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PV Hosting Capacity Dependence on Harmonic Voltage Distortion in Low-Voltage Grids: Model Validation with Experimental Data

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Abstract: This paper introduces a brief analysis on hosting capacity and related concepts as applied to distribution network systems. Furthermore, it addresses the applicability of hosting capacity study methodologies to harmonic voltage distortion caused by photovoltaic panels (PV) connected at a low-voltage (LV) side of a university campus grid. The analysis of the penetration of new distributed generation technologies, such as PV panels, in the distribution grid of the campus was carried out via measurement processes, and later by computer simulations analyzing a new concept of the hosting capacity approach in relation to voltage harmonics distortion. The voltage rise due to harmonic injection is analyzed and discussed with the aim of validating the discussed model and also putting forward recommendations for connecting PV generation across other network systems.

Keywords: hosting capacity; renewable energy; distributed generation; power quality; harmonic background; voltage rise; distribution systems

1. Introduction

Nowadays, traditional centralized electricity generation is not the only source of production delivered to distribution network systems. At present, the term Distributed Generation (DG) has come to be used to refer to new production paradigms, which involve the smart grid concept and its derivatives. In addition to the concept, DG also refers to production methods in which only a fraction of generated electric power is delivered by consumers that own small generation units [1]. These are usually designated as Distributed Energy Resources (DER). DG can also be referred to as decentralized generation or dispersed generation [2,3]. The benefits from DGs range from economic, technical and environmental to others. Over time, the concept of DG has evolved, and in the literature [2] it is possible to find several widely used definitions such as any source of electric power of limited capacity, directly connected to the distribution network wherein it is consumed by end users [2].

Up to this point, DG or more generally DER, integration is expected to increase at a fast pace. The large-scale integration of DER has important impacts on network security, reliability and quality of service. One of the major service impacts of DER integration is voltage magnitude rise [3,4]. This is especially relevant in the case of unitary power factor control of the power electronic converters, which are in the interface of photovoltaic (PV) systems. The integration of DERs may cause other disturbance in normal operating conditions. In fact, a large PV penetration can result in several voltage quality issues.

Note that voltage rise impacts can be amplified by voltage waveform harmonics, which may be significant in PV and other electronically connected generation technologies that inject harmonic currents. Depending on the DER connection point and network characteristics of the electrical network system, voltage distortion caused by harmonic current injection may, or may not, reduce the system hosting capacity beyond the limits imposed by the maximum rise of the fundamental voltage component [4–6].

The impact of DG can be quantified using a set of power indicators. The nature of the impact depends on the characteristics of the network system itself [5–18]. For PV systems, a feeder's PV hosting capacity may be defined as the largest PV generation which can be integrated without violating the limits of these feeders to which it is connected. It is important to emphasize that, according to local standards [7–10], a voltage rise violation is considered as a primary feeder violation when the recorded voltage data registers voltages greater than 1.05 per unit (p.u.).

The present study will address the overvoltage rise, namely, characteristic harmonics, due to low-order non-characteristic harmonics (harmonics and interharmonics up to 2 kHz). For these occurrences, the impact on voltage quality must be studied as well as the impact of emission by other equipment connected to the grid, where this part of the planning should cover a combination of measurements, simulation studies and relevant information about the grid [6,10–21]. Furthermore, capacity limitation, which is derived from the hosting capacity, is a function of the consequent impact on power quality, such as the voltage rise and background harmonic voltage, among others.

According to [6], many studies have been done on the impact of local generation on the grid, where overcurrent and overvoltage, for example, are the capacity limitations most commonly studied to date. In other words, a large scale of active power electronics, either in production or consumption, can result in further phenomena, the interharmonics or supraharmonics cited above. Another aspect has also been considered in current studies: the amount of capacitance connected to the grid that is expected to increase at all voltage levels in the grid, which takes further analysis in order to preclude the impacts on the power quality of the distribution grid. As we can see, [6] shows us an overview of the power quality issues which is related to major challenges in this field. This aspect is detailed in the following section and gives the validity and scope to the present work.

This paper is divided into three main parts. The first section defines the hosting capacity approach and its application to distribution systems. This part also includes a brief discussion of voltage rise and harmonic distortion. The second section presents new formulae for system hosting capacity which take into account harmonic current injection by DERs and the corresponding impacts on voltage rise. Finally, in section three, the formulae are validated with experimental data obtained from a PV installation facility [3]. The underlying phenomena, the performance index used and the analysis approach taken are discussed in the conclusion.

2. Hosting Capacity

Both the concept and application of hosting capacity have been studied by researchers in order to elaborate a new significant strategy to plan and improve network systems, especially for new generation sources. For distributed networks, the hosting capacity approach has been introduced as a communication tool between stakeholders concerning the connection of DG to the electric grid [6]. In this context, hosting capacity is understood as the maximum generation that can be integrated into the distribution grid without causing excessive disturbances in the power quality, where the term excessive means beyond the limits imposed by the standards maximum voltage rise, harmonics, flicker, etc.

The maximum PV generation that can be integrated into the system is called PV hosting capacity [7,11–16]. In this section, PV hosting capacity is defined with respect to voltage rise caused by harmonic voltage disturbances at the point of common coupling (PCC).

Figure 1 illustrates the evolution of a generic performance index for the hosting capacity as a function of the insertion level of a DG [7,12,13]. It is worth noting that there is a restricting range of the hosting capacity defined between two limit curves: the worst-case scenario, for the lower limit curve, and the best-case scenario, for the upper limit curve. The difference between the curves is based on the difference between possible background voltage distortions at the PCC. This approach for the limits of hosting capacity is shown in Figure 1. However, voltage distortions at the PCC can be caused by electronic devices, generators, transformers, non-linear loads and others.

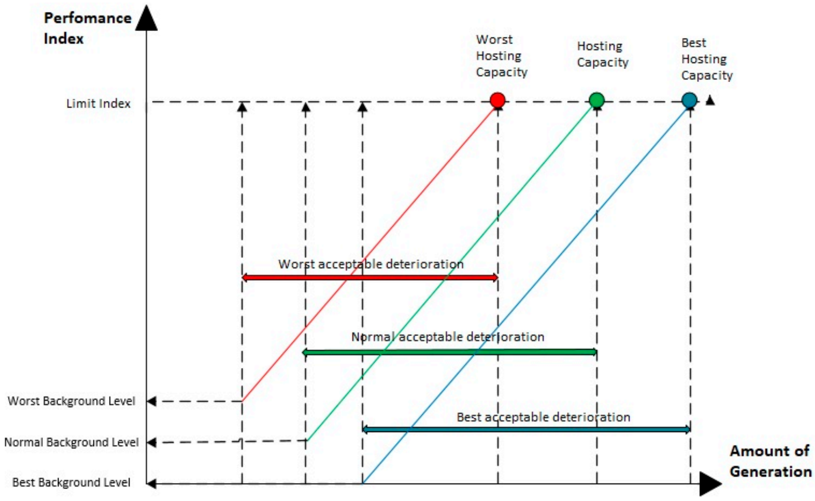

Figure 1. Range curves of a generic performance index versus the amount of distributed generation.

According to the literature [6,7], it is important to take into account uncertainties when conducting a hosting capacity analysis, as they will modify the deterioration region when hosting capacity is analyzed. Possible examples of such uncertainties include customers' type of installations, three-phase or single-phase, customer connection phase if single-phase, PV panel orientation, the type of the inverter, implemented reactive power control if any, and others. As shown in Figure 1, the curve range will represent the acceptable deterioration region between the best hosting capacity range (the line designating the best hosting capacity and the best background level) and the worst capacity range (the line designating the worst hosting capacity and the worst background level), which defines the region where it is possible to keep the system operating, without uncertainties, while respecting its limits index defined by local standards.

2.1. Voltage Rise Due to Harmonic Injection and Its Limits to Define the Local Hosting Capacity

Power electronic devices are expected to inject harmonic currents. The larger the devices are, the greater the impacts will be [6]. As long as the electronic devices are connected to the network and are injecting harmonic currents, voltage distortion will occur and, consequently, voltage rise will occur as a result of root mean square (RMS) magnitude dependence on voltage waveform.

According to international and national standards, the limits for voltage harmonic distortion and voltage rise have been defined (e.g., [8–10]). In the following, we will use both the voltage harmonic distortion limit and the voltage rise limit to define PV hosting capacity.

Assuming that a PV installation can be modeled as a current source and that the PV is connected at the LV side of a secondary substation at a PCC for which the Thévenin's impedance is essentially resistive (i.e., $X \ll R$), the system's hosting capacity P_g^{max} is usually approximated by (1) given a known voltage magnitude at the PCC, V_o [3,4], δV^{max} is the overvoltage relative margin and R_f is the Thévenin's resistance at the PCC:

$$P_g^{max} = \frac{(V_o)^2}{R_f}\delta V^{max} \quad (1)$$

where,

$$\delta V^{max} = (V^{max} - V_o)/V_o. \quad (2)$$

Equation (1) neglects harmonic injection by the PV source and voltage distortion at the PCC. To consider harmonic injection by the source and distortion at the PCC, (1) needs to be rewritten based on typical parameters of a LV feeder model [3]. Details of the feeder model used, and corresponding voltage rise formulae are provided in the following.

Take the model depicted in Figure 2 for which the Thévenin equivalent impedance at the PCC is given by $R_f + jX_f$. The complex power injected by a PV system and the complex power absorbed by the local load are defined as $S_g = P_g + jQ_g$ and $S_L = P_L + jQ_L$, respectively. The net injected active power and reactive power at the PCC are defined as $P = P_g - P_L$ and $Q = Q_g - Q_L$, respectively.

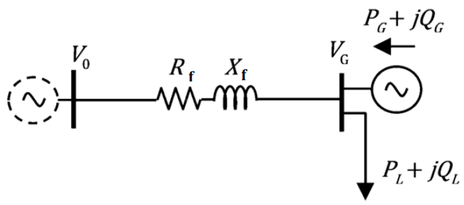

Figure 2. Feeder model with PV [3].

According to the literature [3,11], the voltage difference between the PCC and the voltage source can be expressed, for the fundamental frequency, by (3).

$$\dot{V}_G - \dot{V}_o = \left(R_f + jX_f\right)\left[\frac{P + jQ}{V_G \cdot e^{j\theta}}\right]^* \tag{3}$$

where the voltage at the PCC is denoted by $\dot{V}_G \cdot e^{j\theta}$ and the voltage at the source is $V_o \cdot e^{j0}$.

Applying the combined properties, (3) can be expanded into (4),

$$V_g - V_o = \frac{P\left(R_f \cos\theta - X_f \sin\theta\right) + Q\left(X_f \cos\theta + R_f \sin\theta\right)}{V_g} \tag{4}$$

Assuming that $\cos\theta \approx 1$ and $\sin\theta \approx 0$ [11], (4) can be approximated by (5) for the fundamental frequency $h = 1$.

$$\Delta V^1 = V_g - V_o \approx \frac{PR_f + QX_f}{V_g} \tag{5}$$

Equation (5) can be generalized for other harmonic orders $h \neq 1$ as in the following.

$$\Delta V^h \approx \frac{P^h R_f + Q^h h X_f}{V_g^h} \tag{6}$$

The maximum voltage rise at the PCC is experienced when load (L) is at its minimum and generation (G) at its maximum. Thus, one can use (6) to compute an upper bound for the voltage rise assuming that the power factor (PF) of the net load can be controlled by the PV system at the PCC ($\tan(\varphi) = Q^1/P^1$).

$$\Delta V^1 \cdot V_g^1 \approx P^1 R_f + Q^1 X_f \tag{7}$$

$$\Delta V^1 \cdot V_g^1 \approx P^1 \left(R_f + \tan(\varphi) X_f\right) \tag{8}$$

Neglecting the PV source harmonic content and the voltage distortion at the PCC, the maximum power injected by PV can now be given by (9) assuming that the maximum of ΔV^1 is $V_g^{max,\,1} - V_o^1$, where $V_g^{max,\,1}$ is the voltage limit for the fundamental frequency.

$$P_g^{max,\,1} = \frac{V_g^{max,\,1}(V_g^{max,\,1} - V_o^1)}{R_f(1 + \tan(\varphi)\frac{X_f}{R_f})} + P_L^{min} \tag{9}$$

Assuming that loads have negligible harmonic content, then (9) can be written for other harmonic orders as in the following.

$$P_g^{max,\,h} = \frac{V_g^{max,\,h}(V_g^{max,\,h} - V_o^h)}{R_f(1 + \tan(\varphi)\frac{hX_f}{R_f})} \tag{10}$$

where, V_o^h is the harmonic voltage at the PCC.

As long as the conditions under which the modeled PV is considered a current source, it is possible to explain the sum of the power to represent the hosting capacity of DG. Also, it is equally important to emphasize that the sum of these injected currents will impact the RMS voltage at the PCC. As a consequence, it can be said that the RMS voltage is essentially equal to the square root of the sum of squares of each harmonic voltage, in other words, by (11):

$$V_{RMS} \approx \sqrt{\sum_{h=1}^{51} V_h^2} \tag{11}$$

In this case, the power generated as a function of the RMS voltage can be rewritten as (12), using (11):

$$P_g = \frac{{V_{RMS}}^2}{R_f} = \frac{\left(\sqrt{\sum V_h^2}\right)^2}{R_f} = \frac{\sum V_h^2}{R_f} \tag{12}$$

As the hosting capacity at the PCC can be defined as the sum of the maximum power possible, based on (12), to be injected for each frequency:

$$P_g^{max} = \sum_{h=1}^{h} P_{PV}^{max,\,h} = \frac{1}{R_f}\sum_{h=1}^{51} \frac{V_g^{max,\,h}(V_g^{max,\,h} - V_o^h)}{(1 + \tan(\varphi)\frac{hX_f}{R_f})} \tag{13}$$

where $V_g^{max,\,h}$ is the voltage magnitude allowed for harmonic order h; V_o^h is the actual voltage magnitude of harmonic order h at the PCC; φ is the arcos (PF) where the PF is the power factor at the PCC.

If we use (13) and notice that, for $V \leq 1$ kV, standards require individual voltage distortion to be below 5% for $h \geq 2$ and below 105% for the fundamental frequency, $h = 1$, then, the hosting capacity is given by (14).

$$P_g^{max} = \frac{1.05(1.05 - V_o^1)}{R_f(1 + \tan(\varphi)\frac{X_f}{R_f})} + \frac{1}{R_f}\sum_{h=2}^{h} \frac{0.05(0.05 - V_o^h)}{(1 + \tan(\varphi)\frac{hX_f}{R_f})} \tag{14}$$

2.2. *Sensitivity Analysis of Hosting Capacity*

Several factors may affect hosting capacity, namely, harmonic voltage, power factor, minimum load of the distribution feeder, and voltage regulation equipment, among others [11]. We will elaborate on some of these factors in the following subsections.

2.2.1. Harmonic Voltage

The calculation of the hosting capacity using (14) considers the voltage harmonics, from the fundamental order up to the 51st harmonic order, as well as performance index limits, which depend on local standards [6,11–13]. Moreover, the injection of harmonic current into the system depends on the equipment connected at the PCC and the PV system inverters. The latter can be controlled by a prosumer as the equipment is manufactured according to standards. The former cannot be controlled. The background voltage at the PCC cannot be controlled as it is virtually impossible to know what is causing the harmonic voltage distortion. Therefore, two extreme scenarios will be imposed to analyze how the harmonic injection can impact the hosting capacity.

As an example, let us consider a scenario where the voltage for the fundamental order is set at 1.00 p.u. and the other harmonic voltages for $h \geq 2$, up to 15, are set at 0.03 p.u. It is important to realize that, for this scenario, a high distortion is considered as it is dependent on the background and all the electronic devices connected at the PCC. The other scenarios consider a non-high voltage distortion for $h \geq 2$ up to 15 and the voltage distortion will set in at 0.01 p.u. In fact, a decrease in harmonic voltage would increase the hosting capacity as shown in the equation below:

$$\frac{P_g^{max\prime}}{P_g^{max}} = \frac{1.05(1.05-1)+\sum(0.05-0.01)0.05}{1.05(1.05-1)+\sum(0.05-0.03)0.05} = \frac{0.1525}{0.0775} = 1.12$$

As can be observed, the decrease in harmonic voltage increases the hosting capacity by almost 12%. Therefore, the improvement of the voltage distortion signals depends on the harmonic filters connected to the system. On the other hand, referring to voltage regulation equipment, and keeping the harmonic background constant, ref. [11] argues that a reduction of V_o^1 to 0.98 p.u., for example, would result in 1.5 times higher hosting capacity with respect to (14).

2.2.2. Set Reactive Power on the Inverters

According to the literature [11], the power factor at the PCC can increase the hosting capacity as well. Let us set the base value for the PF at 0.8 ind. In order to demonstrate the sensibility due to the PF change, we compute a new value for the hosting capacity for a new PF value now set at 0.8 cap., which corresponds to the inverter absorbing reactive power instead of generating it. The ratio between hosting capacities is then given by the following expression:

$$\frac{P_g^{max\prime}}{P_g^{max}} = \frac{1+\tan\left(\cos^{-1}(0.8)\right)X/R}{1+\tan\left(-\cos^{-1}(0.8)\right)X/R}$$

which, if we assume that the relation X/R at the PCC is unitary, leads to a new hosting capacity that is about 7 times higher than the base case. In [11], results with smaller PF variations led to ratios of 2.35.

3. Experimental Data, Validation and Analysis

The distribution system for this study and its applicability is a 220 V feeder with one bus, one 150 kVA transformer connected to 13.8 kV–220 V, one PV system with 15 kW_p (solar panels + inverter + autotransformer), published in [5,7]. It's important to notice that peak generation for the minimum load is a number close to 15 kW_p even though the maximum load of this system is 4 kW, where the reminiscent generation is distributed at 13.8 kV as a bidirectional load flow at the university system for the other buildings connected to this same feeder. The electric schematic of the described circuit is shown in Figure 3. In Table 1, the values of parameters are shown as well.

Table 1. Parameters of the CERIn (Center of Excellence in Smart Grids) System.

Parameter	Default Value
Autotransformer	45 kVA, 380/230–220/127 V, Z = 1.2%
Transformer	150 kVA 13.8 kV–220/127 V, Z = 4%
PV cable	18 m, 3F × 6 mm^2, Cu
PV system + Inverters	15 kW_p + 2 Inverters (7.5 kW)
CEMIG 13.8 kV	Scc = 1000 MVA

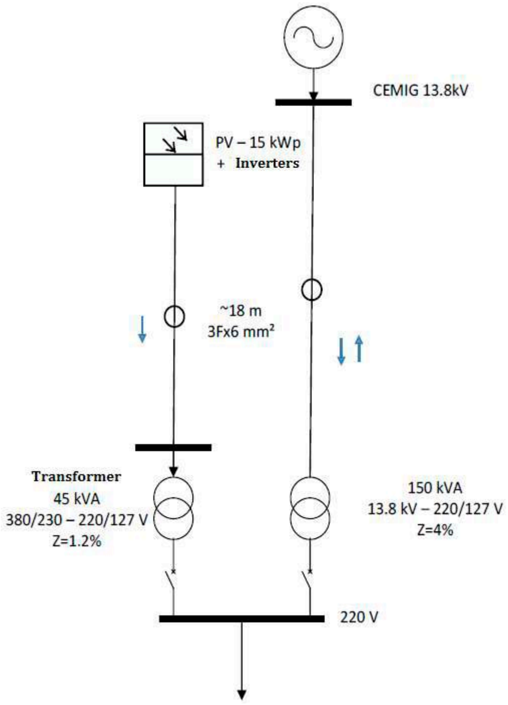

Figure 3. One-line diagram for the PV System of the CERIn sited in UNIFEI's (Federal University of Itajubá) campus.

In this section, in order to illustrate the calculation of hosting capacity by the maximum capacity equation, the voltage rise and harmonic source will be validated by specific measuring equipment to get the equivalent data of the voltage profile, harmonic injection, frequency and others. Both pieces of equipment were installed on the 220 V sides of both the transformer and the autotransformer. As a result, it is possible to measure the bidirectional load flow as well as the voltage profile, simultaneously.

3.1. Experimental Data and a Brief Analysis

Using specific measuring equipment, the RMS magnitude of the nodal voltage and of current injection at the 220 V bus were recorded over the course of one week, with 10-min resolution [5], resulting in 1008 valid data records used for analysis. Harmonic power and other power quality indices were also measured. Measurements were undertaken according to Brazilian standards for power quality regulation [5,8–10]. Based on these obtained data, the results from Equations (1) and (14) are compared against each other as well as against actual measurement data.

Figure 4 shows a sample of the data obtained in different time periods (different dot symbols and colors for different days) projected into two dimensions: (i) active power injected by the 15 kW_p PV systems, at the abscissa axis, and (ii) RMS voltage rise margin at the PCC, at the ordinate axis. The chosen time-range is between 07:00 a.m. to 05:00 p.m. with 10-min resolution, as mentioned before.

Figure 5 filters the data of Figure 4 for just one day, where the amount of energy produced was at its maximum and PF was within a narrow range: we eliminated data records within that day for which the PF was outside the range [0.77; 0.96]. The projection of the filtered data onto δV^{max} and P_g^{max} is then compared with the estimation given by Equations (1) and (14), respectively, using the same overvoltage margin. For the results of Equation (14), we used a constant power factor of 0.80 ind., which represents the average PF in the period. Results show that the derived model expressed by (14) represents the experimental data were obtained quite well, as the data points match the linear equation estimated by (14).

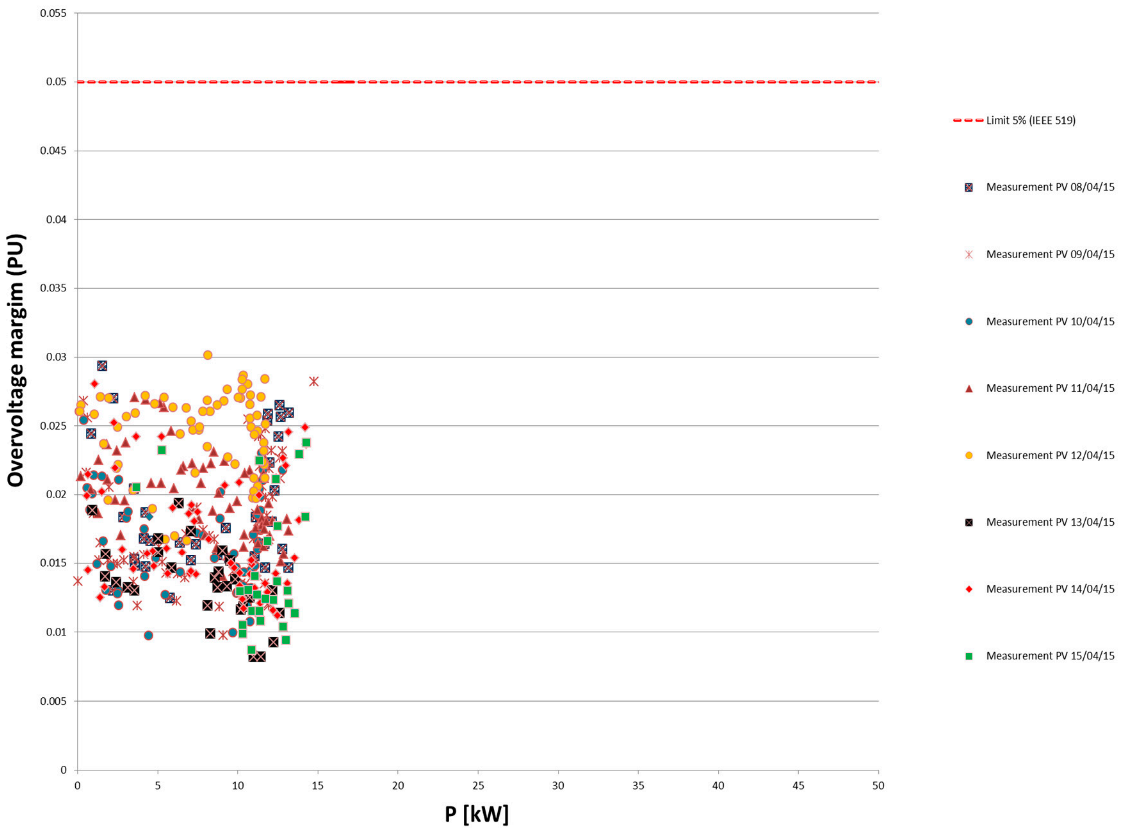

Figure 4. Hosting capacity experimental data.

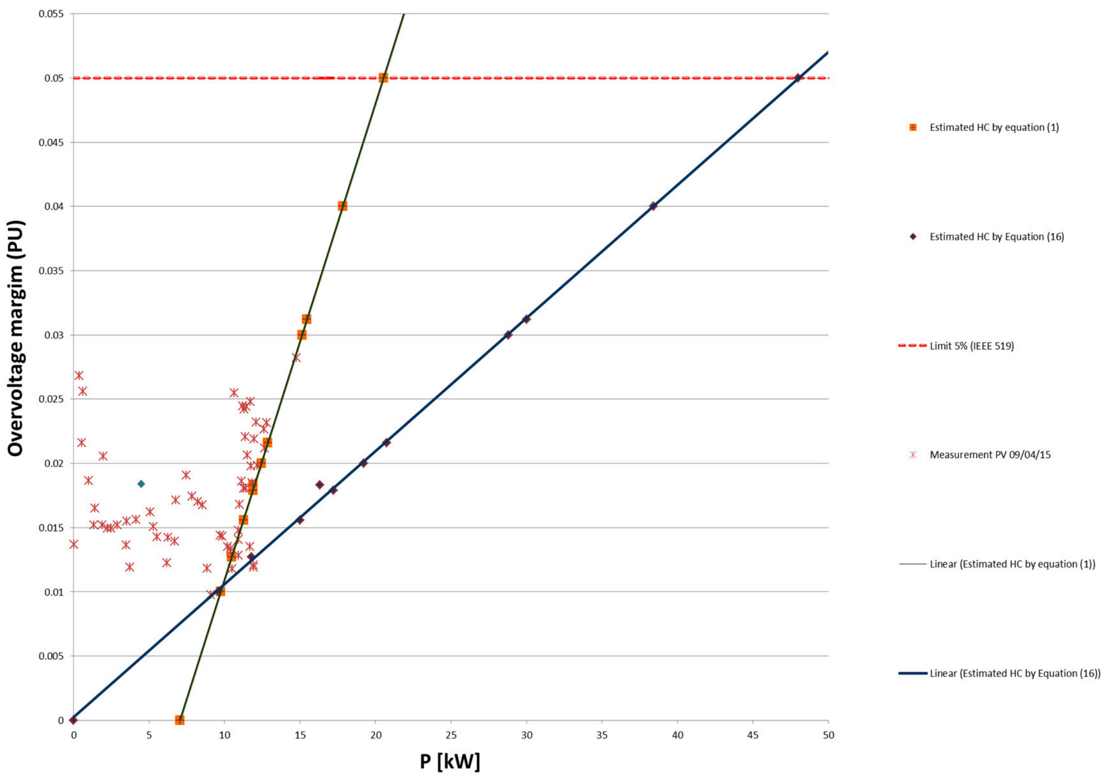

Figure 5. Hosting capacity validation against (1) and (14).

Moreover, and perhaps more importantly, results also show that Equation (1) significantly underestimates the PV system's hosting capacity by neglecting harmonic current injection effects and the power factor at the PCC, which accounts for a significant amount of the difference for the estimated PV production. Note that (1) estimates a 48 kW_p hosting capacity for a 5% allowed voltage rise, while (14), more realistically, limits such capacity to half of that value, i.e., 22 kW_p.

3.2. Calculation Method for Analysis and Planning

In order to illustrate the use of the hosting capacity approach related to the voltage rise and harmonic injection demonstrated in (14), a thorough analysis is shown in this section to exemplify the different impacts and behaviors of the approach discussed earlier. For this application of the hosting capacity approach, we chose to define four different scenarios with the following characteristics:

(i) A worst-case scenario is defined in two strands as part of an extreme situation. First, we consider that all harmonic voltages are 5% for $h \geq 2$, which leads to $\delta V_h = 0$ in equation (14). This situation corresponds to the system being at the maximum harmonic limit. Second, we consider the case where the power factor is at the minimum possible, which in this case is zero. This scenario defines an unacceptable region where our system is where our PV unit cannot be integrated into the distribution system.

(ii) A best-case scenario is also defined in two strands, in a similar way to that used for the worst-case scenario. First, we consider all harmonic voltages as negligible for $h \geq 1$, which leads to $\delta V_h = 5\%$. This situation corresponds to the system having a voltage waveform that is 100% sinusoidal. Secondly, we consider the case where the power factor is at the maximum, which in this case is above 90%.

(iii) A third scenario is defined as the real case wherein the power factor range was [0.77; 0.82].

(iv) Finally, the fourth scenario is used to illustrate the behavior of the hosting capacity approach when only the fundamental frequency is considered in (14) and compared with case (iii), which considers all harmonic orders.

When the hosting capacity is analyzed, it is necessary to define a system's performance index. In this case, the voltage rise limit considered is the performance index for the Brazilian standard [8], where the limit used is 5% at the bus voltage under analysis. For the present analysis, the four scenarios were defined previously, as was the limit performance index for the hosting capacity. This analysis is shown in Figure 6. As a result, it is possible to illustrate the hosting capacity approach taken and its acceptable deterioration region.

In Figure 6, it is possible to observe a sample of the data obtained for the specific time periods as denoted in the figure by the "+" symbols. The data has a direct relation with the power factor at the PCC, which is variable due to the load variation in that period, the solar incidence, etc. The data obtained falls within the power factor's range of [0; 0.9], which results from the characteristics discussed in (i) to (iv).

For the extreme case, it can be noted that there is a hatched region where the system can work as long as the limit performance index is respected. In this case, the system can be set up within a hosting capacity range between 0 and 25 kW_p considering an acceptable deterioration region. However, it is important to underline that the background level at the PCC can be the cause of an important relation between the amount of energy that can be produced and the limit for practical purposes. The curve for a realistic situation, with a power factor set at 0.8, which was described in (iii), considering the existing harmonic background at the PCC, leads to a hosting capacity of about 21 kW_p. On the other hand, from the moment the background distortion at the PCC is neglected, and just the fundamental frequency is considered, the hosting capacity for the same situation decreases abruptly to 14 kW_p, which is below the maximum generation capability of the system. For this reason, it is possible to say that, in this case, the higher the harmonic background is, the larger the hosting capacity. Finally, it is important to highlight that, as PF = 0 has been chosen for the worst-case scenario, the unacceptable deterioration area is nonexistent for logical reasons due to the PV system and its operating characteristics.

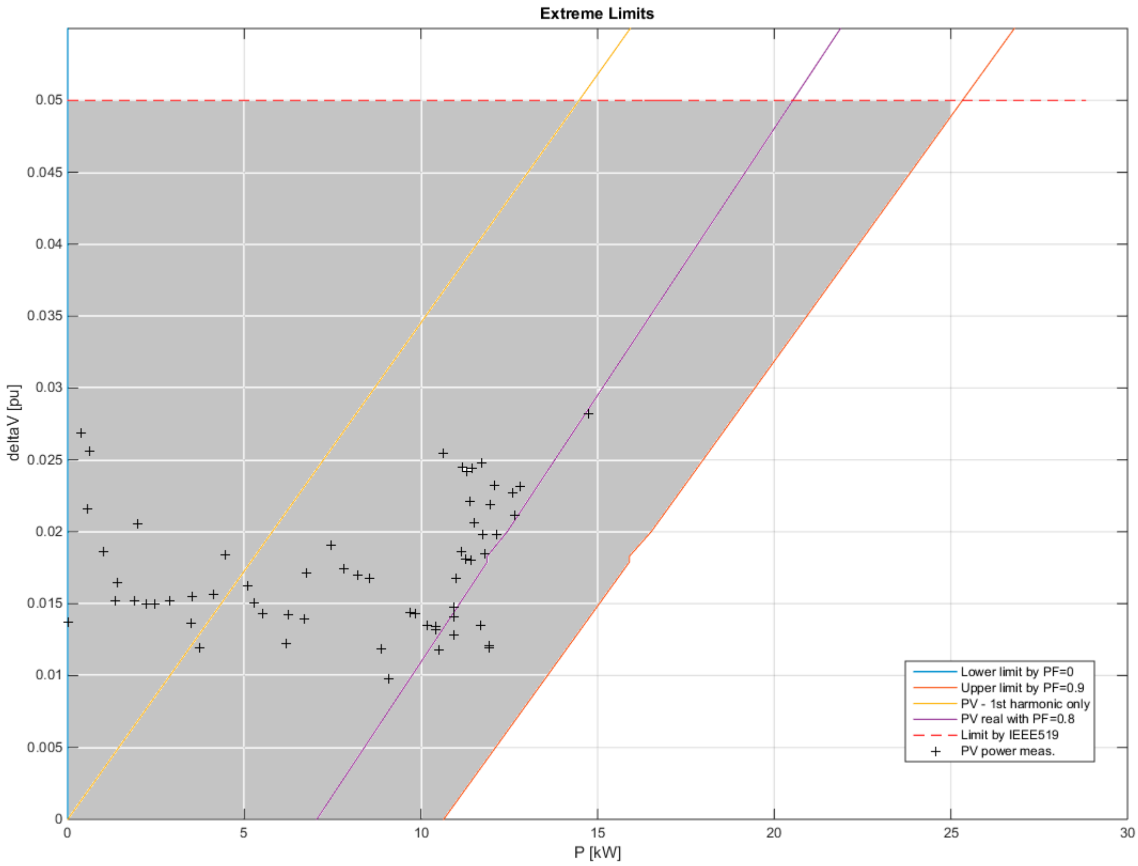

Figure 6. Hosting capacity approach of the four scenarios.

To illustrate the use of the hosting capacity approach discussed before, the following example can define the behavior of the system considering a specific power factor for the lower and upper limits, which will impact the acceptable and unacceptable deterioration regions for the system under analysis. Figure 7 shows the hosting capacity variation for three different power factors: 0.1, 0.6 and 0.9. It is possible to observe that the lower the power factor is, the lower the acceptable deterioration region will be. Moreover, it is important to realize that, even for the best-case scenario, which will set the upper limit, the impact is not as large as the impact in the worst-case scenario, where the amount of energy set is impacted directly by the background at the PCC.

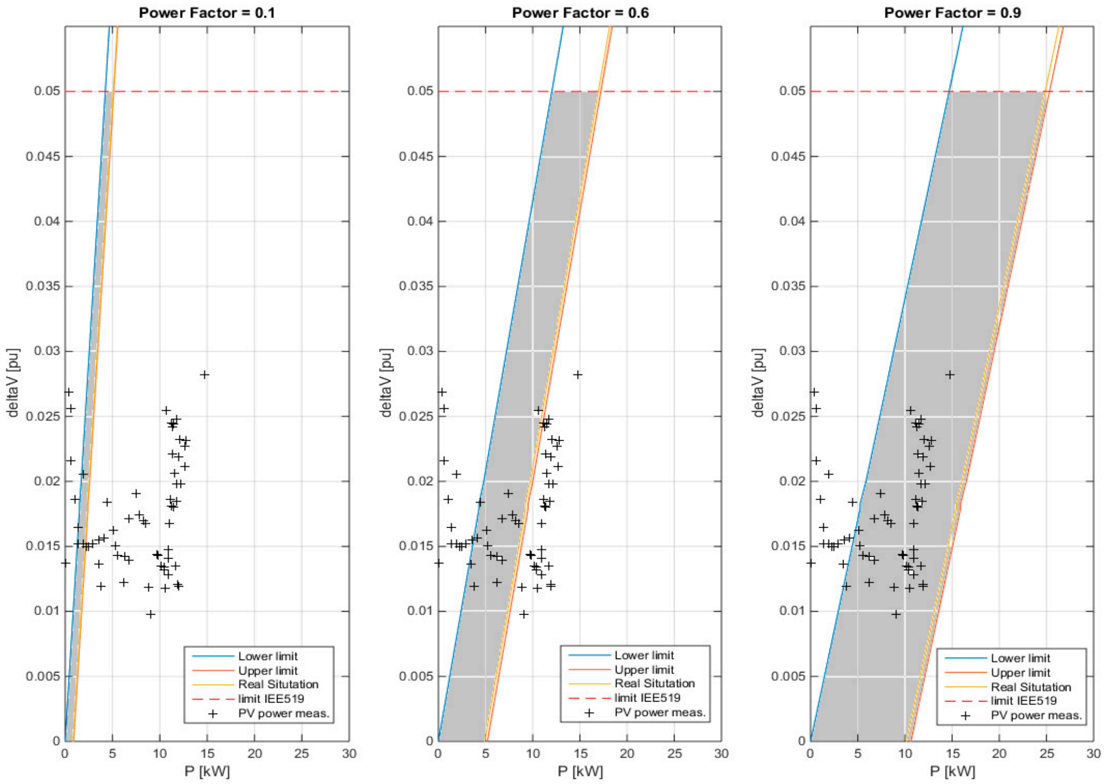

Figure 7. Variation of the hosting capacity region for different power factors.

4. Conclusions

A hosting capacity approach has been introduced as an important planning tool to analyze and predict the impact on power quality of the integration of PV systems into distribution networks. Three concepts were introduced as part of the necessary framework to establish the hosting capacity approach: a performance index, which needs to be established for a specific system under analysis; a corresponding power quality limit, to be defined according to local standards; and a method to calculate the performance index based on the new production and consumption quantities.

The paper proposed a performance index that values voltage rise and harmonic voltage distortion under background harmonic distortion at the PCC for different PV system injection scenarios. Furthermore, the paper compared the proposed approach against other simpler approaches to show that there are significant risks in taking simplistic approaches to determine the system's hosting capacity. The results show, among other things, that the information on background distortion is relevant to determine hosting capacity and that, consequently, one cannot easily determine the generation interconnection limits of a given system without gathering specific data on such distortion.

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Author Contributions: Tiago E. C. de Oliveira conceived and designed the experiments; Tiago E. C. de Oliveira performed the experiments to obtain the data; Tiago E. C. de Oliveira and Pedro M. S. Carvalho analyzed the data obtained; Tiago E. C. de Oliveira, Pedro M. S. Carvalho, Paulo F. Ribeiro, and Benedito D. Bonatto contributed with equipment, models and analysis tools; Tiago E. C. de Oliveira wrote the paper that was further revised by Pedro M. S. Carvalho, Paulo F. Ribeiro, and Benedito D. Bonatto.

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