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Power Quality Analysis for a PV Plant in Uruguay

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Abstract. In this paper is presented the procedure adopted by UTE to study the impact of new Photovoltaic (PV) plants connected into the distribution grid. The studies presented focus on harmonic and flicker emissions. In both cases, international standards are used to estimate emissions in the connection node based on data given by the inverter manufacturers. After this, field measurements are performed first before the new PV plant is connected to evaluate the previous state of the grid, and then after the PV plant is connected, to evaluate the actual impact of the plant. All the measurements and the estimated values obtained in the first stage are compared to the limits provided also by international standards.

The aim of this paper is to present a real case of the first 8MW PV plant connected to the 31,5kV network in Uruguay, along with the standards and criteria adopted. Finally, a brief comparison between theoretical and real values and their limits is presented.

Key words

Harmonic Emission, Flicker Emission, Distributed Generation, Photovoltaic Power Plant, Field Measurements Test.

1. Introduction

One of the most important goals of the Uruguayan Energy policy started in 2005 is to introduce non-conventional renewable energy to cover most of its demand by 2030. Up to now, the most significant part of the non-conventional renewable power generation installed in High Voltage grids is wind and biomass. Photovoltaic energy is mostly connected to Low Voltage (230v and 400V) and Medium Voltage grids (up to 15kV) and represents an almost negligible percentage at a national level.

The first bidding for PV power plants was made in 2013, for 200MW using a feed in tariff mechanism. It´s expected that by 2017, the first 100MW will be connected to the 31,5kV Medium Voltage grid (which can cover the 5% of the peak demand of the country).

The addition of this new power led UTE ("Administración Nacional de Usinas y Transmisiones Eléctricas"), which is a public utility and the only one that performs transmission and distribution activities, to a deep study of the impact of the disturbances produced by the PV systems in the connection node. The generation market consists of UTE and various private agents.

This study can be divided in two stages. The first one consists of calculating the theoretical flicker and harmonic emission based on test reports by the inverter manufacturers and international standards. These standards are [1] and [2]. Until now, [1] was applied only to wind turbine studies, but [2] provides a generalization to all generating units. The second stage consists of analyzing pre and post field measurements. In both stages the data calculated or obtained are compared with the flicker limits defined in [3] and the harmonic limits defined in [4].

The rest of this paper is focused on this study applied to the connection of the first PV plant to the 31,5kV grid. The plant has an installed power of 8MW (13 equal inverters). At the connection node, there is a short circuit apparent power of 83000kVA and the angle of the grid impedance is $\psi_k = 60°$. Measurements were made with a class A equipment, according to [5].

The purpose of this paper is to present the gained experience in the evaluation of the power quality impact of a real PV plant connected to the Medium Voltage grid, how international standards were applied and the criteria adopted in this particular case. The definition for Low, Medium, High and Extra High Voltage systems are taken from [3]. This work sets the basis for all new connection studies in the county.

2. Previous studies

A. Previous study - Harmonic current

During the connectivity study for new PV plants, an important part is to estimate the harmonic current emission at the point of common coupling (PCC). The procedure to do that is the one described in [1]. It is based on data from laboratory tests of harmonic emission of an individual inverter, provided by the manufacturer. The data is presented in a table that for each harmonic from 2 to 50, contains the current for 10% power bins, varying from 0% to 100% of the nominal power. The currents are normalised to the inverter rated current.

The measurements are made on the AC side of the inverter. To pass it to the point of common coupling of the grid, the following equation is applied, according to [6]:

$$I_{h\Sigma} = \sqrt[\beta]{\sum_{i=1}^{N_{wt}} \left(\frac{I_{h,i}}{n_i}\right)^{\beta}} \quad (1)$$

Where:
N_{wt} is the number of inverters connected to the PCC
$I_{h\Sigma}$ is the h'th order harmonic current distortion at the PCC
n_i is the ratio of the transformer
$I_{h,i}$ is the h'th order harmonic current distortion of the i'th inverter
β is the exponent with a value according to table I

Table I. - Summation exponents for harmonics

Harmonic order	β
h <5	1,0
5 ≤ h ≤ 10	1,4
h >10	2,0

As it was said, the values given by the manufacturer are normalised to the rated current so to apply equation (1), and then to express the results again in percentage of the total plant rated current, equation (2) must by applied:

$$I_h = \frac{I_h[\%I_n]}{100} * I_N \quad (2)$$

Where: I_N is the rated current for the AC side of the inverter, or the total rated current of the plant (I_L). The total rated current of the plant is defined as:

$$I_L = \frac{P_N}{\sqrt{3} * U_N} \quad (3)$$

Where:
P_N is the rated power of the plant
U_N is the voltage at the PCC

After this procedure, a similar table from the one given by the manufacturer for one inverter is obtained, but for the whole plant and expressed on the side of the PCC voltage. Each harmonic current distortion (from 2 to 50), expressed in a percentage of the total rated current of the plant, and for each bin (from 0% to 100%) is compared with the limits given in [4] and shown in Table II. The Total Demand Distortion (TDD) is also calculated and compared with the limit in Table II. The equation used to calculate it is:

$$TDD = \frac{\sqrt{\sum_{i=2}^{50} I_{h\Sigma}^{2}}}{I_L} * 100\% \quad (4)$$

Where:
$I_{h\Sigma}$ is the h'th order harmonic current distortion at the PCC
I_L is the maximum load current

Table II. - Current distortion limits from 120V to 69 kV

Maximum harmonic current distortion in percent of I_L					
Individual harmonic order (odd harmonics) [a b]					
3≤h<11	*11≤ h<17*	*17≤ h<23*	*23 ≤h<35*	*35≤h<50*	*TDD*
4,0	2,0	1,5	0,6	0,3	5,0

[a]Even harmonics are limited to 25% of the odd harmonic limits above
[b]Current distortions that result in a dc offset are not allowed

In [4], Table II also depends on the short circuit current, but it is said that all power generation equipment must be limited to the values shown, regardless of the actual short circuit current.

Criteria note: [4] recommends I_L to be the average current of the maximum demand for the preceding 12 months. As this value is difficult to estimate, the criteria adopted is to define it as the total rated current of the plant.

If it is detected that all or some individual harmonics, or the TDD are above the limits, a note is send to the plant owners to inform them of this problem and warn them that if corrective actions are not taken, the plant will not be allowed to connect to the grid.

B. Previous study - Flicker

[1] also describes how to estimate the flicker emission of a whole plant, based on the data given by the manufacturer for an individual inverter. In the case of flicker, this data must be the 99% flicker coefficient $c(\psi_k)$ for some given grid impedance angles (typically 30°,50°, 70° and 85°, as said in [1]). To evaluate the flicker severity, the indicators P_{st} and P_{lt} defined in [7] are used.

As in the harmonic current case, it is necessary to go from one inverter flicker data to the flicker emission of the whole plant. P_{st} and P_{lt} are estimated using the following equation, defined in [1]:

$$P_{st\Sigma} = P_{lt\Sigma} = \frac{1}{S_k} * \sqrt{\sum_{i=1}^{N_{wt}} \left(c_i(\psi_k) * S_{n,i}\right)^2} \quad (5)$$

Where:
S_k is the short-circuit apparent power at the PCC
$c_i(\psi_k)$ is the flicker coefficient of an individual inverter
N_{wt} is the number of inverters connected to the PCC

$S_{n,i}$ is the rated apparent power of an individual inverter
In case of N_{wt} identical inverters, (5) remains as follows:

$$P_{st\Sigma} = P_{lt\Sigma} = \frac{S_n}{S_k} * c_i(\psi_k) * \sqrt{N_{wt}} \quad (6)$$

To compare the obtained P_{st} and P_{lt} values to the standard limits, first they must be calculated. The method is presented in [3]. It sets the compatibility levels for Low Voltage (LV) and Medium Voltage (MV) systems as:

Table III. - Compatibility levels

	Compatibility levels
P_{st}	1,0
P_{lt}	0,8

The planning levels proposed by [3] for Medium, High and Extra High are:

Table IV. - Planning levels

	MV	HV-EHV
P_{st}	0,9	0,8
P_{lt}	0,7	0,6

Considering this planning levels, and a typical transfer coefficient of 0,8 from EHV to HV systems, the global emission levels for HV are:

Table V. –Global emission levels

$G_{Pst\,HV}$	$G_{Plt\,HV}$
0,63	0,47

Based on the global planning levels, individual emission levels can be calculated for each customer connected to the HV system as:

$$E_{Psti} = G_{PstHV} * \sqrt[3]{\frac{S_i}{S_{tHV}}} \quad (7)$$

$$E_{Plti} = G_{PltHV} * \sqrt[3]{\frac{S_i}{S_{tHV}}} \quad (8)$$

Where:
S_i is the agreed power of the customer i
S_{tHV} is the part of the total supply capacity of the HV system which is devoted to HV installations

For customers with low power, the limits calculated in (7) and (8) can be too strict, so [3] defines a minimum basic emission levels as:

Table VI. -Basic emission levels

E_{Psti}	E_{Plti}
0,35	0,25

The planning, global, individual and basic emission levels for HV are presented because in section 4 and 5, a HV case is presented.

Finally, after calculating the estimated P_{st} and P_{lt} and the individual limits, they must be compared. If the estimated values are above the limits, corrective actions must be taken.

3. Adopted criteria

In some cases, standards give some open or ambiguous definitions or criteria, so they must be adopted by the grid owner or together with the plant owners. Following the general criteria adopted by UTE is presented.

After the previous study is done and approved, the plant is connected to the grid and PQ field measurements must be made. The point of measurement must be at the PCC. To consider the measurements valid, they must be of at least 7 consecutive days of normal plant operation and done with a class A equipment, according to [5]. To avoid having to analyze a week when for example there was no sun and no PV unit was generating, it is required for the plant to have produced at least 50% of the rated power, for at least 8 hours (not necessarily consecutives) during that week.

A. Particular criteria for harmonics

Class A equipment provide a minimum, average and maximum value every 10 minutes for each phase for every harmonic and for TDD. Only the average values are compared to the limits in [4]. For the measurement to be approved, for each phase every harmonic and the TDD must be below the limits at least 95% of the time (regardless of the generated power).

B. Particular criteria for flicker

Equations (7) and (8) show how to calculate individual limits, but most recording devices measure global P_{st} and P_{lt}. To calculate the individual emission, two measurements must be done, the first one of one week with the plant disconnected from the grid, and the second one of one week with the plant operating in normal operation, as defined above. As P_{st} and P_{lt} vary throughout the week, 95% percentile of the P_{st} and P_{lt} measurements are taken as the characteristic value. Then, the individual P_{st} emission is calculated, as stated in [3], as:

$$Pst_{plant} = \sqrt[3]{{Pst_{m2}}^3 - {Pst_{m1}}^3} \quad (9)$$

Where:
Pst_{m2} is the 95% percentile of the P_{st} measurement with the plant connected to the grid
Pst_{m1} is the 95% percentile of the P_{st} measurement without the plant connected to the grid

The same procedure is used to calculate Plt_{plant}.

Also, class A equipment have the possibility to flag the measurements where some events (dips, swells or interruptions) happened. The flag function must be enable and flagged data should be excluded from the analysis, because P_{st} and especially P_{lt} are very sensitive to this kind of events. Nevertheless, UTE studies every event to determine if it was caused by the PV plant or it happened somewhere else in the system. In both cases, corrective action should be taken if this events could be frequent.

Finally, as UTE considers the 31,5kV system (defined as MV in [3]) as important as its HV system, HV planning levels are adopted.

4. Application – Previous study

In this section, an application of the procedure for PQ studies is presented for the first PV 8MW plant installed in the 31,5kV grid. It consists of 13 equal inverters with a rated power of 610kW and 7 transformers (31,5/0,38 kV), 6 of 1220kVA and 1 of 610kVA. A simplified electric diagram of the plant is shown below:

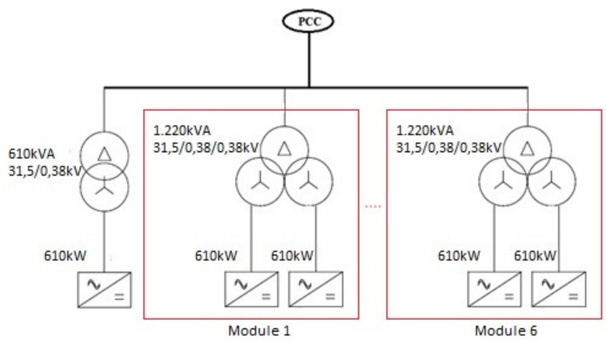

Fig. 1. Simplified electric diagram of the plant

A. Previous study of harmonics

The common data for applying equation (1) for every current harmonic order was:

N_{wt} = 13
n_i = 31,5/0,38

Harmonics for 2 to 50, and for each power bin for 0% to 100%, were compared with values in Table II. All of them were lower than the limits. Due to lack of space, only the estimated values for the first 13 harmonics are shown, expressed in percent of the plant total rated current for each bin:

Table VII- Estimated current harmonic distortion

	Power bin (%)										
h	0	10	20	30	40	50	60	70	80	90	100
2	0,12%	0,22%	0,30%	0,26%	0,26%	0,31%	0,39%	0,40%	0,34%	0,22%	0,29%
3	0,13%	0,19%	0,19%	0,22%	0,36%	0,45%	0,40%	0,33%	0,17%	0,22%	0,39%
4	0,25%	0,27%	0,26%	0,33%	0,34%	0,34%	0,42%	0,42%	0,34%	0,26%	0,36%
5	0,52%	0,57%	0,50%	0,50%	0,49%	0,49%	0,47%	0,49%	0,45%	0,39%	0,53%
6	0,10%	0,10%	0,12%	0,14%	0,18%	0,19%	0,21%	0,21%	0,16%	0,09%	0,17%
7	0,47%	0,61%	0,59%	0,58%	0,60%	0,61%	0,60%	0,58%	0,57%	0,55%	0,63%
8	0,04%	0,05%	0,05%	0,06%	0,07%	0,07%	0,09%	0,09%	0,08%	0,06%	0,06%
9	0,04%	0,05%	0,05%	0,05%	0,05%	0,05%	0,05%	0,05%	0,04%	0,06%	0,05%
10	0,04%	0,05%	0,04%	0,04%	0,05%	0,05%	0,06%	0,05%	0,05%	0,05%	0,05%
11	0,09%	0,10%	0,10%	0,11%	0,11%	0,12%	0,13%	0,13%	0,13%	0,14%	0,14%
12	0,01%	0,02%	0,03%	0,02%	0,02%	0,02%	0,02%	0,02%	0,02%	0,02%	0,02%
13	0,07%	0,08%	0,08%	0,08%	0,07%	0,06%	0,06%	0,06%	0,06%	0,07%	0,07%

B. Previous study of flicker

As stated in section 2, the previous flicker study consist of estimating the emission and determining the limits to apply to the PV plant.
For estimating flicker emission, equation (6) is applied, since all inverters are equal. The data for this particular case was:

S_k = 83000kVA
N_{wt} = 13
$S_{n,i}$ = 610kVA
ψ_k = 60°
$c_i(60°)$ = 3,78

This resulted in an estimated emission for the plant is shown in table VIII:

Table VIII. - PV estimated flicker emission

P_{st}	P_{lt}
0,10	0,10

The data provided by the inverter manufacturer to determine $c_i(\psi_k)$ was:

Table IX. –Flicker coefficients for different grid impedance angles

99% percentile of flicker coefficients for different grid impedances angles				
	Grid impedance angle ψ_k			
	30°	50°	70°	85°
Flicker coefficient $c_i(\psi_k)$	1,31	3,03	4,53	5,09

Since 60° is not in the table, linear interpolation was used to determine $c_i(60°)$.

Flicker emission limits must be also calculated, using equations (7) and (8). To determine S_{tHV} it is necessary to analyse the HV installations involved. That is shown in the simplified diagram below:

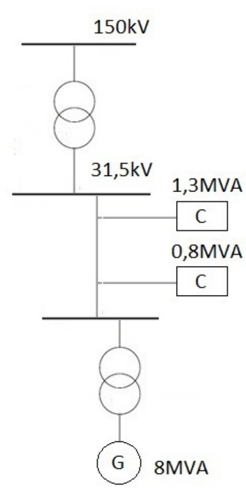

Fig. 2. Simplified electric diagram of the network

Considering this, the data for applying (7) and (8) was:

$S_i = $ 8MVA
S_{tHV} = 10,1MVA
G_{PstHV} = 0,63
G_{PltHV} = 0,47

This resulted in a flicker emission limit of:

Table X. – PV emission limits

E_{Psti}	E_{Plti}
0,58	0,44

Comparing table VIII with table X it is clear that the estimated flicker emissions of the PV plant are lower than its limits.

5. Application – Measurements

As stated in section 3, a measurement in compliance with the requirements is necessary for the plant to be accepted for good. In the case presented, it was one week long and had more than 26 hours producing more than the 50% of its rated power, so it was consider valid.

A. Measurements – Harmonics

Each individual harmonic, from 2 to 50, must be at least 95% of the time below the limits defined in Table II for each phase, expressed in percent of the plant rated current. This was the case for 100% of the time. Below is presented a graph of the most significant harmonics of the plant, which were the 5'th, 7'th, 11'th and 13'th:

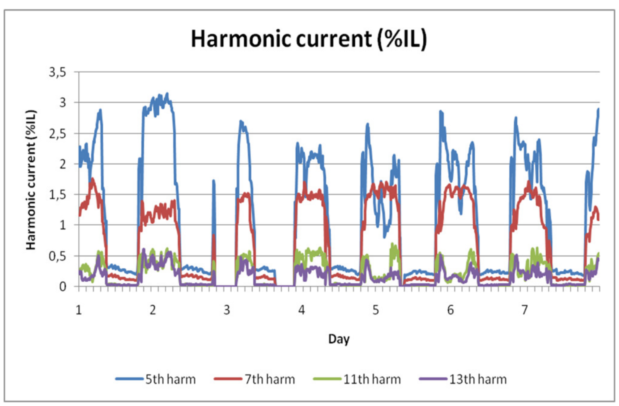

Fig. 3. Most significant plant harmonic emission

It can be seen that all of them are under their limits 100% of the time, so the plant complied the harmonic requirement.

To have an idea of how the emission estimation defined in equation (1) was, a power bin by bin comparison was made. As an example, a graph for the bin 40% (which was the average generated power of the plant, not considering the nighttime) for the first 13 harmonics is shown:

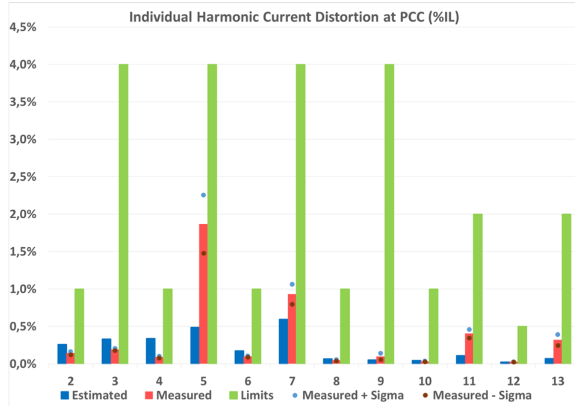

Fig. 4. Harmonic measured, estimated and limits

Note: the measured values shown are the averages of the ones measured when the generated power was between 35% and 45% (around 10% of the total values). The results does not vary very much for the other bins.

It can be seen that for the most significant harmonics, the estimated value is quite smaller than the one measured. For the studied case, the measured values were still always above the limits, but this must be taken into account.

The reason for this phenomenon to appear in these particular harmonics (5'th, 7'th, 11'th and 13'th) is probably that these harmonics are the most common among the grids. To have a better estimation, values of harmonic voltages existing before the plant is installed should be incorporated to the study, especially in weaker grids, where harmonic voltages are most likely to appear.

B. Measurements – Flicker

The following table presents the 95% percentile values of the average of the flicker measurements before (M1) and after (M2) the PV was connected:

Table XI. – Pst and Plt pre and post connection

	M1	M2	Plant*	Limit
P_{st}	0,19	0,26	0,22	0,58
P_{lt}	0,21	0,28	0,23	0,44

Note: in the study the 95% percentile is compared with the limits for each phase, but for space reasons, only the average is presented here.
*plant emission was calculated using equation (9)

The first thing to notice is that the plant flicker emission is below the limit, so the plant complied the flicker requirement.

The estimation for P_{st} and P_{lt} was 0,1 , so it can be seen that estimation was not very accurate for this case.

Some hypothesis can be made for this:
- The 95% percentile may not be the best value to compare with the estimation.

-Equation (9) is based on the cubic sum suggested in [3], but may be that exponent is not the ideal one for this case.
-It also should be noticed that Pst_{m1} and Pst_{m2} are relatively small, so this difference between the estimation and the measurement may be can be ignored.

6. Conclusion

The purpose of this paper is to present a procedure to study and evaluate the PQ effect of the connection of a PV plant to a distribution grid. First it shows how to estimate the flicker and harmonic emission and what limits to apply, using [1], which is widely used for wind farms, for PV plants. Then the evaluation procedure, with the particular criteria adopted by UTE, is shown. To illustrate how it works, an example of the first PV plant study in Uruguay is presented. Finally, a comparison between estimated and measured values is done.

The evaluation procedure and criteria adopted have the advantage of being relatively easy, and have proven to be effective for UTE in the past.

The previous study showed some problems estimating flicker and harmonic emissions. The values measured were, in both cases, bigger than the ones estimated. Even though for the case studied the measured values were acceptable, this particularity must be taken into consideration for future studies. Some suggestions on how to improve the estimations were made, but their effectiveness is yet to be demonstrated.

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