary to identify the aspects that can generate the greatest impact on the connection of distributed resources, to give an optimal vision and use of natural resources that Colombia has, giving it a high potential compared to other countries, intending to have a diversified energy matrix with a strong focus on non-conventional renewable energy sources. [5], [44]

In this sense, one of the most important aspects to take into account due to the direct impact that the integration of renewable energies has on distribution systems is the HC. This definition or criterion mitigates possible connection barriers through optimal management of the existing information that allows classifying and identifying the system to make the most of the connection possibilities without the need for network expansion [33].

Consequently, Chapter 2 presents the theoretical framework with the methods reviewed for the calculation of HC in other countries. In addition, Chapter 3 presents a specific analysis of the Colombian criteria for defining the HC, Chapter 4 shows a comparison of the methods analyzed, obtaining results that represent advantages for the application of the lodging capacity to the Colombian case, and finally, in Chapter 5, some conclusions are drawn after the research is carried out.

II. Theoretical Framework

The excessive penetration of Distributed Generation - DG brings problems to the grid and violations in the operating limits by exceeding the HC limit such as overvoltage, feeder's losses, transformer and feeder overloads, protection failures, and high harmonic distortion [1].

The HC provides indicators to have criteria in front of the requests of connection of the distribution networks with different energy systems. The HC is the maximum DER penetration capacity at which the power systems can operate satisfactorily [4], [7].

According to the cases presented in other countries and the current regulation in Colombia, the increase in DG connection requests, the distribution system operator (DSO), concentrate on which requests to approve or reject to connect to the grid, however, to have a better criterion in this choice, the HC limit must be taken into account [8], [9].

For the calculation of this criterion, voltage variation, frequency, overload, power quality, and protection problems are taken into account. According to the reviewed bibliography, it has been evidenced that overvoltage is the most used parameter at the moment of selecting the most optimal techniques for the calculation of the HC. In addition, the greatest impact of HC is presented in networks with low voltage, followed by medium voltage and high voltage. The most relevant

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problems in distribution systems as a result of DG integration into the network will be described below. The problems and solutions that will be mentioned in this chapter have been reviewed in [1], [2], [10].

a) Hosting Capacity: Performance Limits

1) *Overvoltage Problems:* When the power delivered from the DG unit is greater than the demand at the load, power is injected into the grid, thus increasing the voltage at the load node, with a possible overload on the nearby feeder. The voltage increase and the maximum current in the conductor are the main indicators that exceed the allowable limits at high DG penetration [11].
2) *Overloading and Power Loss Problems:* The correct way to locate DG units reduces generator losses and reduces the load on the generation transformers, it is common practice to connect DG units very close to the load. However, if the power generated is greater than the power consumed, power starts to be injected into the grid and thermal capacity limits on transformers and feeders may be exceeded [12].
3) *Power Quality Problems:* Excessive DG penetration can influence the occurrence of harmonics and voltage drops. Current quality focuses on how the overload impacts the upstream system. On the other hand, voltage disturbances impact the lifetime of the DER and cause malfunctions, and most DER use inverters to connect to the grid, which are considered sources of harmonics that impact the quality of the grid current. Finally, the techniques to mitigate harmonics must be dynamic and flexible to adapt to the harmonic emission caused by DG [13], [15].
4) *Protection Problems:* When DG exceeds the local demand, power flow and protection problems occur because the magnitude and direction of fault currents change. DG sources connected in the radial parts of the network are considered to be the cause of the increase of faults in the system protections. As reviewed, DG can withstand fault currents for a specific time without any damage to its components [14], [16].

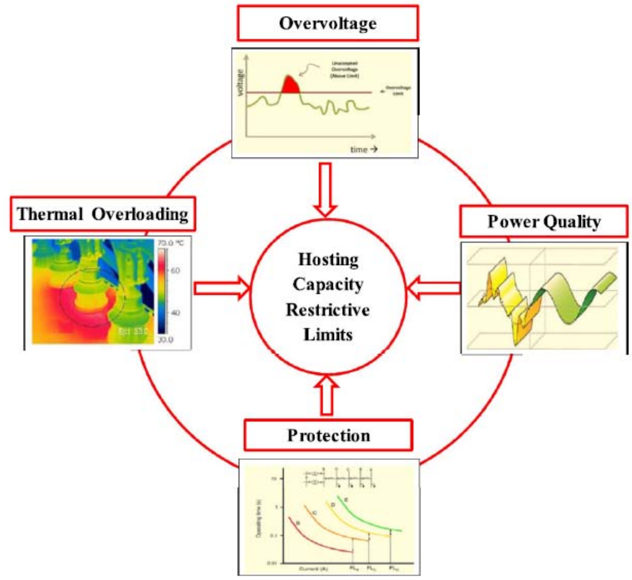

Fig. 1: Performance Indices that can be Considered in the HC Assessment [1]

b) Hosting Capacity: Enhancement Techniques

1) Reactive Power Control: It is the most effective method to mitigate overvoltage problems with RO's and end-users. Various techniques can be used such as capacitor banks, static compensator, and DG controlled by smart inverters. Stochastic mathematical models are used to increase the utilization of reactive power control, and storage systems help mitigate overvoltage problems. However, applying reactive power control in rural areas can lead to unbalances in reactive power flows with high DG penetration, therefore, it is recommended to connect DGs close to substations to balance reactive power [17], [19].

2) Voltage Control using the On-Load Tap Changer (OLTC): This technique allows automatic compensation for the network voltage profile to minimize the overvoltage and energy losses generated by DGs. The steady-state constraints of the voltage busbar are the main factor in the evaluation of the capacitance, in addition, the on-load tap changer control of transformers and decentralized capacitor banks help to increase the level of capacitance and reduce overvoltage [20].

3) Active Power Curtailment: Occurs when the DG unit wishes to decrease the output power according to the required demand, to maintain the operating limits of the network. This technique is widely used in centralized DG stations where the DSO can access the stations and control the power outputs. The overvoltage and thermal overload indicators are the main indicators to evaluate HC [21].

4) Energy Storage Technologies: Energy storage systems help minimize overvoltage, grid losses, and peak loads due to DG penetration, however, energy storage systems can be costly but provide unique benefits that depend on grid topology and generation and load profiles [22].

5) Harmonic Mitigation Techniques: Non-linear loads and large amounts of DG distort the voltage and current as they add harmonics to the network, which generates large losses and low energy efficiency, therefore this indicator should be included to evaluate the HC limit [23].

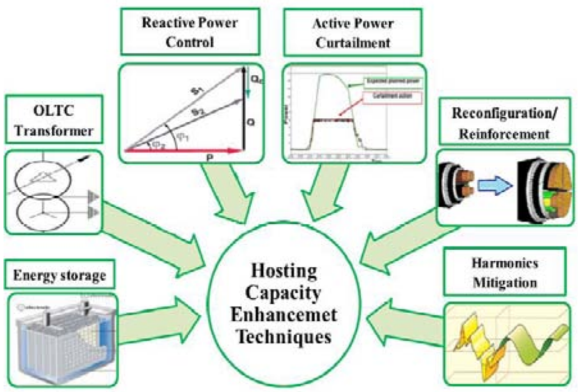

Fig. 2: HC Enhancement Techniques [1]

c) *Review of the Methods for Quantification of HC in Low Voltage Distribution Networks*

Establishing the acceptable range of the HC helps to determine the amount of solar PV energy that can be connected to a grid without additional investments, additionally, this criterion is of relevance for planning the expansion of the DSO grids.

In the HC methodology, three different quantification approaches called deterministic methods, stochastic methods, and time series will be discussed [24], [27].

Before the start of a HC study, it is necessary to know:

- Network parameters (performance indices) to be considered.
- Acceptable limit of the performance indexes.
- Decide on the phenomena (network impacts) to be considered in the study. The phenomena for the evaluation of the HC can be undervoltage, overvoltage, rapid voltage change, voltage unbalance, harmonics (current and voltage), interharmonics, superharmonics, thermal overload, protections, and losses.
- The availability of grid data and data from (future) solar PV installations.

1) *Deterministic Methods:* It is the basic calculation method for the evaluation of the HC of the distribution network, so it can be considered to give a first underestimated value of the HC based on the instantaneous evaluation of the worst-case scenario of solar photovoltaic penetrations.

For the determination of the HC, the most used method is the power flow simulation, where the most considered impacts are the increase of the voltage magnitude and the overload. Also, analytical and rule-based analyses can be applied.

Deterministic methods require known inputs to analyze the impact of solar PV on a low voltage distribution network.

The inputs of deterministic methods use static models that can be used by a stochastic method or also by a time series. Deterministic methods can also be used to compare different control strategies in addition to the determination of the HC [2], [7], [8].

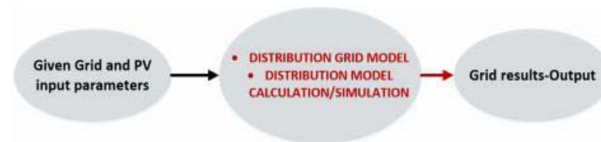

Fig. 3: Deterministic Methods and Model Illustration for Distribution Grid [2]

a) *Shortfalls of Stochastic Methods:*

- To determine the HC of the distribution network in a single large facility, the use of deterministic methods may be sufficient. However, for a large number of small installations, these methods are insufficient, due to the various uncertainties to be considered such as size, location, cloud cover, irradiation changes.
- Uncertainties in solar PV power production and customer energy consumption cannot be addressed with a deterministic approach, since the inclusion of such uncertainties for a large grid involves tens of millions of power flow calculations to assess the HC.
- Fixed inputs are used to obtain fixed outputs at one or more locations as a function of (assumed) injected power. Because solar power production is intermittent in nature, uncertainties must be considered and therefore deterministic methods must be replaced by stochastic methods.

2) *Stochastic Methods:* Solar PV power production is uncertain, as it depends on changing weather conditions. In addition, load consumption, solar PV size, location, and other properties of solar PV installations are often unknown. These variables are distributed in types of uncertainties as follows [2]:

- Random uncertainties or "certain uncertainties": variation in solar PV production and customer energy consumption are unknown variables in the future grid.
- Epistemic uncertainties or "uncertain uncertainties": the size of the solar PV, the location of a customer, number of customers with solar PV, or the type of inverter to be used.

- Both types of uncertainties, random and epistemic, must be considered in determining the HC.

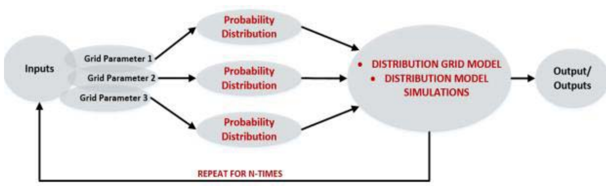

Fig. 4: Stochastic Methods Illustration for a Distribution Grid [2]

The characteristics of the stochastic method are described below:

- Stochastic methods consider the possibility of occurrence and variations that are present in low voltage distribution networks amidst the types of uncertainties. It is an improvement of the deterministic power flow that does not take uncertainties into account.
- A deterministic power flow for many scenarios involving probability distribution functions for the input parameters leads to a probabilistic power flow. The evaluation produces output results that are characterized by a probability distribution function obtained from these functions for the input variables.
- Most stochastic methods generate a large number of deterministic cases, each with a set of values for the input parameters.
- The most studied impacts are stress magnitude and load. In addition, losses and voltage variation are also used to assess the impact of solar PV in determining the HC.
- The more uncertain the variables considered in a stochastic method, the more complex and time-consuming the simulation becomes.

a) *Shortfalls of Deterministic Methods:*

- The main drawback of stochastic methods is that the relationship between system variables over time is lost or not captured.
- The effects of solar PV on voltage control elements on time scales of minutes or less are usually not included in stochastic methods; to include such effects, time series methods are required.
- It is important to evaluate the purpose of the study where the method is to be used since if the only purpose is to size the network, it will have little added value to use the stochastic method where a large number of scenarios with moderate conditions are considered.

3) *Time Series Methods*: Time series methods use actual system measurements, such as energy consumption and solar PV energy production, as input for calculations [25], [26].

- They use stochastic process models to generate time series data over a longer time.
- The time series methods are a suitable way to consider random uncertainties realistically.
- The most commonly studied indices with solar PV penetration are the impacts related to voltage magnitude and thermal load (MV/LV lines and transformer).
- With the use of time series analysis from measurement data, there is a need for a high-resolution data sampling frequency (1 second, 10 minutes, and 1 hour) to capture all variations. The accuracy of the data and hence the determination of the Hosting Capacity are largely related to the time resolution that is selected, so to increase the accuracy of a model in a simulation, higher data accuracy is needed. The time resolution of 1 second for one year is the most commonly used however, it requires more than one million simulations.
- Time series methods consist of time series data from deterministic studies, with time series sets of output values resulting from input values.

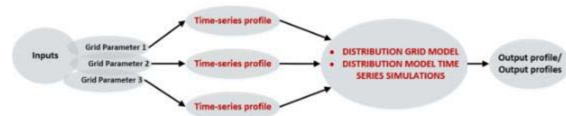

Fig. 5: Time-Series Methods Illustration for a Distribution Grid [2].

a) *Shortfalls of Series Methods*

- Long-term measurements (up to 30 years) are needed to generate the required data, which implies an arduous task for network operators and research groups.
- The required user data are private and mostly not easily accessible for public research [28].
- Stochastic models are capable of generating parameters corresponding to the real-time variation of the input data. However, such studies would suffer enormous computational burdens if performed at 1-second resolution
- We work on the assumption that the future and the past are the same (at least statistically) concerning the different input data required [29].
- Only "certain uncertainties" are considered and not "uncertain uncertainties".

III. Analysis of Regulation in Colombia

According to the theoretical framework presented in this document, it is possible to visualize that to determine the HC several methods have as a common factor the fact that for this calculation several parameters are involved that take into account: the information of the feeder, the location of the connection point, and the information of the demand to be connected [4], [36],[39].

However in Colombia through Resolution CREG 030 of 2018 is established as a criterion or "similarity to the hosting capacity", a limit to the energy that a distributed generator can inject into the grid, this must be equal to or less than 15% of the rated capacity of the circuit, transformer or substation where the connection point is requested [3].

That is a single fixed feeder parameter, also standard without regard to location or demand. Upon further investigation of the 15 % rule in the references of other countries, it was found that this rule is used as a fast-track method and that its objective is to process the large number of connection requests, which is also based on the concept of being a conservative method. However, with the application of this method, the dependence on the real characteristics of the feeder is eliminated from the equation, in addition to the fact that there is no particular information on the location or the demand associated with the connection point. [4].

In this regard, the Energy Transformation Mission referred to the document Focus 3: Regulatory Roadmap for efficient development of distributed resources published in 2020, in which it reiterates the appreciation that the value of the HC is specific to each feeder and depends directly on the topology of the network. Therefore, its calculation requires intensive work in data management and the development of models and procedures.

Additionally, this roadmap is clear and explicit about defining as an unnecessary constraint, a fixed parameter for one of the network components, as this can be very conservative and therefore an unnecessary barrier for the connection of the DG [5].

Finally, the following figure shows a tree of the problem, identifying the causes and effects of the existing criteria in Colombia for the allocation of connection points.

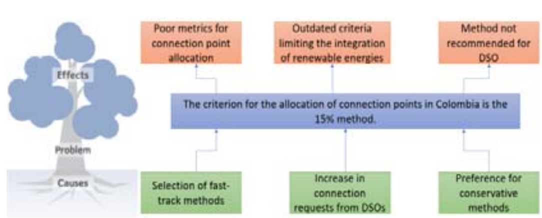

Fig. 6: Problem Tree

a) CREG 030 of 2018 Modifications

Through document D-002-2021, the commission has indicated that, throughout the period of implementation of CREG Res. 030 of 2018, it has received requests for a concept on the resolution in question, where it was possible to establish the need for clarifications regarding the current regulatory provisions that allow continuing guaranteeing the penetration of renewable energies. For the above, the CREG developed the identification of symptoms, causes, and effects presented below [3].

It was concluded that the problem to be solved could be solved by making the definitions, procedures, and regulatory requirements clearer and more precise:

- Follow-up indicators for AGPE and DG penetration.
- Causes for disconnection of an AGPE or DG user.
- Detail the requirements to be met in the information systems.
- Connection procedures.
- Metering systems.
- Options for sale and recognition of surpluses and finally.
- How to pass on the cost to the end-user.

From the above, it can be observed that in the identification of causes that generated the modification, there is no evidence of concern regarding the established integration limit (15%). This limit, as indicated by the commission in the document, was established based on international experience to avoid problems in the networks (voltage, losses, reverse flows, among others) due to the increase in the penetration of distributed resources.

However, the proposed modification establishes a new penetration limit for voltage level 1, going from 15% to 50%. The decision of this modification is made according to the conclusions presented in the document "Design of monitoring and evaluation indicators for the integration of self-generation and distributed generation in the National Interconnected System", which was made known through CREG Circular 021 of 2019, where it is concluded that at a penetration level of 50% the vast majority of networks and transformers are not affected [6].

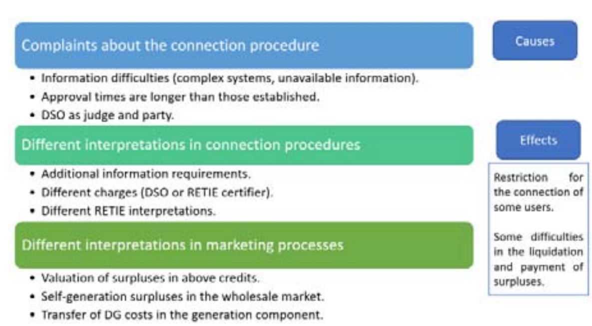

Fig. 7: Identification of Symptoms Causes and Effects [6].

IV. Conclusions and Recommendations

Currently, in Colombia, the 15% criterion is used to calculate the DG capacity that could be connected to the grid. However, in other parts of the world, the concept of HC is used to define the limit of DG that can be connected to the grid without exceeding any operational limit of the grid. This indicator is not calculated only once, on the contrary, it must regularly be calculated for several performance indicators such as voltage and frequency variation.

Other expected changes in the distribution network, such as electric vehicle charging and electric heat pumps, can be addressed by similar HC studies.

Most studies focus on how high penetration of solar PV in low-voltage distribution networks affects voltage magnitude parameters and the loading of lines, cables, and transformers, while other network phenomena receive less attention.

HC is an important tool to operate a Distribution System below the thresholds set by the utility without any adverse impact. A Distribution System must have sufficient HC so that its customers can add their solar PV generation to the system.

The Distribution System's hosting capacity should be recalculated over time as the Distribution System's configuration, load, and equipment changes.

According to the current conditions of the Colombian market, it is considered that the inputs to apply the medium voltage HC model are available, since the necessary information for the characterization of the low voltage system is not currently available, since the advanced metering systems are in the process of being implemented until 2030.

With an expected high penetration of solar PV in Colombia's distribution networks, DSOs need to make a hasty foray into selecting a methodology to determine the HC.

The decision of which methodology to implement for the calculation of HC by a DSO depends on its needs and the availability of input parameters. The advent of smart meters is rapidly increasing the amount of data available, which favors the use of stochastic and time series methods by DSOs. However, not all DSOs are moving at the same speed in all countries, for example, in Colombia to date users with AMI are minimal, and even for those that already have this technology, data is not always available for HC studies.

Stochastic and time series methods are more relevant and realistic for HC studies than deterministic methods since non-conventional generation sources and specifically, solar PV is intermittent in nature. However, when limited data is available, a deterministic method based on estimated sizing or worst-case scenario values could be used.

Based on the studies reviewed, it is concluded that the need for different handling of the two uncertainties, random and epistemic, in HC studies is not highlighted. For certain uncertainties, it is possible to assume the probability distribution functions of the random parameters. For uncertain uncertainties, this is not straightforward, their inclusion in a model for HC determination and assessment based on probability theory may not be entirely correct.

The calculation of the HC in a country is influenced by national regulations and the guidelines of each DSO. This implies that it is susceptible to drastic changes with the elimination and/or modification of subsidy and incentive schemes.

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