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A Comprehensive Assessment of PV Hosting Capacity on Low Voltage Distribution Systems

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***Abstract*— Rooftop PV hosting capacity has become a concern for utilities in scenarios of high penetration due to impacts on voltage quality, such as over/undervoltage and voltage unbalance, and on equipment loading (conductors and transformers). This paper uses a simplified Monte Carlo-based method to analyze this issue, which is applied to 50,000 real LV systems. Results show that it is possible to perform a risk-based analysis of hosting capacity by means of a Lognormal distribution. Furthermore, overvoltage is found to be the most restrictive impact of PV integration; such information can help to guide utility actions to avoid technical violations. Extensive sensitivity studies are also presented to quantify the effects of several factors on the PV hosting capacity. The effects of number of customers with PV generators, PV power factor, voltage magnitude on the MV system, load level and conductor impedances are investigated. It is also shown that the hosting capacity for the entire utility can be estimated by performing simulations only on 1% of the circuits randomly selected. In addition to providing a comprehensive overview of PV hosting capacity in real systems, the method can be used by utilities to improve the management of LV systems with high PV penetration.**

***Index Terms*— Low voltage systems, Monte Carlo simulation, rooftop photovoltaic generation, voltage quality.**

I. Introduction

THE widespread deployment of small-scale photovoltaic (PV) generation in low-voltage (LV) distribution systems (*i.e.*, systems with voltages below 1.0 kV) has become a reality worldwide. In Brazil, for instance, PV installation has been boosted by the document n° 482/2012, issued by the Brazilian regulatory agency, which defines regulation and incentives for PV generators with capacity below 75 kWp. This development, however, can become problematic for utilities if PV penetration levels exceed the hosting capacity of LV systems [1]-[11]. As such, there is an increasing search for a better understanding of LV systems hosting capacity and for identifying simple actions to increase such index.

While PV hosting capacity is a well-known concept and has been widely studied in the past few years [1], [5]-[11], a generalized characterization of this index in a huge set of real LV systems is not yet available. At least three important requirements are not fully understood. First, hosting capacity is generally seen as a system-specific index, *i.e.*, it cannot be applied to other systems without further simulations. Second, overvoltage has been claimed to be one of the main impacts of PV generators [12]-[16]. However, existing information relies mostly on analysis of few systems and there is a lack of wide-scale studies supporting this claim. Third, the quantitative impact of generator and circuit parameters on the hosting capacity has not been properly addressed before.

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Because of the random nature of PV generation, many assessment techniques are based on Monte Carlo simulations [5]-[8]. These works have solved several challenges associated with PV integration by developing techniques to model the uncertainties of the problem (PV location, PV rated capacity, PV phase connection, load profile etc.). These modeling techniques have greatly contributed to our understanding on which are the most important variables to be included in a PV impact assessment study. However, the existing Monte Carlo simulation approaches have not been widely adopted by utilities yet, due to difficulties to obtain proper input data for all random variables of the problem. In this context, it is useful to investigate a simplified Monte Carlo-based approach requiring only information readily available to the engineering department responsible for studies of system reinforcements and expansions.

In order to support the above needs, this paper provides an exhaustive investigation of PV hosting capacity on 50,000 real LV (secondary) systems, representing around 75% of the circuits from a distribution utility located in the Southeast of Brazil. This investigation was conducted by using a simplified Monte Carlo simulation method that caters for PV generation impacts and takes advantage of information that is available to planning engineers. The following operational limits are monitored simultaneously: voltage quality (over/undervoltage and voltage unbalance), conductor thermal capacity and transformer overload. This paper proposes the use of risk-based analyses as a simplified, yet useful means of assessing the characteristics of PV hosting capacity in all LV systems from an entire utility. It also identifies overvoltage as the most restrictive impact of PV generation, and quantifies, through extensive sensitivity studies, the effects of several generator and system characteristics on the PV hosting capacity. With such studies, effective actions to improve the PV hosting capacity of LV systems are identified. The findings of this work can guide utilities on four fronts: (1) risk-based identification of PV penetration levels that threaten the adequate operation of distribution systems; (2) estimation of how PV hosting capacity will evolve over the years due to load/generation variations; (3) identification of the most effective actions to improve the system hosting capacities; (4) identification of the probabilistic PV hosting capacity of new or upgraded LV systems without the need to perform further simulations.

This paper is organized as follows. The main characteristics of the investigated systems are described in Section II. Section III introduces the method used to determine the PV hosting capacity. The results obtained by applying the method to thousands of systems are analyzed in Section IV. Sensitivity studies are presented in Section V. Section VI proposes a simplified method to obtain a risk-based hosting capacity curve. Finally, a discussion is provided in Section VII and the main conclusions are summarized in Section VIII.

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II. Overview of the Characteristics of the LV Distribution Systems

Prior to presenting the Monte Carlo simulation method, the results and analyses, this section provides an overview of the main characteristics of the LV systems in the studied utility. Table I presents some general information about the systems. A total of 50,000 radial LV systems, serving more than 1.8 million customer units in 98 cities, were analyzed. The main rated powers of the service transformers are 30, 45 and 75 kVA (more than 90% of the service transformers have one of these rated powers). The rated line voltage of the primary feeders is 11.4 kV and 0.22 kV in the secondary circuits. Table II outlines other important characteristics of the 50,000 LV systems. In this table, one can observe that, even when a single distribution utility is considered, systems characteristics are widely diverse, so that is hard to identify representative circuits. Quantitatively, this diversity can be seen by the large standard deviation (50% or more with respect to the average value of all parameters, except for the X/R ratio and conductor ampacity) and by the wide range between 5th and 95th percentiles (*i.e.*, the wide "90% range" shown in Table II). As no representative system can be selected, the approach adopted here is to simulate all systems.

TABLE I
MAIN CHARACTERISTICS OF THE 50,000 RADIAL LV SYSTEMS.

<table>
<tr><th>Parameter</th><th colspan="2">Value</th></tr>
<tr><td>Studied LV systems</td><td colspan="2">50,000 (98 cities)</td></tr>
<tr><td>Customer units</td><td colspan="2">1,836,012</td></tr>
<tr><td rowspan="11">Service Transformers</td><td>Side</td><td>Rated line voltage</td></tr>
<tr><td>Medium voltage</td><td>11.4 kV</td></tr>
<tr><td>Low voltage</td><td>0.22 kV</td></tr>
<tr><td>Rated Power (kVA)</td><td>Quantity</td></tr>
<tr><td>30</td><td>12,966 (25.9%)</td></tr>
<tr><td>45</td><td>20,529 (41.1%)</td></tr>
<tr><td>75</td><td>12,045 (24.1%)</td></tr>
<tr><td>112.5</td><td>2,813 (5.6%)</td></tr>
<tr><td>Others</td><td>1,647 (3.3%)</td></tr>
<tr><td>Total</td><td>50,000 (100.0%)</td></tr>
</table>

TABLE II
KEY PARAMETERS OF THE 50,000 RADIAL LV SYSTEMS.

Parameter	Average	Standard deviation	90% range*
Average X/R ratio	1.01	0.27	0.71 - 1.49
Circuit total length (m)	767.92	391.54	209.13 - 1447.62
Distance from transformer to farthest circuit node (m)	171.13	80.47	70.01 - 316.71
Loading level at noon (% of transformer rated power)	24.96	13.25	4.93 - 47.73
Number of customers per LV system	36.72	22.59	7.00 - 77.00
Number of single-phase customers per LV system	20.41	20.35	0.00 - 59.00
Number of two-phase customers per LV system	13.55	12.70	1.00 - 36.00
Number of three-phase customers per LV system	2.77	3.60	0.00 - 9.00
Average conductor ampacity (A)	82.26	15.52	66.29 - 112.00

*This index provides the lower and upper values that cover 90% of the studied systems. The lower value corresponds to the 5th percentile, while the upper value corresponds to the 95th percentile of circuits characteristics.

III. A Monte Carlo Based Method for PV Hosting Capacity Assessment

The PV hosting capacity studies performed in this paper are carried out by employing a Monte Carlo-based method. Differently from the existing Monte Carlo-based methods, the technique adopted here is intended to be simplified, by using only information readily available for utility engineers responsible for studies of system reinforcements and expansions. The method requires a minimum number of random variables, while still supplying relevant information for the planning department. In fact, in the proposed method, the main random variable is PV allocation, which is a parameter that cannot be controlled (or predicted) by planning engineers.

A. System Operational Limits

As known, the hosting capacity is the lowest PV penetration level that causes violation of at least one technical limit. In this work, PV hosting capacity of a given LV system is estimated by considering its impacts on the following operational limits:

- *Over/undervoltage*: Voltage must be below 1.05 pu and above 0.92 pu. A violation is flagged if there are nodal voltages between 1.05 and 1.06 pu or between 0.87 and 0.92 pu for more than 3% of the monitored period (more than 3 not necessarily consecutive 15-minute snapshots in a 24-hour simulation). A violation is also flagged if any voltage is above 1.06 pu or below 0.87 pu at any 15-minute snapshot [17];
- *Voltage unbalance*: Must be lower than 3.0%. A violation is flagged if the maximum voltage unbalance of the circuit exceeds 3.0% for more than 5% of the monitored period (more than 4 not necessarily consecutive 15-minute snapshots in a 24-hour simulation) [17];
- *Conductor thermal capacity*: Conductor currents must be below the conductor thermal limits. A violation is flagged if the maximum branch current of the circuit exceeds the conductor thermal limit for more than 1 hour (more than 4 consecutive 15-minute snapshots in a 24-hour simulation) [18];
- *Transformer overload*: Transformer loading must be lower than 187.5% of transformer rated capacity. A violation is flagged if transformer loading exceeds 187.5% of its capacity for more than 1 hour (more than 4 consecutive 15-minute snapshots in a 24-hour simulation) [19].

Although operational limits are defined for a 24-hour period, the objective is to analyze the PV hosting capacity and, as such, only the 2 most critical hours of the day are simulated to reduce computational effort. For PV generation, these critical hours in terms of potential limits violations are between 11:00 am and 1:00 pm. If no technical limits are violated in this period, it is unlikely that they will be violated in other instants of the day due to the PV installations.

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B. System Model

The variables and corresponding models employed in the Monte Carlo simulation are characterized as follows:

1) Load Consumption Profile

A specific 24-hour load curve with 15-minute time resolution is assigned for each customer, based on its class (residential, commercial, industrial etc.), type of activity, in the case of commercial and industrial customers (bank, supermarket, bakery etc.), and monthly consumption (≤ 100 kWh, 100-220 kWh, 220-500 kWh etc.). These are the actual daily load curves employed during planning studies in the utility where these studies were conducted. In the case of customers connected to LV systems, the load profiles are derived from measurements of thousands of customers, categorized by type of activity and by average monthly energy consumption of the last year, thousands of questionnaires about the usage of energy and statistical methods. The measurements and questionnaires must be statistically representative of the characteristics of customers and circuits from the entire area of the utility. The basic idea of this method was initially described in [20]. According to the Brazilian regulation, all distribution utilities must conduct these studies every four years to update their load profiles.

Although a 24-hour load curve is assigned to each customer, only the 2-hour period from 11:00 am to 1:00 pm is simulated, as this is the period with the highest PV generation.

2) Percentage of Customers with PV Generators (PCPV)

This is a deterministic value that can be established, for instance, based on market data or based on historical information available on the utility database. In this paper, initially, 20% is adopted as the base value for studies. Other percentages are also considered later in the sensitivity studies.

3) PV Generators Location

Customers are randomly selected to have a PV generator, until the number of generators in the studied system reaches the desired PCPV (*e.g.*, 20%). This random selection respects the proportion of customer connection types (*i.e.*, if 40% of the customers have two-phase connection, 40% of PV generators installed will also have two-phase connection). In the analyzed systems, there are single, two and three-phase customers. PV location is the only random variable of the problem. Therefore, these locations will be varied to create hundreds of scenarios for each system under analysis.

4) PV Generator Rated Power

As a net-metering tariff has been adopted in Brazil and many other countries, the rated power of each PV generator is proportional to the average energy consumption of the corresponding customer; and the PV capacity installed in this customer (in kWp) is determined based on the PV penetration level of the corresponding system. In this paper, PV penetration level is not to be confused with the percentage of customers with PV (PCPV). The former is the ratio between total PV installed capacity in a LV system and the transformer rated power. The latter is the ratio between the number of customers with a PV generator and the total number of customers in a given LV system.

5) Period of Interest in the Solar Irradiance Curve

The objective is to determine the impact of PV generation on the voltage quality and equipment loading to obtain the hosting capacity. In this context, it is known that the most critical instant of the day is around noon, when the PV generators produce maximum power. Thus, to reduce simulation time, only 2 hours around noon are considered for loads and generators in the simulation (from 11:00 am to 1:00 pm, as shown in Fig. 1), with PV generators injecting power based on a typical irradiance profile for a clear day (worst case condition). These 2 hours correspond to 9 simulation snapshots, as simulations are performed with 15-minute time resolution. Furthermore, only a single day (rather than one month or one year) is considered in the simulation, because this single day is sufficient to represent the worst-case condition of PV operation.

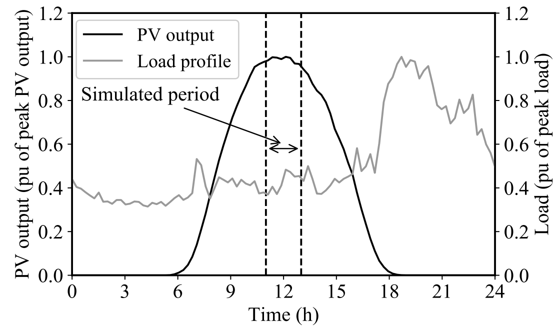

Fig. 1. Two-hour period that is simulated in the studies. The load profile is only one example of the multiple load profiles used in the studies.

6) Distribution Circuits

In Brazil, distribution utilities must register all their assets in a standardized geographic information system (GIS) database, which is yearly sent to the regulatory agency to determine the asset remuneration to be included in the utility tariffs. As a result, these GIS databases are typically well maintained, complete and accurate. Thus, in this paper, the LV systems are modeled in detail and individually by using the information registered into the utility's GIS database. Each LV system was modeled by a three-phase Thévenin equivalent, representing the 11.4 kV medium-voltage (MV) system, a three-phase service transformer and a three-phase LV system with single, two and three-phase loads. The service transformer is delta connected on MV side (11.4 kV) and grounded wye connected on LV side (0.22 kV). The LV system is a three-phase four-wire circuit, which is modeled in detail (characteristics of wire and pole geometry of all circuit segments are modeled). The neutral conductor is grounded on the transformer and on the customer service panels. The circuit topology and customer connection nodes and phases are provided in the utility's GIS database.

7) PV Generators and Circuit Loads

PV generators are modeled as a constant active power injection with unity power factor. Single-phase generators are installed only in single-phase customers, while two-phase generators can be installed in two or three-phase customers. Loads are represented by the constant power model. The load connection type (number of phases, *i.e.*, three, two or one phase) and the connecting phases are obtained from the utility's GIS database.

C. Algorithm

The proposed algorithm to determine the PV hosting capacity (PV_{host_cap}) per system is shown in Fig. 2, which must be run for each LV system. The algorithm can be described as:

1) First, the initial conditions must be established:

- Determine the voltage magnitude of the MV system equivalent. In this study, 1.0 pu is initially adopted to speed up the analyses. Different voltages will be considered later in the sensitivity studies;

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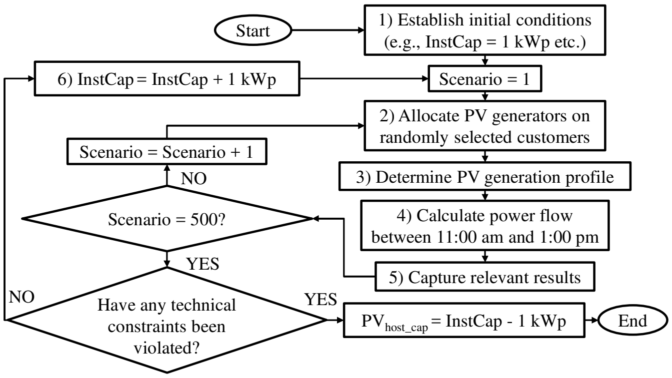

Fig. 2. Monte Carlo simulation algorithm performed for each LV system.

- Determine the short circuit level of the MV system. Based on utility typical values, 150 MVA is assumed. Different values will be considered later in the sensitivity studies;
- Determine the consumption profiles for all customers, following the method described previously. LV customers power factor is fixed in 0.85 inductive;
- Determine the percentage of customers with PV. In this study, 20% is adopted. Different percentage values will be analyzed later;
- Determine the starting total installed capacity (InstCap) of PV generators in the LV system, which will be gradually increased until the limit is reached. For instance, 1 kWp.

Then, the Monte Carlo simulation is carried out by creating hundreds of scenarios where PV allocation is varied. A simulation scenario is established when the characteristics of the PV generators (number of units, location and installed capacity) are determined, *i.e.*, when all variables become known and a deterministic power flow calculation can be performed to estimate voltages, currents etc. The following steps are carried out to determine each scenario:

2) Allocate PV generators in random customers until the established percentage of customers with PV is achieved. PV locations are different in each scenario, this is the main random variable;
3) Determine the power injected by each PV throughout the period to be simulated based on a typical solar irradiance profile and on the generator power capacity. Only the period between 11:00 am and 1:00 pm is simulated. The power capacity of each PV depends on the load level of the customer where it is installed (*i.e.*, depends on the PV location) and, therefore, the power injected by each PV also changes from one scenario to the following;
4) Perform time-series power flow in the period of interest to determine the circuit operating state of the current scenario. Nine power flow simulations are performed for each scenario (15-minute resolution from 11:00 am and 1:00 pm);
5) Capture results of interest, which consist of nodal voltages, voltage unbalance on three-phase buses, branch currents and transformer loading level.

The above procedure for creating a scenario and determining the system operating state (Steps 2 to 5) must be repeated numerous times by allocating PV generators randomly until 500 scenarios are simulated. The Monte Carlo convergence is illustrated in Fig. 3, for a sample LV system where 20% of the customers have a PV generator and the PV penetration is 73% of MV/LV transformer rating. The voltage magnitude not exceeded in 95% of the scenarios is considered in this example.

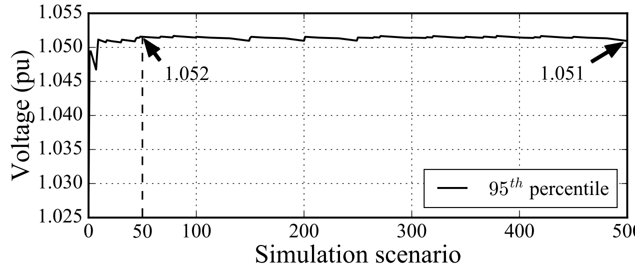

Fig. 3. Illustration of Monte Carlo convergence.

6) If none of the evaluated aspects exceeds statutory limits, the total installed capacity (InstCap) is increased by 1 kWp and the process is repeated from Step 2. Otherwise, the process is terminated and the PV hosting capacity (PV_{Host_Cap}) is obtained for the system under analysis, considering the limits for over/undervoltage, voltage unbalance, conductor thermal capacity and transformer overload simultaneously.

The previous steps must be repeated for each LV system under investigation, which, in this work, is done for 50,000 systems, representing 75% of the circuits existing in the evaluated utility.

This approach was implemented by using Python to program the Monte Carlo method and OpenDSS to solve the time-series power flow [21], [22].

An alternative (and faster) method that has also been implemented to obtain the PV hosting capacity of each system consists in updating the total installed capacity by using the Golden-section search technique rather than gradually increasing it in steps of 1 kWp. In addition, although we have used 500 scenarios as a convergence criterion to obtain a high precision, this number can be considerably smaller as shown in in Fig. 3. For example, in the sensitivities studies presented in Section V, 50 scenarios were used as the convergence criteria.

IV. The Big Picture of PV Hosting Capacity

This section presents a comprehensive analysis of PV hosting capacity characteristics of the 50,000 LV systems.

A. *PV Hosting Capacity*

Fig. 4 shows the PV hosting capacity characteristics of the studied systems by means of a histogram and a cumulative distribution curve. The hosting capacity of a given LV system is the ratio between maximum allowable PV installed capacity and the transformer rated power. Results average is 38.2% and the standard deviation is 17.6%. Furthermore, it can be seen mainly in Fig. 4(b) that the obtained results approximately follow a Lognormal probability density function (pdf) given by:

$$f(x)=\frac{1}{a\cdot x\cdot\sqrt{2\pi}}e^{-\frac{(\ln x-b)^2}{2a^2}} \tag{1}$$

where parameters a and b are given by [23]:

$$a=\sqrt{\ln\left(1+(\sigma/\mu)^2\right)} \tag{2}$$

$$b=\ln\left(\frac{\mu}{\sqrt{1+(\sigma/\mu)^2}}\right) \tag{3}$$

the random variable x represents the potential values of the hosting capacity, and μ and σ are, respectively, the average and the standard deviation of the hosting capacity results.

Parameters μ and σ are sufficient to obtain the curve presented in Fig. 4(b), which provides planning utility engineers

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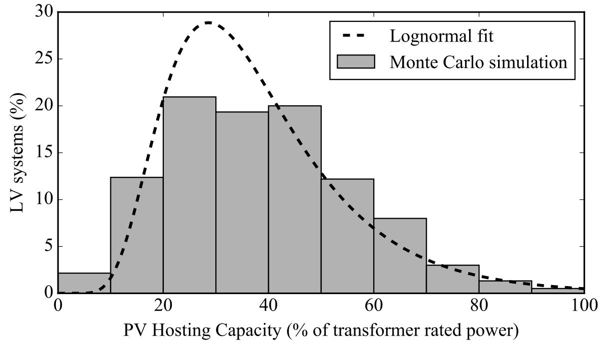
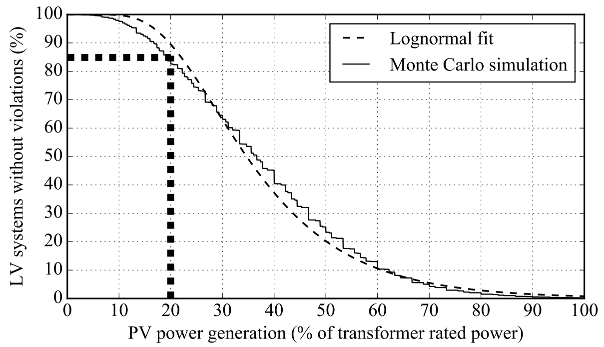


(a)



(b)

Fig. 4. Distribution of PV hosting capacity in the studied LV systems and the Lognormal fit. (a) Hosting capacity histogram; (b) Cumulative distribution curve (risk-based hosting capacity curve).

with a straightforward estimation of potential risks associated with the deployment of PV generation. It reveals, for instance, that while PV penetrations are below 20%, the utility may consider unnecessary to undertake general actions to improve the LV systems hosting capacity, because there is only 15% risk of experiencing violations in any circuit, which can be tackled on a case-by-case basis. In other words, nearly 85% of studied circuits will not experience operational limit violations if PV penetration remains below 20%. Based on the results shown in Fig. 4, the risk of a LV system experiencing violations is:

$$\text{Risk of viol.}(\%) = 100 - \text{LV syst. w/o viol.}(\%) \tag{4}$$

This risk-based hosting capacity curve is useful for utilities and governments to establish penetration thresholds that will trigger general actions, such as system upgrades to increase the hosting capacity, and/or tariff changes to influence the number of new installations. In a more restricted analysis, this curve enables engineers to monitor individual LV systems based on the risk of violations that an utility is willing to accept.

B. PV Hosting Capacity Per Capita

Fig. 5 presents results organized in terms of the ratio between PV hosting capacity of a given LV system and the corresponding number of individuals connected to this circuit, *i.e.*, the maximum allowable installed PV capacity per capita for the studied systems. The average value of this index is 0.22 kW per capita, considerably above the currently installed PV capacity in Brazil (less than 0.01 kW per capita). Germany, on the other hand, currently features an installed capacity of 0.47 kW per capita [24], the largest in the world.

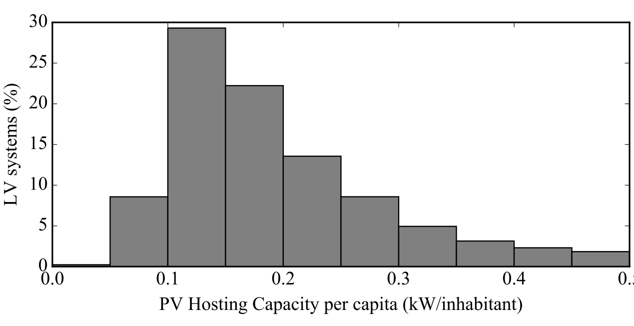


Fig. 5. Distribution of the ratio between PV hosting capacity of a given LV system and the number of individuals supplied by this system.

C. PV Hosting Capacity vs. Midday Loading

PV generation impacts are known to be most pronounced around noon and the extent of such impacts depends on the circuit loading level. Thus, the analyzed systems were segmented by their loading levels at noon. Fig. 6 presents the PV impacts for different ranges of loading levels at noon (0-5%, 5-15%, 15-25% and 25-35% of transformer power rating, which accounts for nearly 80% of the studied circuits). As a general rule, LV circuits with higher midday loading are expected to allow higher PV penetration levels. For example, 30% PV penetration is acceptable in less than 10% of the circuits with 0-5% loading, but it becomes acceptable in nearly 80% of the circuits with 25-35% loading. This is expected, because higher loading results in higher voltage drop along the LV circuit, contrasting with the voltage rise produced by PV generation. However, these results, as well as the other results of this paper, are risk-based results and, as such, are susceptible to exceptions. For instance, although it is stated that LV systems with higher loading generally allow higher PV penetration levels, this may not always be true. The presence of voltage regulators and capacitor banks in the MV feeder, the number of customers and their spatial distribution in the LV circuit, the LV circuit length etc. are factors that also affect the hosting capacity.

Taking a step further, the average and standard deviation of PV hosting capacity for different loading levels is shown in Table III. If this information is applied to (1)-(3), the entire risk-based hosting capacity curve can be obtained. This result can be combined with load forecasting outcomes to estimate how PV hosting capacity will evolve over the years with the increase in system loading.

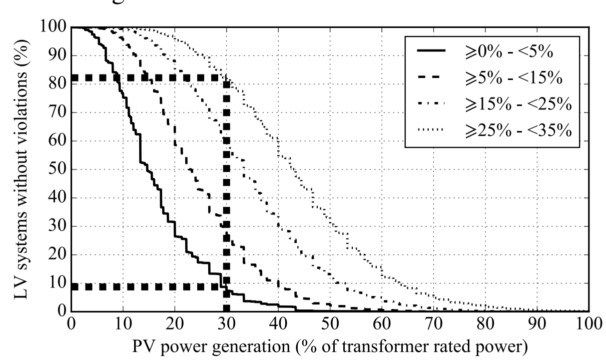


Fig. 6. Percentage of LV systems that can host a given PV generation capacity. Legend: total load demand at noon (% of transformer rated power).

TABLE III
PV HOSTING CAPACITIES FOR DIFFERENT SYSTEM LOADINGS.

System loading (% of transformer rated power)	PV Hosting Capacity (%)	
	Average	Std. Deviation
0-5%	16.7	8.90
5-15%	24.8	10.8
15-25%	34.6	13.2
25-35%	44.0	15.1

D. Most Restrictive Technical Impact

Among the analyzed limits, Fig. 7 outlines the incidence of

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each limit as the most restrictive in the studied systems. One can observe a clear predominance of overvoltage as the most restrictive impact. Voltage unbalance, traditionally neglected in PV hosting capacity assessment, is found to limit PV penetration in 9.6% of the systems. Conductor overload is found to limit PV penetration in 27.7% of the systems, while transformer overload does not limit PV penetration. Undervoltage limits PV penetration in 1.2% of the systems. The undervoltage occurs, in general, on phases without PV generation, when there is high PV power injection in the other phases. This is seen in Fig. 8, where voltages in phases B and C of a specific bus decrease while PV power injected in phase A increases. Therefore, overall, voltage (rise/drop and unbalance), instead of current (asset overload), is found to become the major concern in scenarios with increasing PV penetration. More specifically, overvoltage is the key impact caused by PV generation. These outcomes provide engineers with further guidance on how to properly troubleshoot issues caused by PV generation.

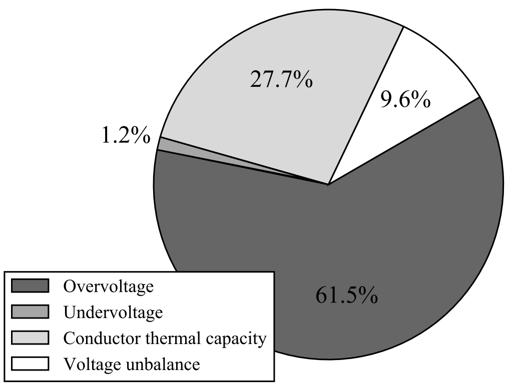

Fig. 7. Incidence of the operational limit first violated by PV generation in the 50,000 studied systems (most restrictive operational limit for PV generation).

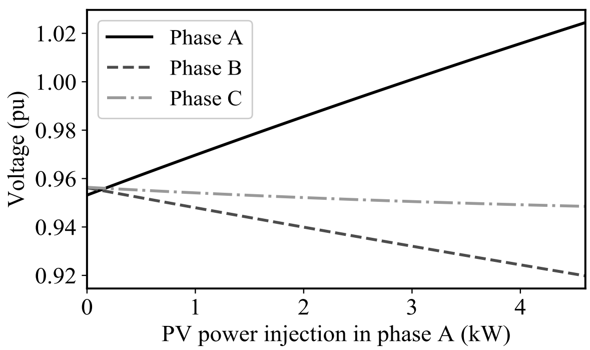

Fig. 8. Undervoltage violation in a specific bus with PV generation in phase A.

V. Sensitivity Studies

In this section, sensitivity studies are performed to identify and quantify the impact of some key factors on the PV hosting capacity of LV systems. These studies are performed in a representative subset of the utility systems composed of 10,013 LV systems (20% of the total). The sensitivity studies cover two types of parameters. The first type is related to PV generation characteristics, not directly managed by the utility, such as number of PV units. The second type is related to parameters typically managed by utilities to improve system operation, such as conductor size and voltage regulation.

A. Percentage of Customers with PV Generators - PCPV

The percentage of customers with PV generators is studied here. It is increased from 20% to 100% of the customers, which means that PV generators are dispersed among an increasing number of customers, and the obtained PV hosting capacity for each of these percentages is presented in Fig. 9. The average hosting capacity and corresponding standard deviation for each PCPV are presented in Table IV. One can observe that both average and standard deviation increase in a relatively linear fashion with respect to PCPV levels, because, as the number of PV generation units increases, the installed capacity of each PV unit reduces (the total installed capacity of the LV system remains constant) and, as such, their global impact becomes less severe. Furthermore, Fig. 10 outlines that, when the number of PV generators increases, overvoltage becomes more restrictive than conductor overload in some circuits where the latter was originally the most restrictive impact. This is because, on the one hand, the increased number of generator connections tends to alleviate the current injected by these units into the system as they feed customers locally. On the other hand, such numerous connections lead to voltage rise in several parts of the circuit, which turns it into the most restrictive impact. A final note is that, although the total PV hosting capacity increases, the allowable capacity per generator decreases. PV impacts are more pronounced close to their installation points, but these generators also affect other parts of the circuit. As such, a larger number of customers with generators causes a reduction in the allowable capacity per generator. For instance, when PCPV increases from 20 to 80%, the average allowable capacity per generator decreases from 6.88% to 3.58% (*i.e.*, from 3.37 kWp to 1.77 kWp). However, the total hosting capacity increases from 37.4% to 80.1% (*i.e.*, from 19.1 kWp to 41.4 kWp).

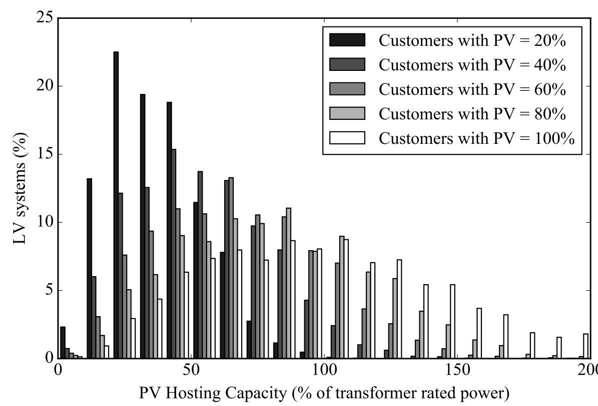

Fig. 9. Impact of percentage of customers with PV generation on PV hosting capacity.

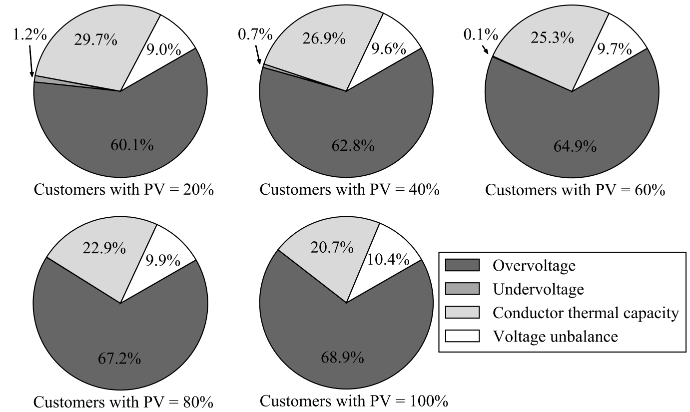

Fig. 10. Impact of percentage of customers with PV generation on the incidence of the operational limit first violated by PV generation.

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TABLE IV
PV HOSTING CAPACITY FOR DIFFERENT PCPVS.

Customers with PV generators (%)	PV Hosting Capacity (%)	
	Average	Std. Deviation
20%	37.4	17.4
40%	53.7	24.8
60%	67.2	30.2
80%	80.1	35.1
100%	96.6	42.3

B. PV Power Factor

Although rooftop PV generators generally operate with unity power factor, inductive power factor operation is known to attenuate PV impact on voltage rise [25]. The global effect of non-unity power factor on PV hosting capacity can be visualized in Fig. 11 and Fig. 12. One can see that when the PV generators operate with 0.95 inductive power factor, the average hosting capacity increases by 6.1% and conductor overload becomes the most restrictive impact. Reactive power consumption counteracts the voltage rise caused by active power injection and voltage magnitude becomes less restrictive, but the currents increase. Although Fig. 12 outlines that the most restrictive impact has changed, Fig. 11 shows that the ultimate effect of inductive power factor on hosting capacity is not so significant. This finding holds for power factors close to unity, which will generally be true for LV-connected PV generators. On the other hand, reactive power injection (capacitive power factor) stresses the voltage rise, resulting in a more significant reduction in the average hosting capacity (11.6% reduction for 0.95 capacitive power factor).

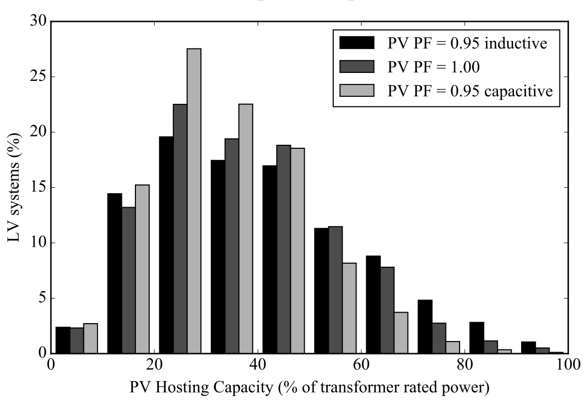

Fig. 11. Impact of PV generators power factor on the PV hosting capacity.

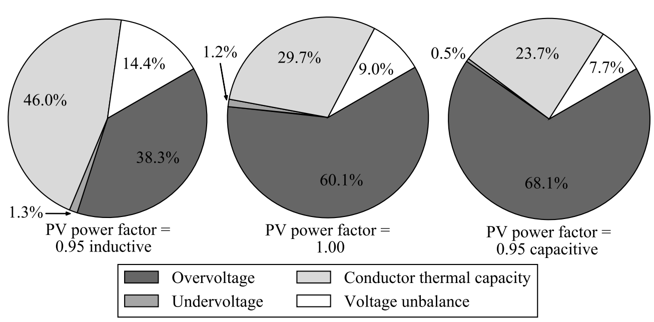

Fig. 12. Impact of PV generators power factor on the incidence of the operational limit first violated by PV generation.

C. Voltage Magnitude of the MV System

The voltage magnitude of the MV system (V_{MV}) at the connection point with the LV system has direct impact on the PV hosting capacity. Such impact is quantified here by increasing V_{MV} from 0.97 to 1.03 pu. Initially, LV systems with violation in the base case, without PV generation, are identified. For the cases when the MV feeder voltages are increased to 1.03 pu, there are no systems with violation. However, when the MV feeder voltages are reduced to 0.97 pu, 186 LV systems have undervoltage violations. These systems are removed to proceed with this sensitivity study (removed only from this subsection V.C). Results obtained for the 9,827 remaining LV systems are revealed in Fig. 13 and Fig. 14. They outline that when V_{MV} is increased, PV hosting capacity reduces significantly, which is expected because the circuit voltage profile without PV generators is closer to the upper limit. On the other hand, the hosting capacity increases when the MV feeder voltage is reduced, but undervoltage violations become more frequent (occur in 7.6% of the systems). This shows that V_{MV} reduction is a complex action that must be analyzed with proper care. Utilities are recommended to investigate if a given MV feeder voltage reduction will lead to undervoltage violations in the feeder under study prior to actually implementing this action. Furthermore, the MV feeder voltage must be raised back to its original value prior to the peak load period of the day to avoid undervoltages during the peak load.

Quantitatively, the effect of V_{MV} on the average PV hosting capacity and its standard deviation are shown in Table V. This type of result, although expected, is important because it allows to measure how much more PV can be hosted in a utility by changing the voltage regulation philosophy.

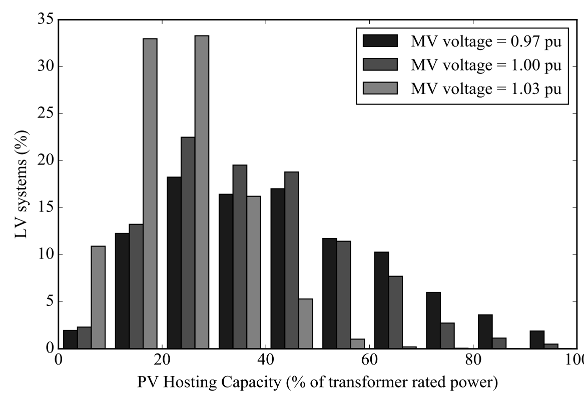

Fig. 13. Impact of MV system voltage on PV hosting capacity.

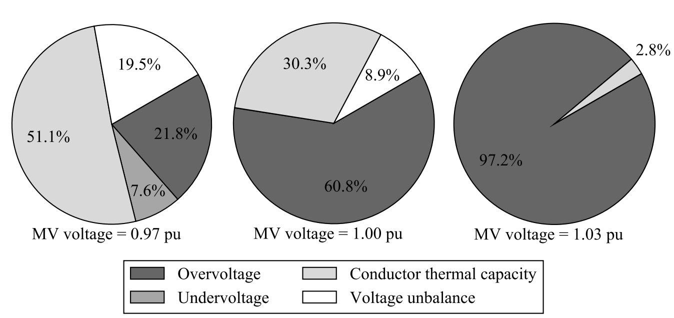

Fig. 14. Impact of MV feeder voltage on the incidence of the operational limit first violated by PV generation.

TABLE V
PV HOSTING CAPACITY FOR DIFFERENT VALUES OF V_{MV}.

V_{MV} (pu)	PV Hosting Capacity (%)	
	Average	Std. Deviation
0.97	42.4	21.1
1.00	37.3	17.3
1.03	22.0	10.5

D. Circuit Conductor Parameters

The impact of circuit reconductoring on PV hosting capacity is also investigated in the 10,013 LV systems. For this study,

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all circuit conductors are upgraded for the conductor that is commercially available and has the next higher cross-sectional area. This action increases the short circuit level of the LV system, leading to a higher PV hosting capacity, as shown in Fig. 15. The number of circuits with hosting capacity above 50% increased significantly, while the share of circuits with hosting capacity below 40% decreased. The average hosting capacity has increased 16.6% (from 37.4% to 43.6%), which happened to be nearly the same proportion of the increase in the average conductor ampacity (17.0% increase, from 81.6 A to 95.5 A). With this upgrade, voltage drop through the circuit has been reduced and, consequently, voltages also become more balanced. Therefore, although reconductoring results in higher conductor ampacities, conductor loading has become the most restrictive impact, as shown in Fig. 16. This finding was further explored with an additional study where conductor currents were allowed to rise up to 150% of the real conductor ampacities. The average hosting capacity increased only 6.1% (from 37.4% to 39.7%), outlining that it is more sensitive to a reduction in conductor impedance than to an increase in the current carrying capacity of the conductors.

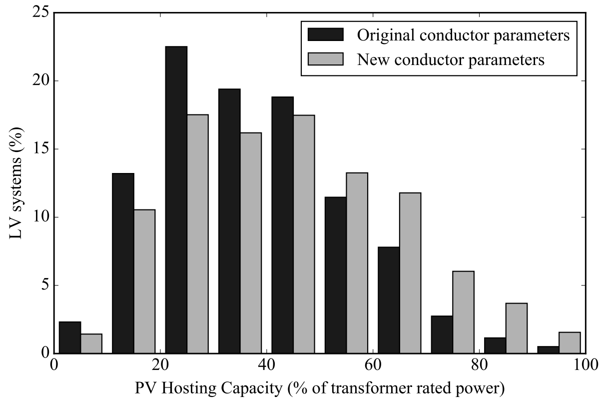

Fig. 15. Impact of reconductoring of LV systems on the PV hosting capacity.

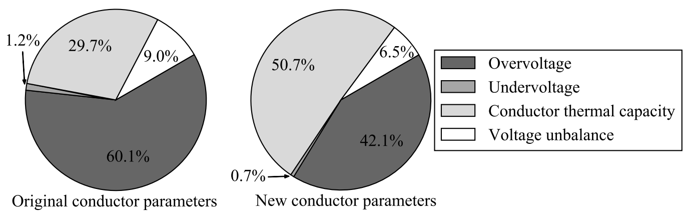

Fig. 16. Impact of reconductoring of LV systems on the incidence of the operational limit first violated by PV generation.

E. Short Circuit Level of the MV System

Simulation studies have been performed by varying the short circuit level of the MV system equivalent from 37.5 to 300 MVA. No significant impacts were observed in the results, which is understandable since the service transformer impedance is much higher than the MV equivalent impedance. The latter, therefore, can be practically neglected and studies can be performed on LV systems by modeling the MV circuit as an infinite bus, whose voltage can be determined by a single calculation of the MV feeder power flow or by any other simplified approach, as done here.

VI. Simplified Method to Obtain Risk-Based Hosting Capacity Curve

Despite being a simplified Monte Carlo-based method, the computational time can still be significantly reduced. This can be achieved by employing (1)-(3), which reveals that average and standard deviation of the hosting capacity are sufficient to obtain the risk-based hosting capacity curve. This section shows that such values can be obtained by simulating only a small number of randomly selected systems. After repeated random trials with different numbers of systems (ranging from 5 to 20,000 systems), it was found that a number as low as 500 circuits (*i.e.*, 1% of the total) is sufficient to provide a good estimate of the probabilistic hosting capacity curve for the utility under analysis. This is illustrated in Fig. 17, where three random circuit selections are carried out (500 circuits are randomly selected on each trial). Obtained curves match well the full result (where the 50,000 systems were simulated), although accuracy is increased when more circuits are considered.

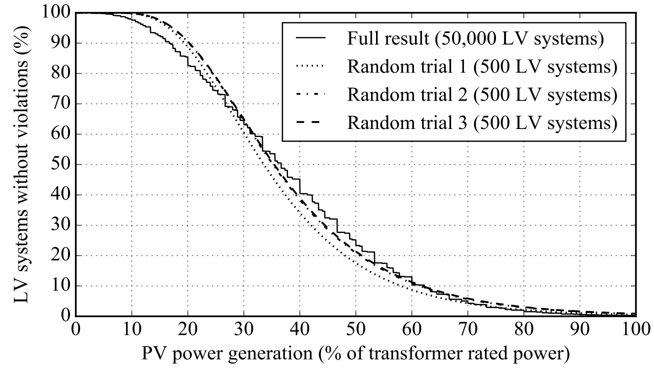

Fig. 17. Risk-based hosting capacity curves obtained from a reduced number of randomly selected circuits (1% of the total number of circuits).

VII. Discussion

It is assumed that the MV feeder voltage (on the primary side of the MV/LV transformer) is 1.0 pu, which is a significant simplification of the approach presented in this paper. However, to be able to study a huge number of circuits, it was important to adopt a simplified model, so that the MV systems are not represented in detail. To accurately represent the voltage value at the MV systems, these systems should be modeled in detail, which would increase considerably the simulation time. Even so, the risk-based approach adopted in this paper provides utilities with a good tradeoff between accuracy of the results and simulation time.

PV location is completely random in this study, that is, the probability of owning a PV generator is equal to all customers. However, researches have been conducted to associate customer socioeconomic profiles, electricity tariffs for different customer classes etc. with the customer likelihood of owning a PV generator [26], [27]. Once this type of information becomes directly available to planning engineers, it can be used to improve the model of the PV location variable discussed in Section III.B.3.

VIII. Conclusions

This paper provided a comprehensive understanding of rooftop PV hosting capacity in LV systems considering voltage quality and equipment loading limits. The investigation was supported by a cohesive and critical analysis of stochastic results obtained from a simplified Monte Carlo-based method applied to 50,000 real LV systems of a utility.

The developed method can provide two main types of useful information for utility and government planners. First, from utility perspective, it offers a risk-based method to guide the planning department to determine strategies to deal with the increase in the PV penetration. For instance, utilities can define the risk level of technical violations (and the corresponding PV penetration) that can be mitigated by using a case-by-case strategy rather than promoting generalized reinforcement actions to guarantee the quality of the service. Likewise, governmental agencies can employ the risk-based curve to establish milestones for updating policies and regulations that address the installation of PV generators. For example, the regulatory agency can change the tariff to influence the number of new installations or to support the necessary reinforcements. Second, quantitative results provided by the method enable utilities and government agencies to estimate the actual cost of increasing the PV hosting capacity. This can be done by confronting the cost of different global utility actions (*e.g.*, circuit reconductoring) with the overall resulting increase in the PV hosting capacity.

From the results, it was quantitatively confirmed that overvoltage is the most restrictive limit. In addition, in the case of three-phase LV systems, voltage unbalance can also restrict the PV hosting capacity in LV systems. Indeed, voltage (rise and unbalance), rather than current (asset overload), was found to become the major concern in scenarios with increasing PV penetration. This can help engineers to narrow down actions to increase the PV hosting capacity.

In addition, it was verified that relevant results can be obtained for other utilities in a rather simpler way, without running Monte Carlo simulations for all systems. It was shown that one needs to randomly select only a small number of systems (such as 1-2%) and, out of them, obtain the PV hosting capacity characteristics for the entire utility grid.

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