

PV Hosting Capacity of LV Distribution Networks using Smart Inverters and Storage Systems: A Practical Margin

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Abstract: This work proposes an approach to evaluate a practical margin for photovoltaic (PV) generation hosting capacity of low voltage distribution networks. This hosting capacity (HC) is determined considering the randomness of the connection points and is supposed to be the maximum value of PV penetration up to which the utility can authorize any interconnection without performing additional case studies. Smart inverter control strategies and battery storage systems are used to avoid costly network expansion solutions. The simulations are performed using actual solar radiation data and residential demand profiles. The results show an increase in the network HC, bringing benefits by deferring network investments such as conductors and asset upgrades.

1. Introduction

The connection of photovoltaic generation in low voltage distribution networks has grown rapidly in recent years. Photovoltaic (PV) microgeneration is characterized by low capacity factor and high intermittence due to non-controllable external factors. Particularly in Brazil, the expansion of PV microgeneration has been intensified after the publication of regulatory resolutions in 2012 and 2015 by the National Electric Energy Agency, in which the credit's compensation model regarding the energy injected into the grid is one of the main benefits to the consumer.

However, the PV penetration increase may lead to voltage regulation and thermal capacity problems, energy losses increase, undesired operations of protection system, phase unbalance and harmonic injection [1]. Authorities and distribution operators want to know the amount of PV that can be connected to the network without violating any of the operating conditions defined by regulations, in order to preserve the system integrity.

Thus, the concept of Hosting Capacity (HC) was introduced, representing the maximum amount of distributed generation (DG) that the distribution network can accept respecting the operational limits [2]. This maximum value is usually obtained by optimization methods that result in specific situations of DG allocation. However, this optimal solution rarely occurs in a real network, given the unpredictable characteristics of DG installation, since it is up to the customer to decide where to connect.

In this work, we propose a more effective approach to obtain the value of hosting capacity that does not cause violations in the system, regardless of where the DG is connected. This value will be referred to as the practical margin of HC, since it represents the margin of DG penetration up to the point where the distribution operator can be reasonably certain that no operating constraint will be violated. The practical aspect comes from the fact that it permits the electric utility to authorize any new DG connection without performing any additional analysis to determine if the penetration level is below this value. This would speed up the process of authorization of DG

connection to the network. It should be noted that once the practical margin of HC has been reached, new DG units can still be connected to the network. However, additional studies must be conducted regarding the specific situation that the feeder will be submitted to, in order to ensure that this new DG unit will not cause violations.

The main problems caused by high level of PV penetration are overvoltage and thermal capacity violations of network assets (conductors, transformers, etc.). Usually, these problems are prevented by network expansion solutions such as conductor and asset replacement, which have high costs. This paper presents a proposal to reduce reinforcement requirement and conventional expansion solution costs by utilizing smart inverters and battery energy storage system, bringing benefits by postponing network investments.

Smart inverters are able to reduce the effects of PV penetration increase by performing active power curtailment and/or reactive compensation. These devices can provide variable control depending on the voltage level, acting on the injected active power limit (Volt-Watt control) or reactive compensation (Volt-VAr control). The Batteries system also helps preserve the integrity of the grid and can be programmed to absorb excess photovoltaic energy generated and store it for later use.

In the literature, several methods for determining the feeder's hosting capacity have been proposed [2]-[10]. A review of methods and strategies to prevent overvoltage in low voltage grids with PV is presented in [3]. Practical options for increasing HC are evaluated in [4]; however, the location of PV installation is fixed, somewhat limiting the analysis. A stochastic analysis taking into account randomness in the location of DG is performed in [5] and [6], however these studies use only hourly demand and irradiance profiles and few steps of penetration. In [7] and [8] the HC is investigated using a seasonal analysis of demand and irradiance, but it includes only a few variations in the analyses such as a summer or winter day and irradiance for sunny or cloudy conditions. The works [2], [9] and [10] performed the photovoltaic HC evaluation in distribution networks, but they do not consider changes in the demand and irradiance profiles,

thus limiting the results by not taking into account variations in these variables.

Hosting capacity computed by traditional methods is used for determining if a feeder has reached the maximum permissible amount of DG. A method widely used by electric distribution companies is to take a percentage of the peak load of the feeder, typically 30% [2]. Thus, if a feeder has an annual peak load of 50 kW, the maximum amount of DG installed would be 15 kWp. However, studies conducted by Electric Power Research Institute have shown that there is only a small correlation between the annual peak load and the hosting capacity [11]. Therefore, adopting a fixed HC percentage for all feeders is not appropriate; instead, the value determined by the method proposed in this paper can overcome the limitation of underestimating or overestimating the allowable amount of DG, besides allowing to obtain HC with the use of controls available on smart inverters.

The practical margin of HC, henceforth just referred to as HC, is evaluated considering the randomness of the PV connection points, smart inverters controls and batteries. The OpenDSS simulation tool [12] is used to analyse sequential operating points that vary according to the availability of solar radiation and residential demand, by dynamic power flow solutions. Actual irradiance data and residential demand profiles are used.

The objective of this paper is to develop a stochastic simulation methodology to obtain a value of HC that enables the electric power utility to authorize new DG connections without the need to perform a case-by-case analysis for each customer request. The adoption of the determined HC can accelerate connections of distributed energy resources in the distribution network, since new DG units can be installed while the penetration value is below the determined margin.

The novelty of this work is to analyse the hosting capacity using yearly profiles of demand and irradiation, selecting the period with the highest occurrence of reverse power flow, which is the condition in which the negative effects of high photovoltaic penetration are intensified. A reduction in the resolution of stochastic simulations is also proposed, resulting in an increase in the number of simulations maintaining a high correlation between the 1- and 10-minute resolution results.

The paper is organized as follows: section 2 briefly describes the main features of photovoltaic generation system; section 3 discusses about battery energy storage systems and section 4 about the concepts of penetration level and host capacity; section 5 explains the proposed methodology to evaluate the HC; section 6 presents the simulation results; and finally, section 7 highlights the conclusions.

2. Photovoltaic generation system

A PV generation system consists basically of photovoltaic modules and an inverter. A photovoltaic module is composed of cells connected in series and/or parallel arrangements to produce voltage and current adequate to the practical use. When there is solar radiation incidence on a module, an electric potential difference arises at its terminals due to the conversion of solar energy into electricity by the photovoltaic effect.

The inverter can be a simple DC-AC converter which provides an output signal with amplitude and frequency according to the nominal values of the system. The inverters

generally use solid-state electronic switches such as insulated gate bipolar transistors or thyristors triggered by a gate signal, which is intended to generate the output signal.

Currently, the residential-scale PV inverters can offer more features than DC-AC conversion with maximum power point tracking. The smart inverters have control functions able to limit the active power and perform reactive compensation [13]. The control strategies usually found in residential-scale smart inverters are [14]: maximum generation limit, fixed power factor, Volt-VAr and Volt-Watt. These controls act in voltage regulation either by reducing the active power injection or by reactive compensation [15].

The Volt-VAr control performs a reactive compensation according to: 1) the voltage at the PV coupling point, 2) the amount of reactive power available from the inverter at a given moment and 3) the set points of the curve shown in Fig. 1 (a).

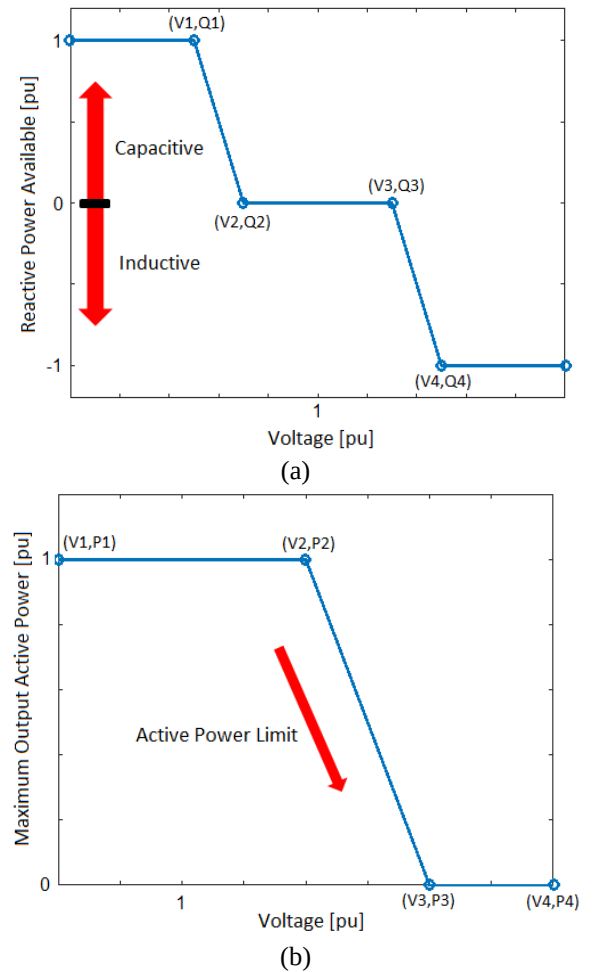


Fig. 1. Control operation curves.
(a) Volt-VAr, (b) Volt-Watt

The reactive power output value is defined as a percentage of available reactive compensation, given the current active power and apparent power of the inverter. The inductive reactive power absorption is triggered if the voltage exceeds the point V3 in the curve. Alternatively, if a voltage below the value set at point V2 is checked, the capacitive reactive power is supplied to the grid in order to keep acceptable voltage level. Generally, the PV connected to the

network causes voltage increasing, and consequently in high active power generation periods, the inverter will operate in the inductive region of the curve [14].

The controls that act directly on the active power, Volt-Watt and maximum generation limit, imply a reduction of the power injected in the network, avoiding the violation of voltage level and also the thermal capacity of conductors and transformers [16].

The Volt-Watt control keeps the voltage at the terminals of the PV system within predefined voltage level, limiting the maximum generation according to the coupling point voltage level and the set points illustrated in Fig. 1(b). For situations where high PV generation and low demand can result in overvoltage, the Volt-Watt control function can be used to reduce the maximum active power of PV systems and therefore, keep the voltage level within the standard. In addition, this control can also be used to mitigate thermal capacity problems by adopting conservative set points while managing the voltage level [13]. Consequently, this control at the PV inverter can allow an increase in the HC of the distribution system.

3. Battery energy storage system

The residential consumer typically has a high electricity demand in the early morning and evening periods, presenting low consumption during the rest of the day. However, due to the natural conditions of the solar radiation, PV systems present their generation peak at around noon. Consequently, PV will inject most of its energy in the distribution system during the daytime and at night the customer will need to make use of the energy from the grid. In this way, the use of Battery Energy Storage System (BESS) is becoming attractive because it allows the use of the excess energy when needed [17].

In conventional operation mode, residential-scale BESS charges the excess energy generated by PVs (net demand) and discharges during the night at a rate proportional to the demand [13]. The discharge period ends when the PV begins to generate energy again in the next day. The use of BESS with this operation mode suffers from two limitations. The first is related to the uncertainty of daily demand and consequently the system may not be able to fully discharge the battery overnight. This issue becomes even more critical in cases where demand is significantly low. The second limitation occurs when the BESS reaches the fully charge early (before midday) because the energy remaining from the previous discharge cycle has not been complete.

Therefore, the conventional operation mode may not provide significant benefits in terms of voltage violation and thermal issues, because the batteries may not be able to absorb excess PV generation during critical periods (around noon), and would not provide an effective increase in the HC of the network.

In this paper the BESS was based on the advanced operation mode [13], which provides at least 50% of its available capacity in the charging cycle at noon (moment with greater probability of overvoltage occurrence) and ensures that the battery is fully discharged during the night. In order to cope with overvoltage problems caused by PVs, the voltage control feature is activated when the voltage at the PV

coupling point reaches the regulatory limit, increasing the charging rate to reduce the voltage level.

4. Photovoltaic penetration and hosting capacity

According to the National Renewable Energy Laboratory [18], the PV penetration level is defined as the ratio of peak photovoltaic power (PV_{power}) to peak load apparent power on the feeder (S_{max}) as shown in (1).

$$PV_{Penetration} = \frac{PV_{power}}{S_{max}} \times 100 [\%] \quad (1)$$

Due to the need to estimate the allowable PV power in a distribution network in order to avoid undesired effects, the concept of hosting capacity was established. According to [6], [11] and [19], the distributed generation penetration level supported by the network can be determined as maximum or minimum hosting capacity. The maximum hosting capacity is usually obtained by an optimization process of the DG allocation and the injected power per node of the distribution network. However, this maximum value is an ideal situation than can only be reached if the optimal allocation conditions are satisfied. However, in a real network, this situation will hardly occur, since the DG connection is a random process and is not subject to the utility decision.

In contrast, the minimum hosting capacity is a penetration level in which there is no violation of the metrics regardless of the configuration in which the DG is connected, and therefore, this value can be adopted as a safe penetration margin. The practical margin of HC proposed in this paper is more adherent to this last concept. This HC value is more practical because it can be adopted by the electric power utility to expedite new DG connections, since more PV can be added at any feeder location without causing metric violations while PV penetration level is lower than this determined margin.

In a typical feeder, voltage amplitude reduction is observed along the circuit due to the voltage drop at radial conductors. As the PV system model resembles a current source, the power injection into the network increases the voltage level at the coupling point. Therefore, if the grid's voltage is below the nominal values, the PV can bring benefits to the distribution network. Conversely, if there is a large amount of PV, overvoltage above the limits can easily occur. Therefore, this behaviour must be taken into account in determining the HC.

Another factor that influences the HC is the position of the PV along the feeder. If the PV is located far away from the substation, the permissible generation level without violating the overvoltage limit will be lower. Conversely, the closer it is to the substation, the amount of power injected into the network may be higher, thus increasing the HC [9].

Each element in an electrical system is characterized by the maximum supported current, which can also be called as the thermal capacity. A high PV penetration can increase the network current, leading to violation of the permissible thermal limits and lifespan reduction of the assets [1].

Therefore, the HC main limiting factors are the voltage level and thermal capacity, with the overvoltage being the most restrictive aspect for increasing penetration

levels [2][19][20]. This is mostly due to the fact that in a residential feeder the demand peak of the PV generation usually occurs at the condition of lower load, causing overvoltage and thermal limit violation [21]-[24]. For this reason, in this paper the focus of the HC calculation is given on the fulfilment of these two factors operating criteria.

5. Proposed methodology

This section presents the proposal to evaluate the practical margin of HC of a low voltage distribution network using stochastic evaluation. It will be detailed the metrics used to evaluate violations, simulation softwares used, the test system, DG data, demand and irradiance profiles.

5.1. Stochastic evaluation

In a low voltage distribution network, the PV connection point is hard to predict, since its acquisition and use are related to a personal decision by the customer. Therefore, deterministic optimization methods often tend to overestimate the HC, since the maximum value calculated is unlikely to be allowed before network updates. For a more realistic evaluation of the HC, it is necessary to use stochastic methods, which depicts a phenomenon that changes in an unpredictable way and thus presents a probabilistic characteristic.

The proposed approach to assess the HC is based on stochastic simulation, but with the main purpose of keeping it simple and replicable by any utility. Therefore, the practical approach consists of the following steps: 1) Define the maximum number of PV systems to be installed; 2) Randomly sample which consumers will have PV installed and assign it a control; 3) Perform the network dynamic power flow with this random configuration; and 4) Check the metrics. If at least one of the metrics is violated, the number of PV systems to be randomly connected is reduced by one unit and the process returns to step 2). The process runs continuously until it reaches a number of PV systems that do not violate any of the metrics. The flowchart of the algorithm is illustrated in Fig. 2.

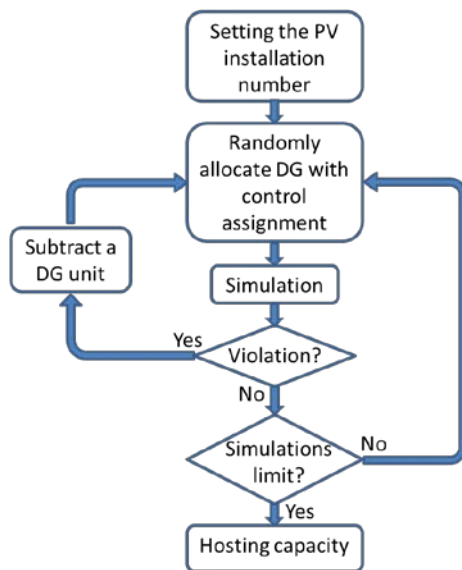


Fig. 2. Flowchart of the algorithm to determine the HC

It is necessary to highlight that the PV number set in step 1 must be high enough to cause a metric violation. In step 2, a MATLAB script was used to randomly allocate the DG among the customers, restricted to the number defined in the previous step. The simulation tool used to perform the dynamic power flow and smart inverter controls operation in the step 3 is the OpenDSS. The implementation of the specific control for the BESS is done in MATLAB and a loop interaction with the OpenDSS is done via the COM interface. The metrics check described in step 4 is performed by a MATLAB script in which the basis of the flowchart has been implemented. The proposed algorithm provides a practical HC margin considering the randomness of PV rooftop installations in the low voltage distribution system.

Since the possibilities of PV allocation for the same level of penetration may be largely depending on the size of the system, and also on the number and type of controls that are being used, to finally determine the HC it is required that a large number of simulations are performed for the same PV penetration level. These simulations, however, will have different connection points and control strategies between them. If during these simulations at least one of the metrics is violated, the number of PV systems is reduced again by one unit and the whole process repeats from this number of PV systems. At the end, the HC will be the maximum amount of PV systems, randomly allocated, that do not cause violation for different configurations of connection points and control strategies. In other words, the HC is given by the PV penetration level (%) calculated by (1) at the end of the process.

It is important to note that when the algorithm reduces a DG unit because it has not reached the total number of simulations, it only reduces the number of customer possibilities that will be allocated with DG, not a consumer in specific. Thus, several consecutive random simulations are required to achieve a convergent HC result.

The approach proposed in this paper calculates the margin of hosting capacity that allows the electric utility to authorize new PV connections up to this limit. The knowledge of this HC value provides an acceleration in the process of authorization of PV connection, since new connections could be admitted until this value is reached. When reached, it may still be possible to add new PV to the system, but then it will be necessary to perform a study regarding the specific situation that the feeder will be submitted in order to check if this new unit will not cause violations.

As a realistic example of how the proposed methodology may be applied, it can be cited that in some electric power utilities, a case-by-case analysis is usually performed for each DG connection request received, before the authorization to operate is granted. With the proposed methodology, the electric power utility may authorize DG units addition to the network without causing any metric violation until the specified HC margin is reached, no longer needing to do a specific analysis for each new connection requested.

The algorithm proposed in this work can be applied to microgrids, since they are characterized by small-scale versions of the power system which can generate, distribute, and regulate the flow of electricity to consumers at a local level. The generation in these subsystems is mainly composed of DER, such as solar photovoltaic modules, small wind

turbines, other small renewables (such as biogas digestors) and energy storage [25][26].

Therefore, the use of the methodology presented in this paper for obtaining the HC, associated with smart inverters and the advanced control of BESS, make it possible to preserve the operational integrity and reliability of the microgrids, following a worldwide trend of growth of this type of grid.

The simulation tool used to perform the dynamic power flow and smart inverter controls operation is the OpenDSS [12]. The implementation of the specific control for the BESS is done in Matlab and a loop interaction with the OpenDSS is done via the COM interface.

5.2. Voltage and thermal capacity metrics

The metrics used to evaluate violations are in accordance with the standards adopted in Brazil to assess voltage level and thermal capacity. The voltage range classification for the distribution system is defined by the National Electric Energy Agency according to Table 1.

Table 1 Voltage level classification (<1kV)

Range	Measured voltage (V_M) in pu
Appropriate	$0.92 \leq V_M \leq 1.05$
Precarious	$0.87 \leq V_M < 0.92$ ou $1.05 < V_M \leq 1.06$
Critical	$V_M < 0.87$ ou $V_M > 1.06$

The index for precarious range (DRP) and the index for critical range (DRC) are determined by (2) and (3), where nlp and nlc are the number of measures in the precarious and critical bands, respectively. The set of measures required to calculate these indexes are composed of 1008 measures obtained at each consecutive 10-minute interval, thus totalling a seven-days measurement period. According to the regulation, the maximum limit of DRP and DRC are, respectively, 3% and 0.5%.

$$DRP = \frac{nlp}{1008} \times 100 \text{ [%]} \quad (2)$$

$$DRC = \frac{nlc}{1008} \times 100 \text{ [%]} \quad (3)$$

The criteria used for thermal capacity analysis are in accordance with the Brazilian standard NBR 5416:1997 that deals with power transformers loading. The standard determines that the transformer must withstand an overload for a given time and must not exceed 150% of its rated capacity. This allowed overload value may be reduced due to some factors such as external temperature and loading cycle.

Since the loading cycle of transformers has great variability, it was adopted a conservative value to assess the thermal capacity. It was assumed an initial load of 70%, an external temperature of 40°C and a permissible overload period of 30 minutes, resulting in a maximum overload of 129%.

5.3. Test system

The low voltage (LV) network used to evaluate the HC was the IEEE European Low Voltage Test Feeder [27], which has 55 consumers distributed between the three phases and

nominal phase-to-neutral voltage of 240 V. As can be seen in Fig. 3, phases A, B and C have, respectively 21, 19 and 15 single-phase consumers, representing approximately 38%, 35% and 27% of the total number of consumers. The PV random allocation has been done taking into consideration the phases.

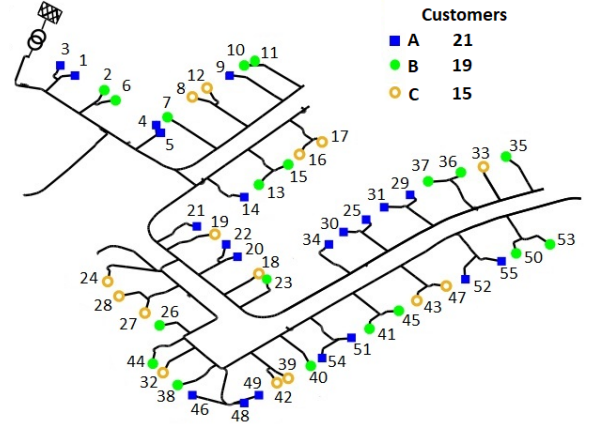


Fig. 3. Distribution of customers by phase

The LV network has been connected to the medium voltage (MV) 4.16 kV network IEEE 13 Node Test Feeder [27] at node 634 of the latter. The potential interactions with the MV network as large amount of PV is connected to the LV network have also been considered as limiting to the hosting capacity [28].

5.4. Demand and irradiance profiles

Demand and irradiance profiles with 1-minute resolution were used in the simulations. This resolution becomes necessary to properly assess the inverter controls performance, since variations in the solar radiation occur continuously and the controls act in real time [29]. As required by the voltage metric, profiles with seven days period were used.

Due to the difficulty to obtain actual load profile with high resolution, the tool CREST Demand Model [30] was used to produce residential energy consumption data with 1-minute resolution, based on patterns of daily occupation and activity. Different annual demand profiles were used for each consumer.

A maximum annual load of 80 kVA was measured for the LV network with the 55 demand profiles. This value was adopted as S_{max} in equation (1) to define the hosting capacity and in the definition of the rated power to the LV/MV transformer, 112.5 kVA, which is the nearest higher commercial value in Brazil.

The annual irradiance profile with 1-minute resolution was obtained from the Project Sonda of the National Institute of Space Research [31]. This project has measurement stations scattered throughout Brazil for solar and wind energy resources. The 2015 year measurements of Natal station located in the state of Rio Grande do Norte was used.

Then, an annual simulation was performed with the demand and irradiance profiles to determine the period of seven consecutive days with the highest PV energy exported from the LV to MV network (reverse flow). The reason for the use of seven days in which there is greater energy

exportation, instead of the period of greater irradiance, is to have an operating condition where overvoltage and thermal capacity issues are intensified, since this period corresponds to the worst combination of high generation and low demand. Therefore, analysing the chosen condition implies that if in the chosen period there is no violation of metrics, there will be no violation in any other period of the year.

The data from the selected 7-day period of consumer demand and irradiance profiles were used in all simulations performed in this work. Residential demand profile is different for each consumer and the irradiance profile was considered the same for all PV units due to the proximity of customers. Using the same irradiance profile for all PV makes the assessment conservative because it assumes that there is no shading and the panels are not influenced by the position of their installation.

Just to illustrate the chosen profiles, one single day was selected from the seven day interval. The day with the highest irradiance is show in Fig. 4 and the demand profile of one consumer during a day is presented in Fig. 5.

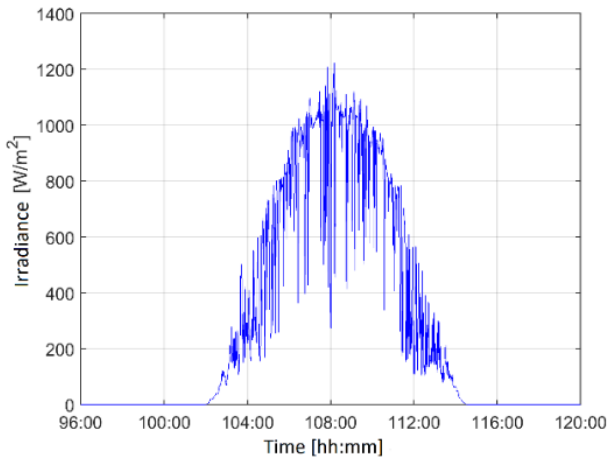


Fig. 4. Day with greater radiation (within the selected 7-day interval)

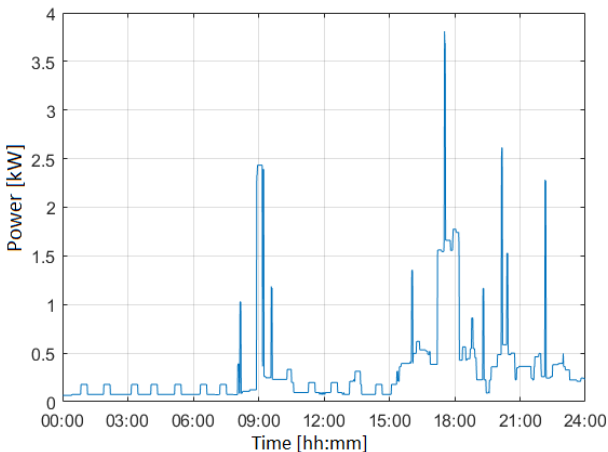


Fig. 5. Example of consumer demand profile

5.5. PV, inverters and BESS data

Studies conducted in Brazil have shown that approximately 80% of the PV generation units are residential and about 72% of them have rated power below 5 kWp [32]. Therefore, this rated capacity was adopted in this work.

Initially, the hosting capacity was evaluated with PV

without the smart inverter controls. Subsequently the Volt-VAr, Volt-Watt and BESS controls and some combinations between these controls were analysed. The Volt-VAr control settings shown in Fig. 1 (a) were as: $V1=0.95$, $V2=0.96$, $V3=1.04$ and $V4=1.05$. Likewise, the Volt-Watt control settings shown in Fig. 1 (b) were as: $V2=1.04$ and $V3=1.05$.

The batterie storage capacity was considered as 10 kWh and the maximum power of the battery converter as 5 kW. The minimum and maximum State of Charge (SoC) were set as 10% and 90%, respectively. For the BESS control with advanced operation mode, it was considered that the charging period is between 6 AM and 6 PM and the discharging during the rest of 24 hours.

6. Results

This section presents the results and a comparison of the HC calculated by deterministic and stochastic methods, initially without combining the DG control methods. The stochastic method that is the focus of this paper, results in a practical margin of hosting capacity that can be adopted to prevent networks violations regardless of the DG location. Subsequently, the analysis of six cases is made with the combination of different DG control methods. Normally, the customers want the best self-cost-effectiveness and this alternative may not to be the best network solution. In the following three study cases, it is analysed the situation when the electricity regulatory agency decides which DG control method has to be used by the customers. Finally, the number of simulations is expanded in order to increase the amount of DG allocation possibilities repeating all performed analyses.

6.1. Maximum hosting capacity (deterministic)

The maximum HC (obtained by an optimization model) for the simulated controls is presented in Table 2, where PV means the number of 5 kWp PV units connected. It is worth emphasizing that these values were only calculated in order to be compared with the proposed approach. Because it is an optimized allocation method, this DG location setting is unlikely to occur in a real distribution network.

Table 2 Maximum hosting capacity

Case	PV	HC [%]
Volt-Watt + BESS	55	343.75
Volt-VAr + BESS	52	325.00
Volt-VAr + Volt-Watt	43	268.75
BESS	43	268.75
Volt-Watt	36	225.00
Volt-VAr	36	225.00
PV without control	21	131.25

The strong relation between active power and the control of voltage levels in LV network [16], [33] is validated by the results, where the controls related to active power result in larger hosting capacities. The controls that are combined with BESS present the best results for the HC. However, this option has an average cost 2 times greater than the other solutions [34].

6.2. Practical hosting capacity margin (stochastic)

Table 3 shows the results for the HC obtained by the stochastic approach.

Table 3 Practical margin of hosting capacity

Case	PV	HC [%]
Volt-Watt + BESS	34	212.50
Volt-VAr + BESS	27	168.75
Volt-VAr + Volt-Watt	40	250.00
BESS	19	118.75
Volt-Watt	14	87.5
Volt-VAr	8	50.00
PV without control	6	37.50

The comparison between the stochastic and deterministic results shows a large reduction in the HC for all cases. This shows the importance of using stochastic evaluation for calculating a more realistic value of HC for distribution network. The HC reduction of the stochastic approach is due to the non-optimal allocation of the PV units. For example, in some cases the random allocation has designated most of the PV units to consumers of the same phase and at the end of the feeder, thus causing overvoltage violation in the respective phase and consequently making it impossible to achieve the maximum HC.

The verified penetration level for all simulated controls maintained the same efficacy order in both approaches. In the stochastic approach, a difference was observed in the HC with Volt-VAr and Volt-Watt controls, evidencing the advantage of the latter in maintaining voltage levels.

The best result was for the Volt-VAr + Volt-Watt control. This solution practically did not suffer HC reduction in the stochastic approach and does not include additional costs with storage system. However, this control presents a high active power curtailment and, consequently, a lower PV capacity factor.

Comparing the HC result to the condition of DG without control it is noted that the value of 37.5% was relatively close to 30% as proposed in the maximum annual peak load method used by some electric utilities [2]. However, adopting the methodology proposed by this work will result in a correct evaluation of feeder HC and also has the benefit of being able to evaluate the amount of GD allowed with smart inverter controls.

The HC determined in this section are consistent with those found in the literature, about 30% for PV with conventional inverters, and showed an increase with the use of smart inverter controls [2][3][8][11]. Therefore, the results demonstrate the effectiveness of the proposed methodology.

6.3. Control associations analysis

In the stochastic simulations performed above, the random process was executed only for sampling what consumer would have PV, but the same control was assigned to all customers. In this section, the randomness of the control strategy was included in the stochastic process. This scenario increases the number of combinations, including the possibility of the Volt-VAr and Volt-Watt controls to be enabled on different inverters in the same network.

Three cases were simulated considering one control at each PV, two controls at each PV, and one or two controls at each PV, resulting in the following possibilities for each consumer as shown in Table 4.

Table 4 Association possibilities of DG control methods

Control Methods	Case 1	Case 2	Case 3
BESS	✓		✓
Volt-Watt	✓		✓
Volt-VAr	✓		✓
No PV	✓	✓	✓
Volt-VAr + Volt-Watt		✓	✓
Volt-Watt + BESS		✓	✓
Volt-VAr + BESS		✓	✓

The HC for these cases is presented in Table 5. As can be seen, case 2 resulted in the higher HC and case 1 presented the worst result. However, it should be noted that both cases correspond to the range of values found when the same controls were used in all PV in the previous simulations. As expected, in case 3, which merged the two possibilities, the HC was between the maximum and minimum values of these two cases.

Table 5 HC with controls association

Case	PV	HC [%]
1	18	112.50
2	34	212.50
3	24	150.00
4	14	87.50
5	24	150.00
6	17	106.25
7	12	75.00
8	15	93.75
9	17	106.25

In addition to the unpredictability of PV connection, it may be important to analyse the possibility of existing consumers with an old PV system which has no smart inverter controls (conventional inverters). New cases were created considering also this possibility for each consumer, and were renamed to Case 4, 5 and 6, respectively as shown in Table 6.

Table 6 Association possibilities of DG control methods including conventional inverters

Control Methods	Case 4	Case 5	Case 6
BESS	✓		✓
Volt-Watt	✓		✓
Volt-VAr	✓		✓
No PV	✓	✓	✓
PV without control	✓	✓	✓
Volt-VAr + Volt-Watt		✓	✓
Volt-Watt + BESS		✓	✓
Volt-VAr + BESS		✓	✓

Table 5 shows the HC reduction by the addition of the possibility of existing in the system consumers that have PV without the presence of any type of overvoltage control. Although there was a HC reduction, the inclusion of this possibility provides a more realistic scenario that may be present in the distribution network.

6.4. Regulation imposed control analysis

In some countries, the smart inverter controls are imposed by regulations. In Germany, for example, since 2012 it has been determined that the inverter cannot generate more than 70% of its nominal capacity [35]. In Australia, inverters are conditioned to use the Volt-Watt control [36] and in California, Rule 21 established the use of Volt-VAr control [37].

Generally, after the establishment of a control standard to be adopted in a region, all customers who purchase DG will be required to install certified equipment for compliance with the regulation. However, installations in operation prior to this date are not required to purchase a new equipment. This fact implies that after a certain interval from the imposed rule, there will be the presence of inverters operating with and without control.

As the HC for the condition where the customer has PV without control is 6 units (see Table 3), the random process was limited to allocate at most this number of PV without control. The reason to limit this number is based on the fact that after the compulsory use of controls, the number of pre-existing PV without control could never be higher than the HC calculated for this condition.

In the simulations performed in this section, it was defined that only one control would be enabled, thus the inverters in the same network are not allowed to operate with different control strategies. The Volt-VAr + Volt-Watt control was still considered because both functions are active in the same inverter. Three cases were simulated considering the Volt-VAr, the Volt-Watt, and Volt-VAr + Volt-Watt controls, resulting in the following possibilities for each consumer as shown in Table 7.

Table 7 Control association possibilities imposed by regulation

Control Methods	Case 7	Case 8	Case 9
Volt-Watt + BESS		✓	
Volt-Watt		✓	
Volt-VAr	✓		
Volt-VAr + BESS	✓		
BESS	✓	✓	✓
No PV	✓	✓	✓
PV without control	✓	✓	✓
Volt-VAr + Volt-Watt			✓
Volt-VAr + Volt-Watt + BESS			✓

The HC for these cases is presented in Table 5. The results, once again highlights the effectiveness of the Volt-Watt control over the Volt-VAr in the mitigation of problems related to overvoltage and thermal capacity. Considering that the stochastic HC without use of control was 37.5%, the adoption of any of the three solutions would result in a considerable penetration increase.

The simulated cases in this section present a condition closer to a real distribution network situation, and the determined HC remains consistent with the results obtained so far in practical studies, as in [2], [3], [8] and [11].

During the definition of which control should be adopted, the regulatory agencies should take into account that the Volt-VAr control is a good alternative because it does not reduce the active power generation, but it increases the losses due to the reactive compensation. The Volt-Watt control can allow a greater penetration, but if configured with very aggressive generation reduction, it can discourage the consumers to acquire PV. Despite its good effectiveness, BESS control implies a considerable increase in installation costs, consequently many consumers will not have the financial availability to use this solution.

6.5. Increase in the number of simulations

Normally, the electric power utilities do not collect measures with a 1-minute resolution of residential demand,

being more common to find these data in hourly resolution. However, the voltage metric uses measurements with a 10-minutes interval. Thus, to fit this difference, the demand resolution was converted to a 1-hour interval and later the hourly levels were replicated to the 10-minute intervals within each same hour. The irradiance was converted directly to the 10-minutes resolution averaging each interval in order to make it compatible with the simulation step.

The new resolution reduces the computational effort for each simulation and consequently allows executing a larger number of stochastic simulations. After the resolution conversion, the procedure of Fig. 2 was executed increasing to 1000 simulations in each case analysed. In order to check the adequacy of this number, Fig. 6 shows the evolution of the mean DRP metric as the number of simulations increase. As can be verified, at 1000 simulations the metric is already at a stable level, indicating that this number is sufficient to capture the variability of possible allocations scenarios.

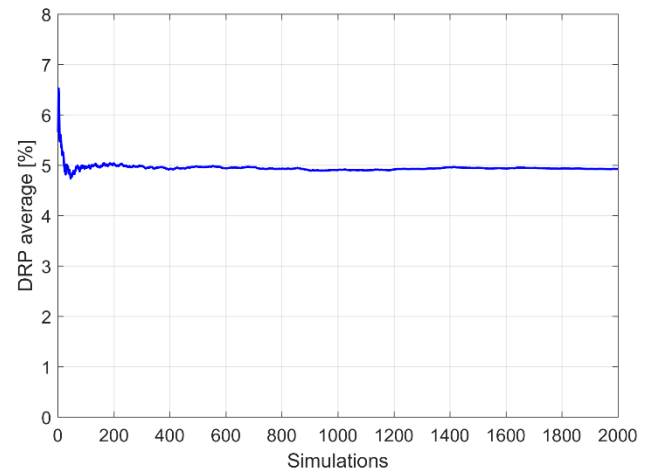


Fig. 6. DRP average of 2000 simulations

The new hosting capacity results for the 10-minutes resolution is presented in Table 8.

Table 8 HC with controls association

Case	HC [%]	Case	HC [%]
Volt-Watt + BESS	212.50	1	56.25
Volt-VAr + BESS	118.75	2	106.25
Volt-VAr + Volt-Watt	250.00	3	156.25
BESS	75.00	4	50.00
Volt-Watt	56.25	5	62.50
Volt-VAr	37.50	6	81.25
PV without control	25.00	7	43.80
		8	56.25
		9	75.00

The results with 10-minute resolution showed in general a HC reduction. A reason for the HC reduction is that the voltage metric at the 1-minute resolution uses measurements every 10 minutes (ignoring values between this range), and the arithmetic mean calculated in the conversion from 1 to 10 minutes resulted in a higher level. Therefore, the simulations with average of 10 minutes deal with higher values and hence it is more difficult to avoid overvoltage. Even though, there was no hosting capacity reduction in Volt-VAr + Volt-Watt and Volt-Watt + BESS controls, thus demonstrating a robustness of these controls to keep the voltage levels within the regulatory levels.

To assess if the new simulation step provides reliable results, the PV allocation configurations for the violation

cases in 10-minutes resolution were tested with the 1-minute resolution, because the controls act in real time. The results showed that in 90% of the cases, the metrics violation occurred in both resolutions, meaning that the analysis using the 10-minutes resolution permits to obtain results with satisfactory accuracy at a much lower computational effort. The similarity of the results obtained before and after the increase of the number of simulated cases to 1000 confirms the validity of the determined HC.

7. Conclusions

This paper evaluated the hosting capacity increase through the controls available in smart inverters and battery energy storage system. The proposed approach allowed obtaining a more realistic HC of the distribution network, by taking into account the randomness of the PV connection, and can be considered as a safe penetration margin. The HC calculated by the approach can be adopted by the electric power utility to expedite the authorization of new PV connections, since more PV units can be added at any feeder location without causing metric violations if the PV penetration level is lower than the calculated HC.

The results demonstrated that in relation to allowing a high hosting capacity and presenting a good cost-benefit, the most indicated solution would be the use of the Volt-VAr + Volt-Watt control. When consumers randomly allocated with this control association, the test system can accommodate 40 PV systems among the 55 customers (HC = 250%).

As a single control, the Volt-Watt has confirmed its effectiveness in reducing the adverse effects of high PV penetration in LV distribution networks in comparison with the Volt-VAr, presenting HC of 56.25% for the first and 37.5% for the second. As expected, the X/R ratio present in this type of network provides a greater correlation of voltage control with active curtailment.

Even though Volt-VAr is the least effective control, it still provides 37.5% of hosting capacity, however reactive compensation can lead to increased system losses. Although the Volt-VAr control increases the HC without limiting generation, the reactive compensation increases the losses. The BESS is a good option to increase the HC (75%), and its effect is enhanced when associated with other controls (118.75% with Volt-VAr and 212.5% with Volt-Watt). However, its high cost is still a barrier to its large-scale use.

Simulations that considered a scenario closer to a real network, where only one type of control can be used by customers and that consumers with conventional PV systems (without control) were present, demonstrated that the hosting capacity can range from at least 43.8 to 75%.

8. References

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