Measurement Based Power Quality Analysis of Real Distribution Networks with High PV Penetration

Tiago R. Ricciardi, Walmir Freitas
Department of Systems and Energy
University of Campinas (UNICAMP)
Campinas, SP, Brazil
{ricciardi,walmir}@ieee.org

Fabio K. Taniguchi, Glaucio R. T. Hax
Converged Networks Division
Centre for R&D in Telecom (CPqD)
Campinas, SP, Brazil
{fabiokt,gtessmer}@cpqd.com.br

Rafael Moya, Giulianno B. Archilli
Strategy and Innovation Division
CPFL Energia
Campinas, SP, Brazil
{moya,giulianno}@cpfl.com.br

***Abstract*—The growth of photovoltaic (PV) systems connection into distribution networks is presenting new challenges to distribution utilities. To prepare itself for this new scenario, CPFL Energia has installed 231 PV systems, totalizing 885 kWp, into a same distribution area in Brazil, to serve as a living laboratory for research. During this project, extensive power quality (PQ) measurements were conducted in different transformers and customers. This paper presents the results of this measurement based PQ analysis for this real distribution networks with high PV penetration. The results show that the most significant PQ issues found related with massive PV penetration are, in order, voltage magnitude rise, current harmonic distortion, voltage unbalance and voltage harmonic distortion.**

***Index Terms*—Distributed power generation, distribution systems, photovoltaics, power quality measurements.**

I. INTRODUCTION

Due to reasons such as the increase in electricity tariffs combined with the reduction of costs in photovoltaic components, the commitment with the transition to cleaner energy sources, and regulatory mechanisms that incentivize the adoption of the technology, the number of small-scale distributed PV systems is growing in Brazil, as in several other countries. The cumulative number of micro (less than 75 kWp) and mini (between 75 and 5,000 kWp) photovoltaic-based distributed generators installations in Brazil over the last years is presented in Fig. 1. Later than in other countries, in Brazil this process started in April 2012, with the introduction of the normative resolution ANEEL 482/2012 [1]. This regulatory act, which defines the conditions to micro and mini generation access to distribution systems, introduced a net metering scheme that allows remote self-consumption and up to 5 years for PV owners spend their generation surplus injected into the grid.

Despite the social, economic and environmental benefits of widespread small-scale PV generation, the increasing penetration of such renewable energy source is posing technical challenges for distribution utilities [2]. Since roughly 90% of more than 23,000 micro or mini PV systems in Brazil has an installed capacity smaller than 15 kWp [3], most of those small distributed energy resources are connected into low voltage (LV) distribution networks, which traditionally were not designed to accommodate significant power generation [4]. The connection of those PV systems can lead to undesired technical issues, especially in aspects related to voltage quality (voltage rise beyond the statutory levels, three-phase voltage unbalance, and harmonic distortion, to cite some). Distribution utilities are concerned with this new scenario, which might result in changes on their planning and operation procedures to cope with the ongoing increase of PV connections into their LV networks.

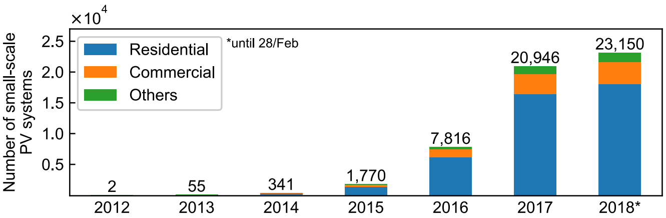

Fig. 1. Number of small-scale PV systems connections in Brazil [3].

In this context, CPFL Energia, a major distribution utility in Brazil, recently installed 231 PV systems concentrated in two medium voltage (MV) distribution feeders in São Paulo state, within the scope of the Solar Rooftop R&D Project. This initiative aims to serve as a living laboratory where utility engineers and researchers are developing solutions to mitigate technical issues related with the massive connection of PV systems in distribution networks. Extensive measurements have been collected from several points of this living laboratory such as service transformers and customer premises to investigate power quality issues related to PV distributed generation.

The main objective of this paper is to present and analyze the obtained results, identifying and discussing the impacts of PVs into the network voltage quality and harmonic distortions. The remaining sections are organized as follows. Section II presents an overview of the project, describing the characteristics of the distribution network, the PV systems, and the power quality apparatus used to collect the measurement data. The evaluation of the performance ratio of the installed PV systems are presented in section III. Section IV presents the main results of this paper, analyzing the voltage quality and harmonic distortion. The conclusions are presented in section V.

II. OVERVIEW OF THE SOLAR ROOFTOP PROJECT

The Solar Rooftop Project has developed a living lab in the city of Campinas, SP, Brazil, where measurement data from PV systems are being collected to investigate the impacts and develop solutions for the technical issues related to the massive penetration of distributed solar generation. This section presents an overview of the distribution network and the PV systems involved in the Solar Rooftop Project as well as the apparatus installed for measurements.

978-1-5386-0517-2/18/$31.00 ©2018 IEEE

A. MV and LV Distribution Network

The rooftop PV systems were installed in 68 LV networks of 2 MV feeders of the same distribution substation, as presented in Fig. 2. The LV networks are three-phase, four-wires (220 V) and the MV feeders are three-phase (11.4 kV), both radial with overhead lines. The pole-mounted Δ-Y connected transformers that supplies those 68 LV networks ranges from 15 to 150 kVA and from 2 to 122 customers. This distribution network supplies an urban area, where 90% of customers are residential and 9% are commercial, with daily load peaks of 9.5 MVA in average.

B. Rooftop PV Systems

A total of 231 rooftop PV systems were installed within the scope of the project, with capacities ranging from 2 kWp (small households) to 50 kWp (medium commercial customer). The aggregated installed capacity of PV generation is 885 kWp, with 310 kWp in Feeder 1 and 575 kWp in Feeder 2. All the PV systems use the same model of PV panel (Canadian Solar CS6P), but different manufacturers and models of inverters.

Considering the ratio between the aggregated PV generation per feeder (kW) and the corresponding feeder loading measured at the head of the feeder (kW), the PV generation corresponds to average daily peaks of 3-4% in Feeder 1 and 15-20% in Feeder 2. Although those numbers are relatively low when compared with some parts where distributed PV generation are much more developed than in Brazil, some LV networks in the project has much higher penetrations. For instance, the 10 LV networks with higher PV penetrations (the ratio between the aggregated PV capacity, in kWp, and the transformer capacity, in kVA) are presented in Table I. Notice that all of them have penetration levels higher than 44%.

C. Power Quality Measurements Apparatus

The measurements that will be later discussed were collected by two PQ meters model Fluke 435 Series II, named meters A and B. Although the project has monitored more than 50 points among customers and transformers, this paper focus in the 12 points presented in Table II, where the corresponding period of monitoring and the meter used are presented. The type column refers either to a MV/LV transformer (TR) or to a customer (CM). In the transformers, the PQ meter is installed in the secondary side while in the customers it is installed in the service cable, close to the customer energy meter. The transformers listed in Table II supplies 25% of the customers participating in the project, have different PV penetrations and locations within the MV feeder. The 12 points also includes the largest PV systems (50 and 20 kWp) and 4 of the 10 transformers with the highest PV penetrations. Therefore, this set selected for analysis can be considered representative of the Solar Rooftop Project.

The PQ meters registered RMS measurements of voltages and currents (magnitude and phase angle) per phase and neutral up to the 50th harmonic, as well as some related quantities (Total Harmonic Distortion, Total Demand Distortion, Unbalance Factor, complex power, etc.). The measured values were registered in intervals of 10 seconds. In the following sections, the main power quality aspects related with the massive penetration of distributed PV generation will be assessed based on the data collected from the PQ meters.

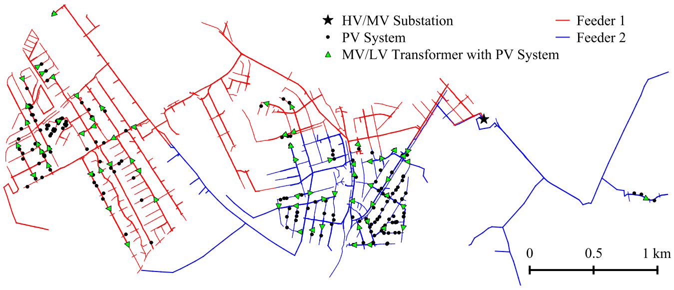

Fig. 2. Solar rooftop project living laboratory distribution network.

TABLE I. MV/LV TRANSFORMERS WITH THE HIGHEST PV PENETRATIONS

Transformer	*Customers with PV Systems*	*Number of Customers*	*PV Capacity (kWp)*	*Transformer Capacity (kVA)*	*Penetration (%)*
34101007	14	36	43	45	96
34101555	5	14	14	15	93
34099438	27	47	67.5	75	90
34101752	15	65	36.2	45	80
34101681	7	18	23.2	30	77
34100924	3	46	27.6	45	61
34101824	7	23	17.2	30	57
34101053	6	51	25.2	45	56
34101837	9	27	25.2	45	56
34101427	1	20	50	112.5	44

TABLE II. SCHEDULE OF THE PQ MEASUREMENT DATA COLLECTED

#	*Type*	*ID*	*Feeder*	*Meter*	*From*	*Until*	*Duration*
1	TR	34099438	1	A	14/03/2017 16:21:51	20/04/2017 10:19:31	36d 17h 57m 50s
2	CM	35408618	1	B	15/03/2017 13:41:17	04/04/2017 13:33:37	19d 23h 52m 30s
3	TR	34101752	2	B	07/04/2017 14:22:46	05/05/2017 13:28:36	27d 23h 6m 00s
4	TR	34099185	1	A	20/04/2017 10:44:12	20/05/2017 10:44:02	30d 00h 00m 00s
5	CM	42060630	1	B	10/05/2017 11:49:12	22/05/2017 14:59:02	12d 03h 10m 00s
6	CM	10617604	2	B	12/06/2017 10:01:44	21/06/2017 09:06:04	08d 23h 04m 30s
7	CM	10636331	2	B	26/06/2017 09:38:13	04/07/2017 10:03:13	08d 00h 25m 10s
8	TR	34101837	2	A	06/06/2017 15:23:12	06/07/2017 15:23:02	30d 00h 00m 00s
9	CM	10639985	2	B	31/07/2017 09:40:28	09/08/2017 13:18:48	09d 03h 38m 30s
10	TR	34101427	2	A	28/07/2017 10:33:17	27/08/2017 10:33:07	30d 00h 00m 00s
11	TR	227062439	2	A	06/09/2017 10:11:06	06/10/2017 10:10:56	30d 00h 00m 00s
12	CM	10638385	2	B	11/09/2017 14:05:03	21/09/2017 13:55:53	09d 23h 50m 50s

III. PV SYSTEMS PERFORMANCE RATIO

Each one of the 231 PV systems has a local measurement and monitoring system, capable to measure, record and transmit data to a remote server. The collected measurements are voltages, currents, and active powers, per phase and per PV panel string, at both sides (AC and DC) of the PV inverter, in intervals of 1 minute. A schematic diagram of the PV systems, with the measurement and monitoring system, is presented in Fig. 3. Moreover, a weather station with a pyranometer was also installed in the area of the living laboratory, measuring the temperatures and solar irradiances in intervals of 1 minute. With the data acquired from the monitoring systems and the weather station, it is possible to evaluate the PV systems efficiency and the performance ratio (PR) index.

The performance ratio, usually given in percentage, is a parameter of the performance of the PV system, independent of the location and often described as a quality factor of the installation [5]. Equation (1) indicates how to calculate the PR of the PV system.

$$PR = \frac{E_{ac}}{I_S \cdot A \cdot \eta_p \cdot \eta_i} \cdot 100\% \qquad (1)$$

where E_{AC} is the output energy generated at the AC terminal of the inverter (kWh), I_S is the solar irradiance (kWh/m^2), A is the area of PV panels (m^2), η_p is the PV panels (modules) efficiency (%), and η_i is the PV inverter efficiency (%).

The closer the PR calculated for a PV system approaches 100%, more efficient is the installation. For this analysis, it was

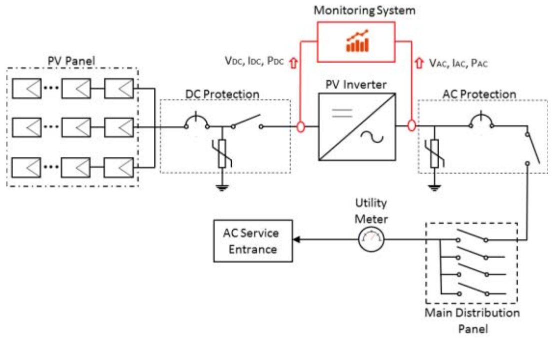

Fig. 3. Schematic diagram of the PV systems connection and the corresponding measurement and monitoring system.

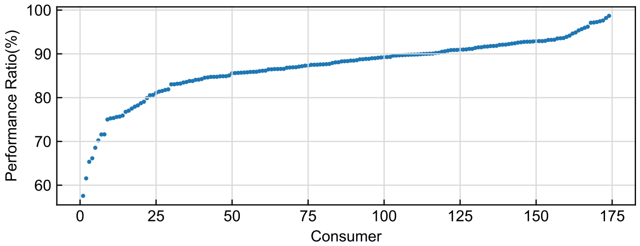

Fig. 4. Performance ratio of the PV systems for the period Mar-Sep/2017.

considered the values measured by the monitoring systems and the weather station between March and September 2017. Figure 4 shows the PR values of the PV systems for this period, where 64 PV systems presented a PR lower than 80% and the remaining 167 presented a PR higher than 80%. The low PR in some installations are due to partial shading on PV modules caused by obstacles such as trees and buildings.

IV. POWER QUALITY ANALYSIS

This section presents the power quality analysis of the impact of the PV systems connection in the distribution system of the living laboratory of the Solar Rooftop Project. The power quality indices are evaluated according to the Electric Power Distribution Procedures (PRODIST), a standard elaborated by the Brazilian Electricity Regulatory Agency (ANEEL), which establishes the technical aspects regarding distribution systems in Brazil, including power quality [6].

It is important to emphasize that the PV inverters used in the project are certified according to the ABNT NBR 16149 [8]. This standard stablishes specific recommendations for the interface between PV systems and the distribution network and define limits for current harmonic distortions. This standard is mainly based on the international standards IEC 60364-7-712, IEC 61000-3-3, IEC 61000-3-11 and IEC 61000-3-5.

A. Methodology

The measurements were performed with two analyzers capable of recording the measurement data and to calculate several power quality indicators, in accordance with IEC 61000-4-30 [7]. The PQ meters were installed simultaneously, one at the secondary of a transformer and another at one of the corresponding customers with a PV system connection. Figure 5 shows an example of the PQ meters installation at the transformer and in one of its PV customers.

(a) (b)

Fig. 5. PQ meter installed (a) at the secondary of the transformer 34099438 and (b) at the point of connection of the customer 35408618.

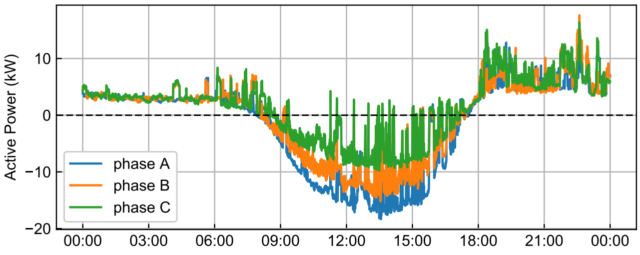

Fig. 6. Active power flow at transformer 34099438 on 29/Mar/2017.

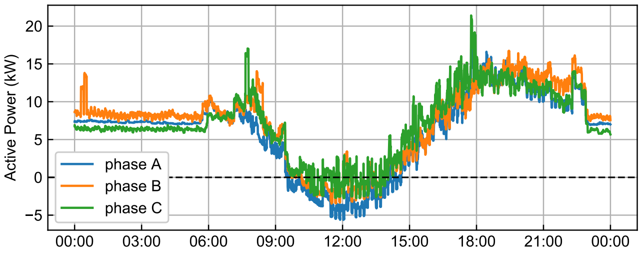

Fig. 7. Active power flow at transformer 34101427 on 24/Aug/2017.

The analysis is focused on the measurements of 2 customers and their corresponding 2 MV/LV transformers (#1-2 and 9-10 in Table II). Later, power quality indices for other points monitored will be presented, summarized at the end of this paper. The first group consist of measurements at the transformer (34099438) and at one customer (35408618) of a LV network with 90% of PV penetration. This LV network supplies 47 residential customers, 36 supplied by 3-phases, 4-wires and 11 supplied by 2-phases, 3-wires. A total of 67.5 kWp of PV generation is connected into this LV network (27 PV systems of 2.5 kWp / 220 V, i.e., line-to-line connected). The LV network transformer has a nominal capacity of 75 kVA.

The second group consist of measurements at the transformer (34101427) and at one photovoltaic customer (10639985) of a LV network with 44% of PV penetration. This LV network supplies 20 customers, 12 residential (1 three-phases, four-wires, 4 two-phases, three-wires, and 7 single-phase, two-wires) and 8 commercial (3 three-phases, four-wires and 5 two-phases, three-wires). One of the commercial customers has a three-phase 50 kWp PV system. The LV network transformer has a nominal capacity of 112.5 kVA.

It is important to highlight that in both cases there is significant reverse active power flow at the transformers during some intervals of high aggregated generation combined with low aggregated demand. Examples of this condition can be seen in Fig. 6, presenting the aggregated load curve of the transformer 34099438 for March 29th, and in Fig. 7, in the aggregated load curve of the transformer 34101427 for August 24th.

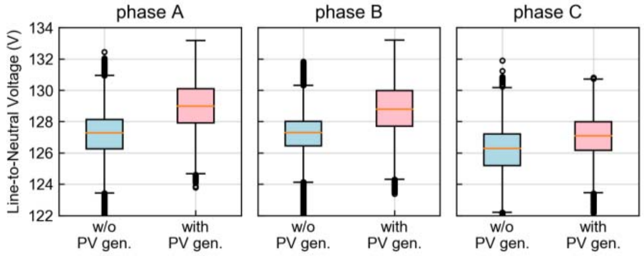

Fig. 8. Distribution of voltage magnitude per phase for customer 35408618, considering the periods with and without PV generation.

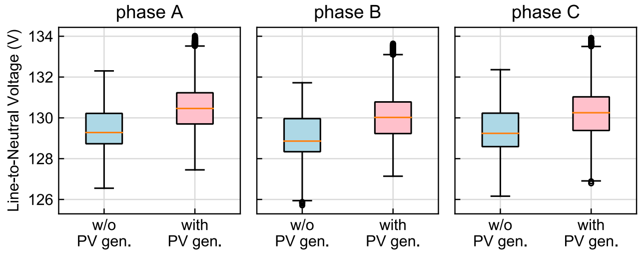

Fig. 9. Distribution of voltage magnitude per phase for customer 10639985, considering the periods with and without PV generation.

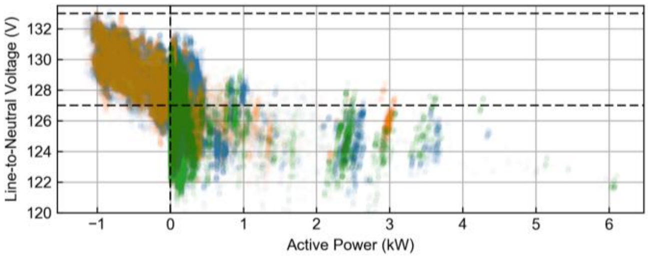

Fig. 10. Relation between voltage and power for customer 35408618.

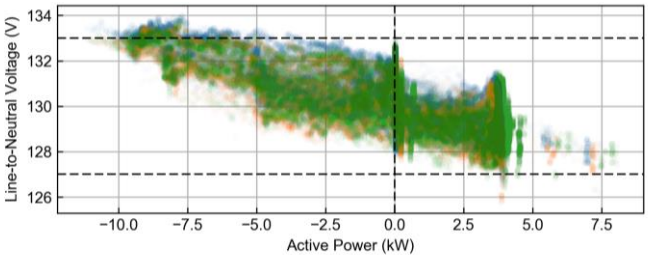

Fig. 11. Relation between voltage and power for customer 10639985.

B. Voltage Magnitude

Section 8.1.2 of PRODIST categorizes the steady-state voltage magnitude at the point of common coupling between the customer and the distribution network (V_m) in three classes:

- Adequate: $117\text{ V} \leqslant V_m \leq 133\text{ V}$
- Precarious: $110\text{ V} \leqslant V_m < 117\text{ V}$ or $133\text{ V} < V_m \leq 135\text{ V}$
- Critical: $V_m < 110\text{ V}$ or $V_m > 135\text{ V}$

A transgression occurs if the 97th percentile of the 10-minute average measurements over a week is classified as precarious and/or if the 99.5th percentile is classified as critical. For the customer 35408618, it was obtained 131.79 and 130.61 V for the 97th and the 99.5th percentiles; for the customer 10639985, the values obtained for the same percentiles are, respectively, 133.51 and 133.09 V. The second customer has, therefore precarious overvoltage while the first, although has adequate voltage supply, is close to the statutory limits.

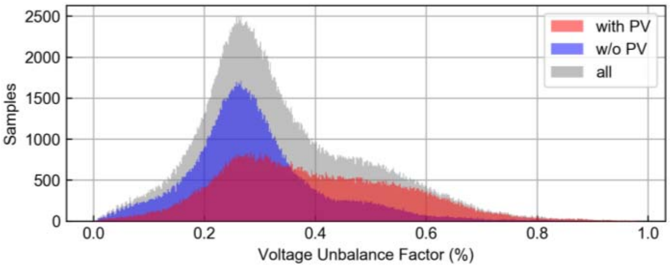

Fig. 12. Voltage unbalance factor distribution for transformer 34099438.

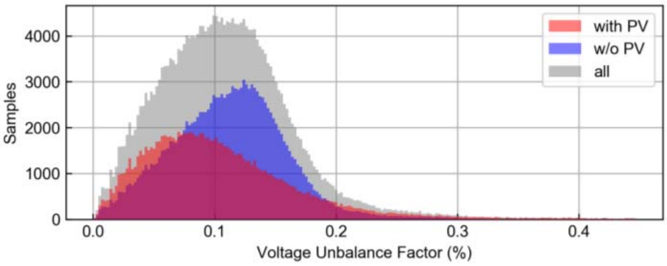

Fig. 13. Voltage unbalance factor distribution for transformer 34101427.

The distribution of the voltage magnitude at the customers 35408618 and 10639985 connection points are respectively presented in Fig. 8 and Fig. 9 using boxplots per each phase, during the periods with and without PV generation (based on the solar irradiance measured at the weather station). It can be noted an increase in the voltage magnitude values during the periods with PV generation. Furthermore, to complement this analysis, Fig. 10 and Fig. 11 shows how the voltage magnitude increases with the reversion of the active power flow respectively on customers 35408618 and 10639985, where negative values denote power injection into the network.

C. Voltage Unbalance

Most of LV customers in Brazil are served by two- or three-phases with three- or four-wires. This allows a connection of PV inverters better balanced than single-phase, line-to-neutral ones. Therefore, compared to some North-American or European network topologies, the increase penetration of PV systems in Brazilian LV networks may not result in significant voltage unbalance during generation periods.

According to PRODIST section 8.1.5, the Voltage Unbalance Factor (VUF), given in percentage, can be calculated by the ratio between the negative (V_-) and the positive (V_+) sequence voltage magnitude, as shown in (2). For MV and LV networks it should be limited in 3% based on the 95th percentile of the 10-minute average measurements over a week.

$$VUF = \frac{V_-}{V_+} \cdot 100\% \tag{2}$$

Histograms for the VUF distribution considering periods with and without PV generation are shown in Fig. 12 (xfmr. 34099438) and in Fig. 13 (xfmr. 34101427). In the first case, with multiple two-phase inverters randomly connected in the LV network, it can be seen a voltage unbalance increase due to PV generation, although yet far from the 3 % limit. This is different in the second case; the presence of a single three-phase 50 kWp inverter helps to balance the network and, therefore, it can be noted a VUF reduction during periods of solar generation.

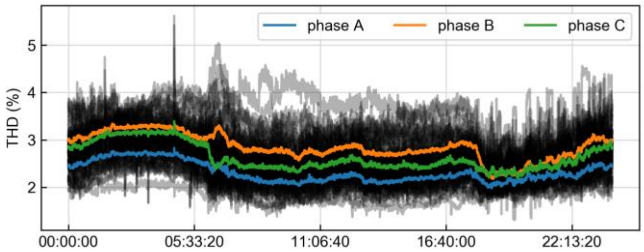

Fig. 14. THD_v profile measured for customer 35408618.

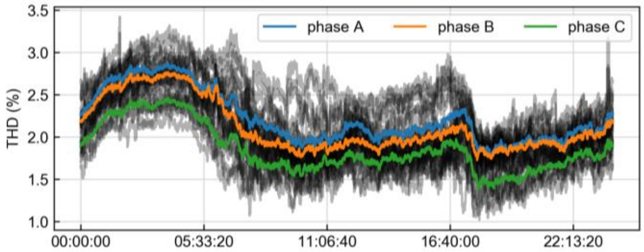

Fig. 15. THD_v profile measured for customer 10639985.

D. Voltage Harmonic Distortion

It is well known that the proliferation either at the utility or customer sides of nonlinear electronic equipment such as PV inverters can cause harmonic distortion of voltage and current waveforms, resulting in potential transformer and cables overheating, resonance and false operation of protection devices, which eventually decreases power quality [9].

Harmonic distortion related with inverter-based DG are, therefore, a major concern for utilities. In the presented analysis, to investigate if the connection of PV systems is resulting in such issue, the Total Voltage Harmonic Distortion (THD_v) and Individual Voltage Harmonic Distortions (IHD_v) for odd components up to the 15th order were evaluated. According to PRODIST, the limits for the voltage harmonic distortion should be applied in the 95th percentile of the 10-min average measurements over a week. The THD_{v95} values obtained were 3.71, 2.91, 3.58, and 2.89% for customer 35408618, 10639985 and xfmr. 34099438, 34101427, respectively. The 5th harmonic voltage distortion ($IHD_v{}^{5}{}_{95}$) is the individual component with the highest distortion observed, with 3.26, 2.39, 3.21, and 3.11%.

To explore if there is any correlation between the THD_v observed and the PV generation, its values for multiple days were overlapped in a 24-hours window in Fig. 14 for customer 35408618 and in Fig. 15 for customer 10639985, together with curves for the average behavior among multiple days. In both cases, there is no evidence that the connection of inverters has increased the THD_v: the voltage distortion is, in general, higher during the night, i.e., without PV generation, and the 95th percentile values are exceeded generally during periods without generation. Furthermore, the correlation coefficient between the THD_v and the PV power is -0.16 and -0.23 for customers 35408618 and 10639985; these values indicate a weak correlation and reinforce that no evidence linking the connection of inverters with increase in THD_v was found in the project.

These results are due to the fact that, while PV inverters are certified according to standards, other appliances do not have limits for harmonic injection. For instance, it is common in Brazilian households the use of electric showers greater than 4 kW with TRIACs to regulate the water temperature, generating more harmonic distortion than the PV inverters.

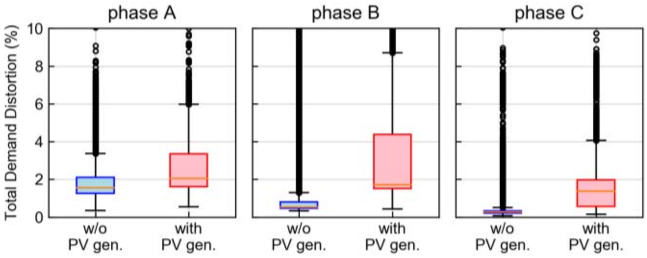

Fig. 16. Distribution of TDD per phase for customer 35408618, considering the periods with and without PV generation.

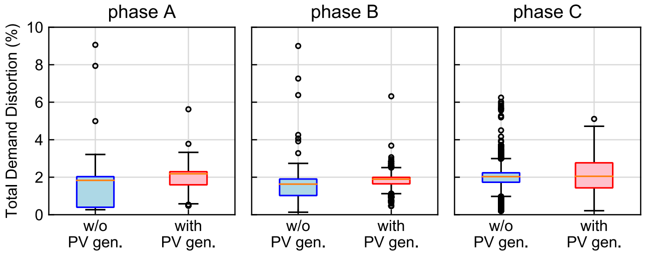

Fig. 17. Distribution of TDD per phase for customer 10639855, considering the periods with and without PV generation.

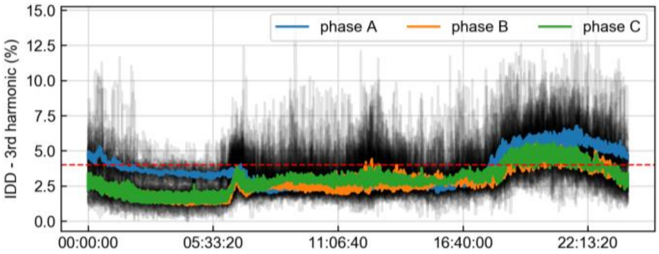

Fig. 18. IDD_3 profile measured for transformer 34099438.

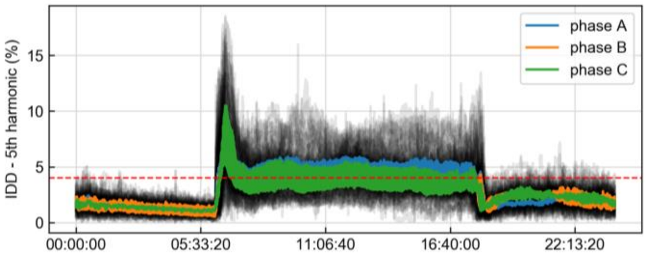

Fig. 19. IDD_5 profile measured for transformer 34099438.

E. Current Harmonic Distortion

Since PRODIST does not stablishes limits for current harmonic distortions, this analysis considers the guidelines of IEEE Std. 519-2014 [10], where it recommends the limits according to the relation between the maximum short-circuit current at the point of common coupling (I_{SC}) and the maximum Demand Distortion (TDD) obtained from the measurements are presented in Fig. 16 for customer 35408618 and in Fig. 17 for customer 10639855, where can be clearly noted an increase on the TDD during periods of PV generation.

To further investigate the relation between current harmonic distortion and the PV generation, Fig. 18 and Fig. 19 shows values for IDD for 3rd and 5th harmonic order measured at the xfmr. 34099438 for multiple days overlapped in a 24-hours window. The measurements compiled in those figures indicate

TABLE III. SUMMARY OF THE POWER QUALITY INDICATORS MEASURED DURING THE SOLAR ROOFTOP PROJECT

	Metric	Limit	Transformer					Customer					
			34099438	**34101752**	**34101837**	**34101427**	**227062439**	**35408618**	**42060630**	**10617604**	**10636331**	**10639985**	**10638385**
Voltage Magnitude	**V_{max} (V)**	**-**	135.47	135.35	134.47	133.21	137.29	133.21	131.44	137.86	133.99	134.02	134.57
	$V_{99.5}$ (V)	**135**	130.50	134.25	133.67	132.47	133.34	131.79	129.66	**137.10**	133.00	133.51	133.74
	V_{97} (V)	**133**	129.89	**133.71**	**133.29**	132.11	**133.09**	130.61	128.92	**136.50**	132.31	**133.09**	**133.48**
Voltage Unbalance	**VUF_{95} (%)**	**3.0**	0.63	0.63	0.97	0.20	0.21	1.35	*	1.26	*	0.23	0.68
Voltage Distortion	**$THDv_{95}$ (%)**	**10.0**	3.58	3.10	3.38	2.89	2.53	3.71	4.19	3.44	2.97	2.91	2.63
	$IHDv^{3}_{95}$ (%)	**6.5**	0.78	1.40	1.51	0.91	0.55	1.32	3.05	0.82	1.67	0.77	0.85
	$IHDv^{5}_{95}$ (%)	**7.5**	3.21	3.48	3.96	3.11	2.72	3.26	4.33	3.01	2.54	2.39	2.74
	$IHDv^{7}_{95}$ (%)	**6.5**	1.45	2.04	2.11	2.12	2.02	1.52	2.44	1.93	1.59	1.60	2.05
	$IHDv^{9}_{95}$ (%)	**2.0**	0.29	0.55	0.58	0.43	0.37	0.73	1.53	0.30	0.63	0.39	0.48
	$IHDv^{11}_{95}$ (%)	**4.5**	0.43	0.80	0.74	0.72	0.58	0.60	1.09	0.54	0.68	0.69	0.63
	$IHDv^{13}_{95}$ (%)	**4.0**	0.18	0.47	0.38	0.59	0.29	0.24	0.65	0.33	0.33	0.57	0.35
	$IHDv^{15}_{95}$ (%)	**1.0**	0.17	0.40	0.42	0.34	0.15	0.38	0.84	0.22	0.33	0.31	0.20
Current Distortion	**TDD_{95} (%)**	**5.0**	**8.85**	**8.86**	**7.27**	**7.07**	**10.63**	**5.73**	**6.02**	3.52	**6.32**	3.13	**10.26**
	IDD^{3}_{95} (%)	**4.0**	**6.33**	**8.09**	**6.60**	**4.35**	**8.34**	2.69	3.60	2.81	2.49	1.93	**8.72**
	IDD^{5}_{95} (%)	**4.0**	**7.51**	3.85	3.13	**4.23**	**6.98**	2.74	**5.88**	1.56	1.82	1.89	**7.30**
	IDD^{7}_{95} (%)	**4.0**	2.51	2.15	1.89	3.71	2.99	3.51	**4.07**	1.17	1.14	1.36	**5.77**
	IDD^{9}_{95} (%)	**4.0**	1.15	1.40	1.24	1.51	2.10	2.89	3.39	0.75	0.67	0.83	2.68
	IDD^{11}_{95} (%)	**2.0**	1.08	1.34	0.82	1.71	1.63	1.09	1.81	0.64	0.48	0.58	1.51
	IDD^{13}_{95} (%)	**2.0**	0.61	0.93	0.65	1.27	0.79	0.48	0.68	0.50	0.48	0.57	1.87
	IDD^{15}_{95} (%)	**2.0**	0.51	0.81	0.51	0.72	0.47	0.38	0.68	0.31	0.42	0.36	0.68

*For customers supplied by two-phase, three-wire service cables it is not possible to evaluate the voltage unbalance factor at the point of common coupling.

current harmonic distortion above the recommended levels; the 3rd harmonic distortion does not reveal evidence that it is correlated with the PV generation, but for the 5th harmonic there are indications that it is related with the operation of the PV inverters. The 3rd harmonic current distortion is likely being produced by the house appliances of the customers supplied by the xfmr. 34099438 and the 5th harmonic current distortion can be either being produced by the inverters or being filtered by the inverters due to the relatively high level oh 5th harmonic voltage distortion. For the data presented in Fig. 18 and Fig. 19, the correlation coefficients between IDD^3, IDD^5 and the PV generation are -0.25 and 0.54. This suggests a weak correlation between the 3rd harmonic current distortion and the PV generation, and some relevant correlation between the 5th harmonic current distortion and the PV generation.

V. CONCLUSIONS

This paper presented the results of a measurement based power quality analysis of real distribution networks from the Solar Rooftop Project, where to investigate the impacts resulting from the expected growth in PV penetration, CPFL Energia has installed 231 small-scale photovoltaic generators in 68 different LV networks of 2 MV distribution feeders in the city of Campinas, SP, Brazil. In terms of voltage quality, the most impacted aspect due to the massive penetration of small-scale distributed PV systems is the rise in the voltage magnitude. This is mainly caused because of the combination of reversed power flow (high generation, low demand) and the resistive characteristic of the LV network conductors. Voltage unbalance can also be affected by the connection of PV systems; however, this issue is solved relatively easy if the phase connection of the customers and the PV inverters are properly rebalanced.

The measurements do not present any compelling evidence that voltage harmonic distortion is a major issue to be considered by the distribution utility. The levels of distortion observed over the day, during the periods of solar generation, are smaller than observed over the night, when the distortion is accentuated due to the normally light loading of the distribution networks. Regarding current distortion, although not limited in Brazil by PRODIST, some evidences that the PV inverters might be increasing the distortion were found, although further investigation should be done.

A summary of the power quality indicators obtained during the monitoring of six customers with its six corresponding service transformers is presented in Table V. From the results it can be noted that, regarding voltage quality aspects, the following order of relevance should be considered by the utility: voltage magnitude, voltage unbalance, voltage distortion; and current distortion might be affected.

ACKNOWLEDGMENT

This work has been funded by CPFL Energia under the ANEEL R&D program PD-0063-3012/2014.

VI. REFERENCES

[1] Brazilian Electricity Regulatory Agency (ANEEL), "Normative Resolution 482/2012," April 2012.

[2] J. R. Agüero and S. J. Steffel, "Integration challenges of photovoltaic distributed generation on power distribution systems," in *Proc. 2011 IEEE PES General Meeting*, pp.1–6.

[3] Brazilian Electricity Regulatory Agency (ANEEL), "Consumer units with distributed generation." [Online]. Available: http://www2.aneel.gov.br/scg/gd/gd.asp.

[4] L. F. Ochoa and P. Mancarella, "Low-carbon LV networks: challenges for planning and operation," in *Proc. 2012 IEEE PES General Meeting*, pp.1–2.

[5] SMA, "Performance ratio: Quality factor for the PV plant." Available: http://files.sma.de/dl/7680/Perfratio-TI-en-11.pdf

[6] Brazilian Electricity Regulatory Agency (ANEEL), "PRODIST – Distribution Procedures." [Online]. Available: http://www.aneel.gov.br/prodist.

[7] IEC 61000-4-30:2015, "Electromagnetic compatibility (EMC) - Part 4-30: Testing and measurement techniques - Power quality measurement methods," pp.1–146.

[8] ABNT 16149:2013, "Photovoltaic systems – Characteristics of the utility interface," pp1–12.

[9] M. Farhoodnea, A. Mohamed, H. Shareef and H. Zayandehroodi, "Power quality impact of grid-connected photovoltaic generation system in distribution networks," in *Proc. 2012 IEEE Student Conference on Research and Development* (SCOReD), pp.1–6.

[10] IEEE Std. 519-2014, "IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems," pp.1–29.