International Journal of Advanced Engineering Research and Science (IJAERS)
Peer-Reviewed Journal
ISSN: 2349-6495(P) | 2456-1908(O)
Vol-9, Issue-6; Jun, 2022
Journal Home Page Available: https://ijaers.com/
Article DOI: https://dx.doi.org/10.22161/ijaers.96.30

Study of the hosting capacity of photovoltaic distributed generators in low voltage distribution networks: A probabilistic approach using Monte Carlo simulations

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Received: 25 May 2022,

Received in revised form: 14 Jun 2022,

Accepted: 21 Jun 2022,

Available online: 27 Jun 2022

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***Keywords*—Distributed generation, Hosting capacity, Photovoltaic system, Power flow, Power quality, Voltage level, Voltage unbalance.**

***Abstract*— This paper aims to present the study and quantification of the hosting capacity (HC) of a low voltage distribution network composed by photovoltaic distributed generation. The methodology used becomes possible through the implementation of the Probabilistic Method of Monte Carlo with the use of the Python programming language, where the connection point of the distributed photovoltaic generation, power of the generators and the amount of generation systems is randomly chosen. To perform the calculation of the power flow, it is used the OpenDSS software (Open Distribution System Simulator) integrated into the tool in Python from a DLL (Dynamic Link Library). After all the scenarios created, the power, imbalance and RMS voltage are measured in the loads that were installed at the photovoltaic generators and also in the secondary of the transformer. A statistical analysis is performed in order to determine the hosting capacity of the network, that establishes minimum parameters for the imbalance and RMS voltage level to maintain a good Power quality. And finally, since the hosting capacity is dynamic, and cannot be generalized, because at each point of the system has its characteristics and thus it is necessary to identify the HC separately for each busbar. However, it can be pre-established around 60% or 70% of photovoltaic penetration level, since power utilities can install battery banks or relocate consumers to other phases in order to mitigate impacts on the network.*

I. INTRODUCTION

With the search for methods of generating electricity from renewable sources, distributed photovoltaic generators (DPVGs) connected to the distribution system have received worldwide prominence due to tax and financial incentives. In addition, investment and studies on these technologies have increased significantly in the last decade due to the increased demand for clean energy. Thus, in Brazil, these technologies are encouraged and supported by Normative Resolutions (NRs) of the Brazilian Electrical Agency (ANEEL) such as NR 482/2012 that allows the Brazilian consumer to have their own generation of electricity in a sustainable way and inject the surplus of active power into the local distribution network [1], NR 687/2015 subdividing photovoltaic systems (PVs) connected to the microgeneration network characterized by having an installed power less than or equal to 75kW, mini-generation defined with power exceeding 75kW up to 5MW and generation plants above 5MW of installed capacity [2], and finally, NR 786/2017 which aims to complement NR 482/2012 and adds the right of installation or adequacy of equipment in distribution of existing electricity in order to maintain quality, reliability and/or increase distribution capacity, and also allowing sending or receiving credits to different Consumer Units (CUs) under the same ownership condition, ensuring shared generation and remote self-consumption [3].

In addition, on January 6, 2022, Law No. 14300 [4] was sanctioned, generating a new framework for Distributed Generation (DG) and changing some provisions of the NRs.

Moreover, Law No. 14300 does not annul regulation 482 of 2012, however, because it has a hierarchical higher power to the NR, it implicitly revokes all the provisions of 482 that opposes any provision presented by law, such as in NR 482/2012 classified distributed photovoltaic mini-generation up to 5MW, however, with Law No. 14300, there was a reduction of this power to 3MW involving all types of electricity generation from non-dispatchable sources, that is, sources that are not controlled by the ONS (Brazilian Electrical Operator) where its produced energy is injected directly into the network through its primary resource.

To define HC, electric power utilities need tools and methodologies that may be able to perform this work in order to ensure that Power Quality parameters are within the limits established by Module 8 of the Brazilian Electric Distribution Procedures (PRODIST) [5]-[6]-[7].

The distributed photovoltaic generation, although being beneficial to the electrical system, on a large scale can cause instability in the electrical power system (EPS) and may be accentuated, since the distribution networks use old topologies created before the possibility of the consumer being able to generate its energy and inject the surplus into the distribution network.

The techniques presented in this paper show ways to determine limits of the insertion of DGs in the distribution network bypassing impacts, avoiding high investments made by the electric power concessionaire and allowing to reduce costs in electrical equipment and protections. Thus, through probabilistic studies, a simulation routine developed from the Python programming language is created and a series of scenarios are obtained, including the insertion of photovoltaic solar energy at different power levels and distinct points of the distribution network. Finally, statistical analyses are made aimed at changes in voltage levels in order to determine the hosting capacity of distributed photovoltaic generators.

The performance of this work is made possible by implementing a computational routine together with the EPS load flow simulation performed by OpenDSS DLL access with Python programming that can be better understood using the OpenDSS manual [8].

II. IMPACTS CAUSED BY DISTRIBUTED GENERATION

The modeling of the Brazilian electrical system is part of the large power generating plants such as hydroelectric, thermoelectric, nuclear or other forms of generation, these are located in remote locations and far from urban civilization, because they present the need to be close to the natural resources used for the conversion of potential, kinetic or thermal energy into electricity. This electricity generation structure is called centralized and creates a one-way power flow, which originates in generating plants and has residential, commercial or rural consumers at the end point of the power supply. During this route, the transport of electricity passes through different subdivisions of the electrical system, starting in the generating plants, traveling through the transmission lines to lowering substations and / or elevators where are present conversion, protection and measurement equipment such as voltage transformers, relays and disconnector slats, PTs (Potential Transformers) and CTs (Current Transformers), and completing its journey in consumers who are at the end of the electrical system. Throughout the power delivery route, there are elements that have been sized by adopting the one-way flow of power through the model mentioned above. And with distributed generation this sense begins to change by bidirectional way.

Renewable energy sources in turn impact the electricity distribution network by changing its topology, since the actual distribution system is passive and is designed to have only one generating source and one-way power flow. Distributed generation systems are active and can act as generators and energy consumers and thus produce a two-way flow of power. And because actual electric systems are not designed to receive this type of two-way power flow may present some problems due to DG [9].

According to Trevisan [10], a low insertion rate of distributed generators produces few impacts to the electrical distribution system if the system is not weak. Nevertheless, Brazil and the world have the propensity for growth of DG, thus making the emergence of a significant amount of this type of energy supply. And what will be addressed in this work is to quantify the hosting capacity through the massive insertion of distributed generation in particular photovoltaic and for this must be taken into account the impacts caused to the network. From this, some Power quality problems can be listed, such as: voltage swell, voltage regulation, frequency oscillation, voltage unbalance, harmonics, interruptions; besides short circuit parameters changing, power flow changes, and others.

III. HOSTING CAPACITY OF A LOW VOLTAGE DISTRIBUTION NETWORK

The hosting capacity (HC) can be understood as the performance index of the electrical system showing the characteristic of including distributed generation without violations of power quality parameter limits. In order to calculate HC, it is necessary to identify and determine the performance indices that will be used. The calculation of these limits should not be defined as a definitive method to perform this evaluation, because it is a prediction of its value, since the hosting capacity is dynamic and the more indexes considered better will be its reliability in the results, however, it becomes more complex to find the hosting capacity.

The need to conduct studies on the electric systems behavior and, consequently, to quantify the impacts originated from the high level of photovoltaic generation concentration in the energy distribution system is a primary factor for the identification of HC. The impacts caused by photovoltaic generation connected to the DG, due to the two-way flow of power, have the property of causing the voltage variation at the connection point of the network where the photovoltaic system was installed [11] and may cause damage to electrical equipment installed in that location because it has higher limits than the rated ones supported. Thus, having a way to quantify the maximum distributed generation capacity connected to the distribution network respecting its limits of the reference indexes, the credibility and reliability of the regulatory agencies is obtained, allowing the accommodation of this technology in a conscious and appropriate way.

Overvoltage, voltage imbalance, power factor deterioration, electrical losses, transformer charging are some indicators connected to the network and common DG coupling points. In this work will be used the indexes of allowed overvoltage and voltage imbalance for the determination of hosting capacity.

That said, whatever the performance index chosen there will be a limit that must be respected in order to accommodate the largest number of distributed generators. Thus, the performance of the system is inversely proportional to the number of DGs connected to the network. Fig. 1 shows the performance of the electrical system in a generic way, in relation to the increase in the number of generators.

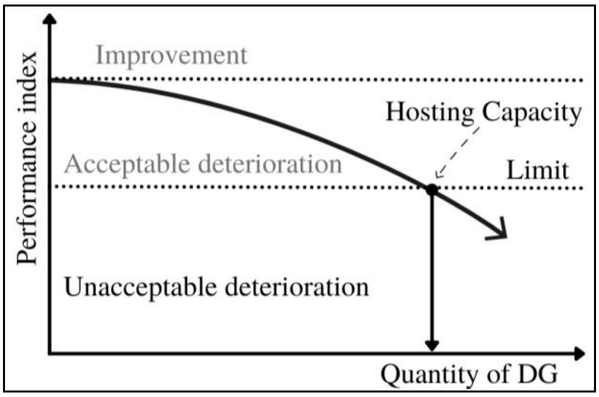

Fig. 1: Approximate hosting capacity according to high performance index [12].

In this model, it shows that the smaller the number of connections from DGs on the network, there will be few impacts on system performance. Therefore, it is understood that the maximum performance is found when there is no generation, and as generators are included its performance is attenuated. However, this methodology is not constantly applied because most ideal models address low performance values for better network performance.

Fig. 2 shows the calculation for hosting capacity making the use of acceptable overvoltage, showing that the higher the amount of distributed generation will mean a greater deterioration of the power quality provided and the increase in the performance index. Since, in places more distant from the power point of the network, a depreciation in the voltage magnitude is caused. That said, with small plots of distributed generator insertion the voltage increase will be low, already for large amounts of penetrations of DPVGs the voltage can rise a lot and becoming unacceptably high and thus there is violation of the limit of hosting capacity.

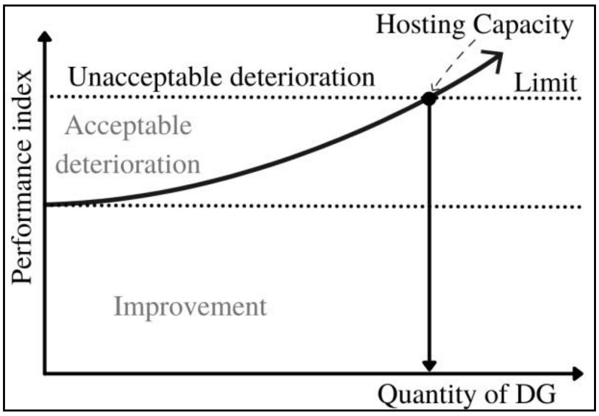

Fig. 2: Approximate hosting capacity according to low performance index [12].

However, there are specific cases that when inserting DGs will initially cause an increase in the performance index, but in large cases will deteriorate. In other words, it is possible to have more than one hosting capacity for the same system, represented in Fig. 3 where the first HC achieved presents acceptable deterioration, that is, lower quality when compared to the absence of generation, but still providing reliability in the supply from the insertion of generators. In the second HC, this deterioration becomes unacceptable, presenting the maximum supported limit. In both cases, there is an improvement in the index with the reduction of electrical losses and risks of overloads for small amounts of distributed generation, but if the number of DGs increases it will deteriorate performance making it unacceptable.

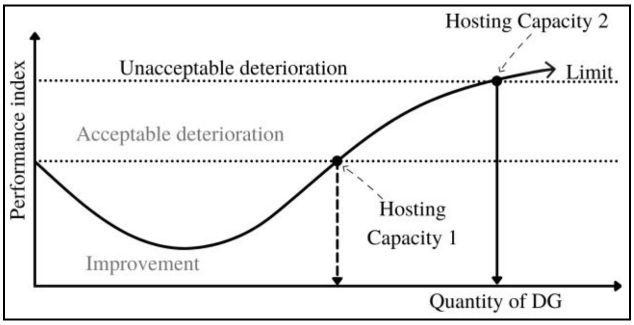

Fig. 3: Approximate hosting capacity with improved performance index [12].

According to Bollen and Hassan in [13], to determine the hosting capacity is required:

- Choose the type of phenomenon and the desired performance indices;
- Establish the appropriate limits for each event;
- Delimit performance indexes relative to the amount of distributed generation connected to the network;
- Perform the calculation of HC.

During the calculation process it may be that more than one hosting capacity is found in the choice of two or more phenomena or performance indices, thus it is essential to adopt the lowest value found, as it will ensure that for the worst case all parameters will be within acceptable limits. And, as stated earlier in this work, three electrical energy quality indexes will be used for the calculation of HC, they are: allowed overvoltage, voltage imbalance and transformer charging.

IV. MONTE CARLO SIMULATION

Monte Carlo Simulation (MCS) is a technique widely used in probabilistic analysis for a given system. This tool consists of a numerical manipulation to obtain the statistics of the output variables of a computational modeling. In each simulation, the input variables sampled through probability distributions are defined and thus the output values are calculated using the computational model. From the output variables, statistical analyzes are performed to interpret the problem faced [14]-[15].

This tool belongs to the collection of techniques called Monte Carlo Methods (MCM) which involves computational algorithms for the solution of several problems that require large random samples, prediction of possible future scenarios, integration and optimization of mathematical problems, generation of numerous possibilities for facilitating decision-making, asking prices and multiples related to the financial market, are some examples of the practical application of these methods.

MCS is commonly used in two circumstances, for the validation of descriptive analytical methods and for the solution of complex models that require a large number of calculations or that are not capable of being numerically solved, requiring analytical approximations that are difficult to perform. For the second case, the Monte Carlo Simulation performs several deterministic analyzes of the different scenarios created using probability distributions for the input variables.

The use of probabilistic simulations of a given system allows generating numerous occurrences of events regardless of the model. That is, no matter which problem is being faced, through the Monte Carlo Simulation it will be possible to create different types of scenarios, interpret the output variables in a statistical way and later take results based on the analyzes performed. Each simulation originates a new series, different from the previous one, but with the same statistical characteristics. As each scenario is different from each other, it is possible to obtain several results from each MCS, unlike the deterministic approach where a single result is obtained. In this way, the probabilistic analysis of Monte Carlo Simulations allows the analyst to make decisions based, not on an isolated case, but through several studied events.

In this work, the Monte Carlo simulation has the role of enabling the creation of several scenarios, where the installed power will be chosen through a probability distribution constructed through the ANEEL database [17] and will be presented later in this chapter and also the PVs connection point chosen based on a uniform distribution.

V. OPENDSS AND THE RIGGED DISTRIBUTION SYSTEM

The Open Distribution System Simulator (OpenDSS) is a software responsible for performing simulations that are linked to the electrical energy distribution system, published in 1997 with the intention of providing support and analysis of electrical systems. It was developed in three versions, the first being a standalone executable program (OpenDSS.exe) with a basic interface based on text commands and as help mechanisms to assist the user in the development of their code, the second, a COM server (Component Object Model) implemented through a DLL (OpenDSSEngine.DLL). Finally, the third version, a command DLL that provides all the functions of the COM server (OpenDSSDirect.DLL), can be used in high-level programming languages that do not support COM or require Thread-safe that request a lot of data and parts of the code using multi-threads. [7]

Thread-safe is a computer programming notion that applies to the context of multi-threaded programs. A fraction of the code is called Thread-safe when it works with shared data structures in order to guarantee safe execution by requesting multiple threads simultaneously. Initially, OpenDSS, just called DSS, was created by researchers and electrical engineers Roger Dugan and Thomas McDemontt, and its objective was to analyze the electrical distribution system from the insertion of distributed generation. However, in 2004 it was bought by the company EPRI (Electric Power Research Institute) and in 2008 it became a software with free license, receiving the name of OpenDSS. [7]

The software performs most of the analysis in the sinusoidal steady state, frequency domain, normally used to supervise and design electric power distribution systems. In addition to supporting modern forms of analysis that can meet future needs that are being mentioned by energy utilities around the world in relation to Smart Grids. Other supported features are energy efficiency and harmonic distortion analyses. OpenDSS was created with the mission to be expandable and can be updated to meet many futures uses both in general and for individual users.

In this work, the third version was used through OpenDSSDirect.DLL, as this alternative was created to accelerate the simulation speed between OpenDSS and external programs. Normally, in programming languages that operate at a high level, they do not support connections with the COM server, which present late connections and, due to the delay of the information, overload the simulation process, especially when loops of repetitions are executed [17]. Python was connected to OpenDSS through the py-dss-interface module, created by Paulo Radatz, Ênio Viana and Rodolfo Pilar Londero. All documentation and information can be found in [7].

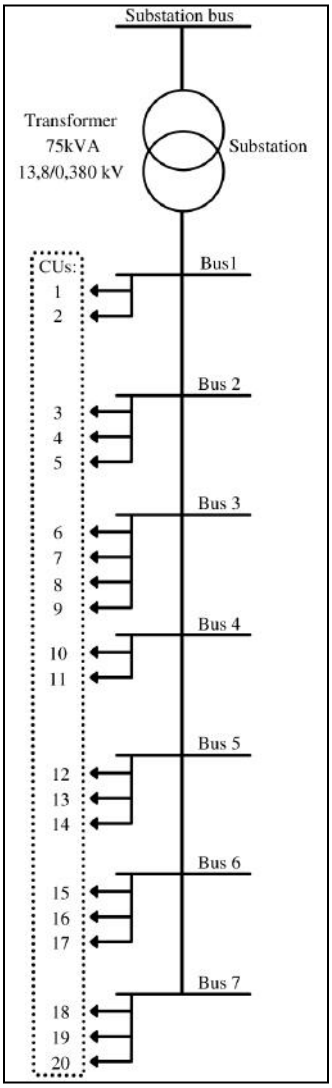

Fig. 4: Unifilar diagram of the electrical system used

Fig. 4 shows the electrical distribution system used and later modeled within OpenDSS. Composed of a 75 kVA transformer, with its high side connected to 13.8 kV and low side to 380/220 V, 7 busbar, 20 single-phase consumers and a total line length of 885 meters. This information was made available by the electricity concessionaire CPFL Energia (Companhia Paulista de Força e Luz) from a branch supplied especially at this voltage level. All other manipulated system data and advanced computational modeling are described in [18].

In the simulations, in order to determine the hosting capacity of the distribution system, each consumer unit will receive a distributed photovoltaic generator randomly, with each consumer unit having the same probability of installing this distributed photovoltaic generator, until the predetermined value of the photovoltaic penetration level established in the program.

VI. PROGRAMMING LOGIC

For the programming logic, an algorithm was developed in Python where it receives as data input: number of MCS (Monte Carlo Simulations), number of photovoltaic generators called PL (photovoltaic penetration level) and the number of CUs (Consumer Units) to be considered.

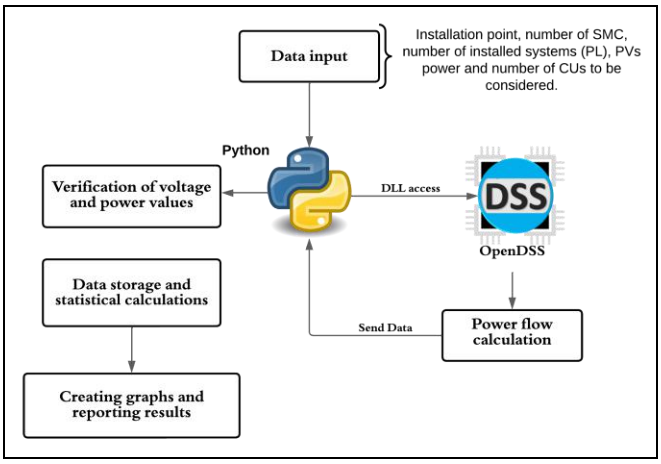

Fig 5: Flowchart of programming logic

In Fig 5, the programming logic is shown in the form of a flowchart in order to exemplify the method used. Through the Python-OpenDSS connection, some loops of repetition are created for the execution of the Monte Carlo simulation, such as: loops for counting and carrying out the MCS, implementation of different levels of photovoltaic penetration (NP), creation of different connection points of the PV generators and a loop to randomly select the PV power through a probability distribution constructed using the parameters obtained from the ANEEL database [15] for residential installations of up to 10 kW in the city of Itumbiara in the State of Goiás.

After data entry, this information is passed to the developed code and the creation of several photovoltaic generation scenarios begins, which are then inserted into the network. That said, the power flow calculation is performed in OpenDSS and each scenario goes through the voltage limit check among the values provided by ANEEL that are presented in Table. *1*.

Table. 1: Connection points in Rated Voltage equal to or less than 1 kV (at the base of 380 V/220 V) [5]

VOLTAGE	RANGE OF VARIATION OF READING VOLTAGE (TL) IN RELATION TO THE REFERENCE VOLTAGE (TR)
Adequate	(0.9210 TR ≤ TL ≤ 1.05 TR) / (0.9182 TR ≤ TL ≤ 1.05 TR)
Precarious	(0.8710 TR ≤ TL < 0.9210 TR or 1.05 TR < TL ≤ 1.0605 TR)/ (0.8682 TR ≤ TL < 0.9182 TR or 1.05 TR < TL ≤ 1.0590 TR)
Criticism	(TL < 0.8710 TR or TL > 1.0605 TR) / (TL < 0.9455 TR or TL > 1.0590 TR)

In Fig. 6, the probability distribution constructed and later implemented in the Monte Carlo Simulation code is presented to ensure unpredictability and randomness of the created scenarios.

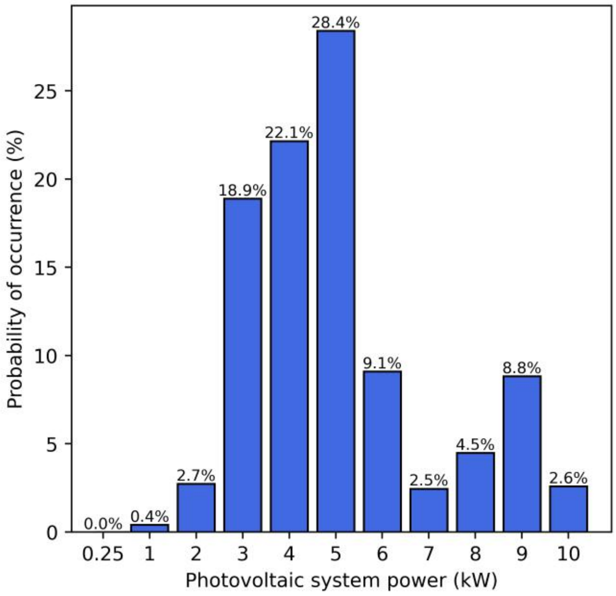

Fig. 6: Probability distribution according to photovoltaic systems installed up to 10 kW in Itumbiara - GO

As the Monte Carlo Simulation is a probabilistic method, it is necessary to identify some random variables, and in this case the choice of each photovoltaic system power is interpreted as one of the main randomness for the construction of this work, since the electric power utility has neither control nor certainty of the power value of a new customer's system. Therefore, it is essential to carry out statistical research in order to find a relationship between the installed power and the number of access requests with that specific capacity. From this, the ANEEL database was analyzed, filtering the installed photovoltaic systems of up to 10 kW in the city of Itumbiara, in the state of Goiás. This power value was established because all the DGs that will be installed are single-phase, and in the current market the availability of photovoltaic inverters for this type of connection is a maximum of 10 kW.

In addition to the uncertainty in the choice of PV power, the point or place of installation of the DPVGs, ambient temperature, solar irradiance and the customer's consumption profile are other random variables that neither the utility nor the customer has control over their values. And for that, the installation point is defined from a uniform probability distribution, that is, all customers present in the network have the same chance to install a PVs, in this way, it is guaranteed an approximation of the reality that the concessionaires are going through, where more and more customers want to have a type of DG installed in their home. The temperature is set for a clear day in order to guarantee ideal thermal balance for the rated operation of the modules, and also with a "perfect" irradiance, because if this occurs it will be the worst possible scenario for the power network when it comes to impacts. caused by DG.

VII. RESULTS

Through the Monte Carlo simulation, several scenarios are generated through the different probability distributions for the connection points of the photovoltaic systems and the powers of the GDFVs. Thus, a large volume of data is obtained, which will be presented through graphic and statistical analyzes related to voltage amplitudes, voltage imbalance, both for the busbar and for the grid feeder and the photovoltaic power installed at the grid connection points. For the simulation process, the following input variables were used:

- MCS = 500 Monte Carlo simulations;
- PL = 0 to 100% with a step of 10%;
- CUs = 20 consumer units considered.

The measurement interval of electrical quantities was fixed at 1 minute, resulting in 1440 measurements during the 24 hours of a day. With the intention of reducing the computational effort and accelerating the simulation process, the simulation day with the best solar irradiation shown in Fig. 7 is considered, as the irradiation coefficient implemented in OpenDSS, so the voltages generated by the photovoltaic modules will be the rated, therefore, this curve model is a conservative choice, and if this type of event occurs, it will result in the most worrying scenarios, considering the impacts caused to the distribution network.

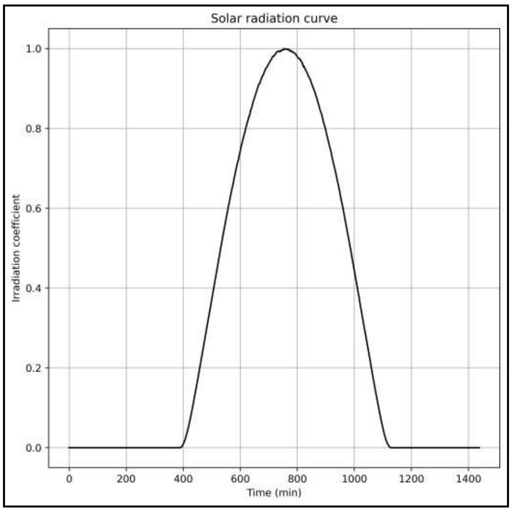

Fig. 7: Solar irradiation curve implemented in OpenDSS

Fig. 8 shows the load curve for residential consumers as a function of active power. This curve is said to be the typical behavior of each CU connected to the modeled electrical system and its function is to allow the temporal variation of energy expenditure interpreted by OpenDSS to occur.

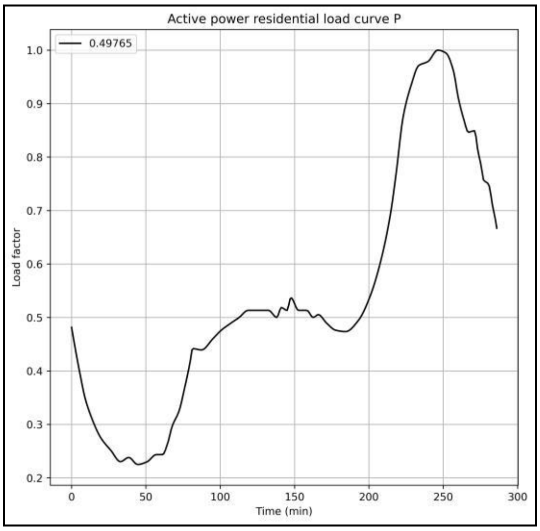

Fig. 8: Active power residential load curve P

A relevant factor of this work for the identification of HC is the use of the probabilistic technique, Monte Carlo

Simulation, which allows approaching the cases that will be presented as close to the reality that is happening with the electric energy concessionaires, since they do not know at which point the DPVGs will be allocated nor the power of these generators. Thus, when performing numerous simulations, great results are obtained. In order to justify the number of simulations chosen for this work, the Coefficient of Variation (CV) is calculated for some metrics by Equation (1).

$$CV = \frac{\sigma}{\mu \times \sqrt{n}} \quad (1)$$

Where:

σ = Standard deviation of the chosen metric;

μ = Metric mean;

n = Number of simulations performed.

The CV is calculated from the second MCS, as the intention is to find the variation that exists between one simulation and another, with the increase of the MCS value a new coefficient of variation is obtained and, thus, until the last simulation. These values are stored to be used in the generation of graphs for the purpose of being analyzed.

To facilitate understanding and reduce data presentation, only the data for the transformer and busbar 7, will be shown, as it represents the most worrying busbar related to voltage levels. In Fig 9, the coefficient of variation for the maximum stresses at busbar 7 in each PL (Photovoltaic Penetration Level) are presented in order to find the necessary amount of MCS that would converge the CV.

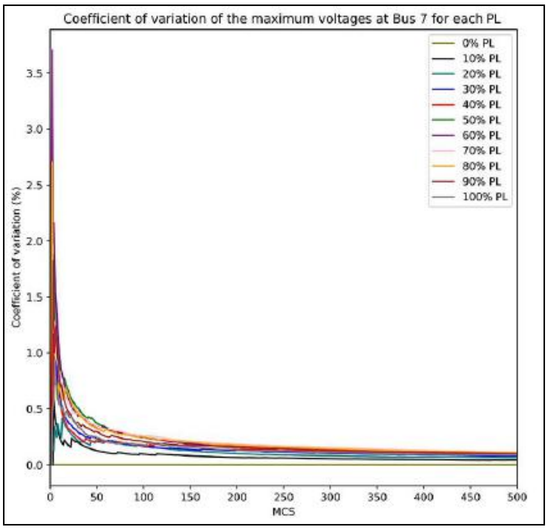

Fig 9: Coefficient of variation of maximum stresses in Busbar 7 for each PL

From Fig 9, it is noted that with 500 MCSs the value stabilizes, showing little variation. Thus, avoiding the need to perform more simulations and reducing the computational cost. However, with 300 MCSs, it would be enough to have good results and make reliable analyses, but this work has undergone some improvements in its code, thus being able to perform 500 Monte Carlo Simulations without harming the efficiency of the machine used.

In order to better understand the concept adopted for PL in this work, its value is directly related to the number of distributed photovoltaic generators that are installed in the consumer units present in the network, as shown in Table. *2*. It is important have this knowledge, as there are standards from concessionaires in the United States and standards by the IEEE that determine the concept of photovoltaic penetration level as a percentage relationship with the rated power of the transformer. For this work, the PL is adopted as the number of GDFVs inserted in the network.

Table. 2: Equivalence of PL number

PL percentage	Number of equivalent PVs
0%	0
10%	2
20%	4
30%	6
40%	8
50%	10
60%	12
70%	14
80%	16
90%	18
100%	20

In Fig. 10, the evolution of the number of violations is shown for all penetration levels of photovoltaic generators and it is seen that in some cases the higher the PL the greater the number of violations and, in this way, it shows that busbar 5, 6 and 7, are the most problematic if a large volume of DPVGs is entered. Because when excess energy is injected into the system, the voltage at that point tends to increase and this effect is more pronounced when the short-circuit level in the busbar is lower, causing any voltage variation to reach high levels.

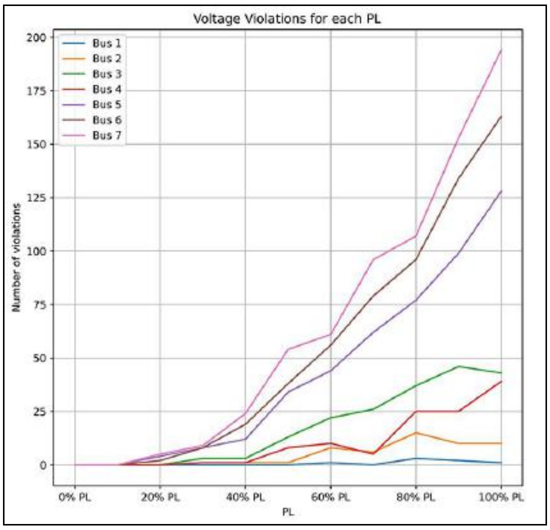

Fig. 10: Voltage violations for each PL

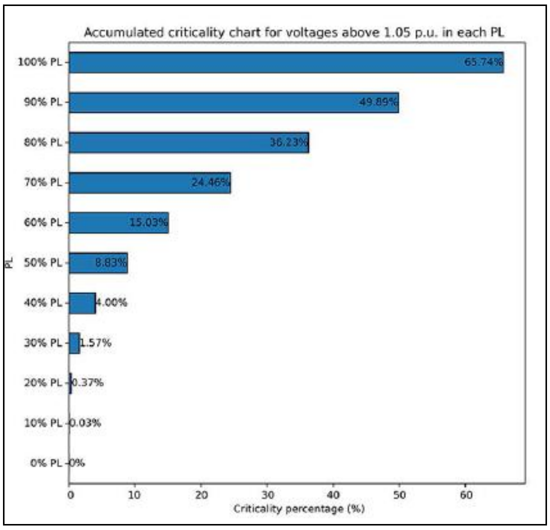

Fig 11: Statement of accumulated criticality for stresses above 1.05 p.u. in the bars in each PL

From the analysis of Fig. 10, it can be concluded that for the more distant busbar, the HC of the network is compromised, presenting a greater number of voltage violations. Thus, for this analysis methodology at 50% of photovoltaic penetration level, busbars 5, 6 and 7 began to show violations more frequently, since the other busbars remain with the number of violations below 50.

An important metric to analyze how worrying the overvoltage impacts caused to the network will be and making it possible to identify the HC of the network for a certain level of photovoltaic penetration is the cumulative criticality statement, shown in Fig 11.

This graphic methodology shows that if there is a penetration of DPVGs of 100%, there will be a 65.74% chance of a voltage rise greater than 1.05 p.u. at some system busbar is similar for the other PL values. It is worth mentioning that if there is, for example, 90% of PL in the network, the criticality potential of the previous PL is considered plus the value in question and works in the same way for all other percentages. In this way, the HC is identified from the percentage of occurrence of voltage violations. In Fig 12, the graph of the number of violations referring to voltage unbalance values greater than 3% measured in the 500 MCSs for each PL is shown.

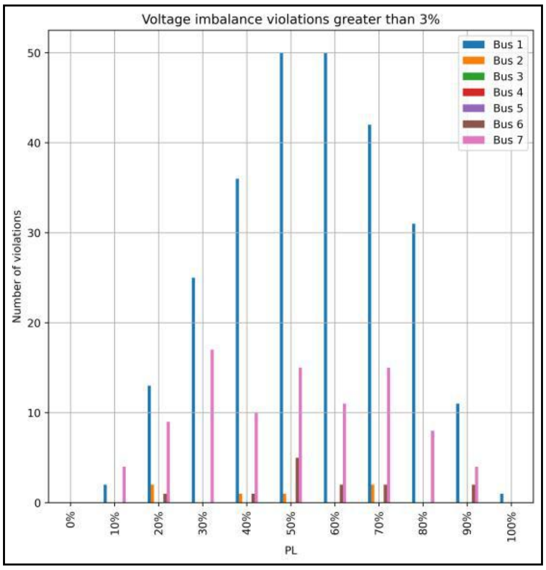

Fig 12: Voltage imbalance violations > 3%

In order to facilitate the analysis, Fig. 13 shows the maximum voltage obtained in the 500 simulations for each transformer phase and at which penetration level this value occurred.

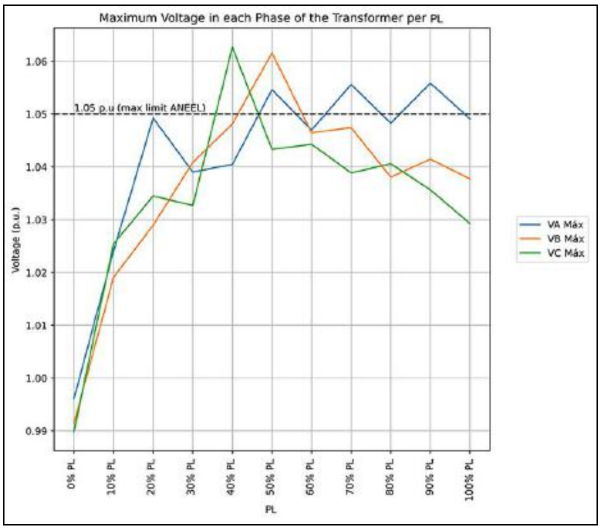

Fig. 13: Maximum voltage at each phase of the transformer per PL

It is important to know at what levels of penetration it becomes harmful to the network and to indicate to the electric energy concessionaire when they should make improvements in the network or techniques for relocating consumer units, since, for example, in 40% of PL in phase A the violation of 1.05 p.u. does not occur, but it already happens in phase C for that same level of penetration. Thus, a possible solution would be to migrate consumers from the problematic phase to another that is not or also carrying out the installation of battery at strategic points in the network based on the analysis of the busbars, for example, in order to store excess power flow avoiding voltage surges.

Next, in Fig. 14, the maximum voltage imbalance for each photovoltaic penetration level is presented, the imbalance index is another metric for the analysis of the network HC since the acceptable limit, in Brazil, is a maximum of 3%, defined in Module 8 of PRODIST [5].

In the Fig. 14, it is noted that there is no voltage imbalance above 3% and this is because the transformer is a robust equipment being powered at medium voltage and for having full influence on the distribution system and thus the amount of photovoltaic implemented in this network did not have the necessary power to unbalance the voltage in the transformer, but it was seen in the previous topics that in the busbar this effect occurs in a very accentuated way. Therefore, it could be said that in relation to the voltage imbalance in the feeder, this network has a considerable HC, starting from the point that the highest percentage of imbalance was from 1.5% to 40% and 60% of PL, but it is worth mentioning that the same HC should not be adopted for the entire network, through this analysis index. In Fig. 15, the total result of the transformer loading is presented.

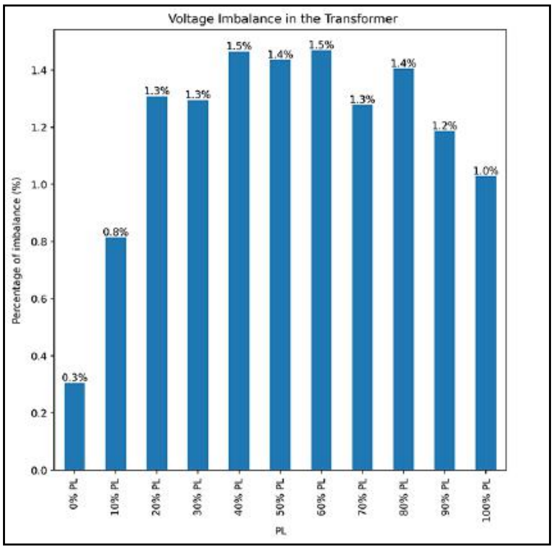

Fig. 14: Voltage imbalance in the transformer

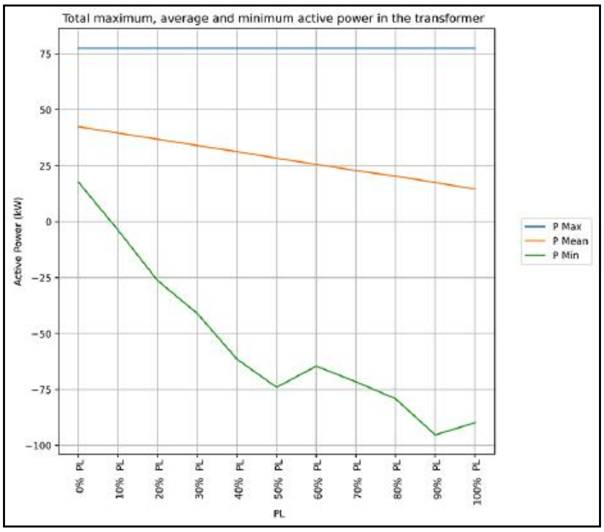

Fig. 15: Maximum, average and total active power in the transformer

From Fig. 15, it is noted that for 80%, 90% and 100% of PL, the rated power limit of the transformer is exceeded (75 kW, adopting unitary power factor for the analysis), but it is known that these can work oversized, however it is necessary that the electric power company is attentive and evaluates if excessive damage will occur to the feeder. By analyzing the transformer loading as shown, the hosting capacity is identified. It is worth mentioning that, in the graph, the power that must be used for analysis is the one that represents the minimum value, since OpenDSS adopts positive the flux that leaves the feeder to the network, and negative the flux that comes from the network and enters the transformer.

VIII. CONCLUSION

This work presented a probabilistic approach to determine the HC of distributed photovoltaic generators in the electricity distribution system. The use of the Monte Carlo method for the analysis of HC is a differential factor of this work, and, in most cases, this is done in a deterministic way and thus ignoring data that should be present when performing this type of study.

Most of the published works are research focused only on the system transformer or only on the network connection points. And as it was seen, it is important to carry out both punctual and feeder analyzes and this is another differential of this work. As stated, all the research developed was based on real data for the probability distributions, making it gain strength and solidity to reach the conclusion of the exposed results.

It is important to point out that the HC is dynamic, as it depends on random variables and at each point of the electrical system there is its own characteristic, causing the HC to change from one point to another. Thus, it is not correct to generalize it to the entire EPS model, however, with the help of Fig 11, it can be concluded that the ideal HC for this distribution system would be between 60% or 70% of photovoltaic penetration level, because in these PL values there are not so many voltage violations, which as seen is the most worrying indicator, and thus the electric energy concessionaire will be able to use techniques to mitigate this and other impacts caused to the grid, through the installation of battery banks or reallocation of consumers to other phases, for example.

The simulation process was implemented through the Python programming language connected via DLL with OpenDSS and executed on an Intel® Core (TM) i7-2670QM CPU @ 2.2 GHz computer with 4 cores, 8 logic processors and 8.0 GB of RAM spending approximately 2 hours and 20 minutes for the total power flow simulation.

ACKNOWLEDGEMENTS

The authors would like to thanks CNPq, CAPES and FAPEG for the financial support and IFG for the structure and material.

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