DOI: 10.48011/asba.v2i1.1626

A Long Term Evaluation of Photovoltaic Systems under Power Quality Problems

Fernanda M. Q. Silva*. Igor A. Pires.**
Thales A. C. Maia***

**Programa de Pós-Graduação em Engenharia Elétrica, Universidade Federal de Minas Gerais, Belo Horizonte, MG*
Brazil (e-mail: fquintaosilva@gmail.com).
***Departamento de Engenharia Eletrônica, Universidade Federal de Minas Gerais, Belo Horizonte, MG*
Brazil (e-mail: iap@ufmg.br)
**** Departamento de Engenharia Elétrica, Universidade Federal de Minas Gerais, Belo Horizonte, MG*
Brazil (e-mail: thalesmaia@cpdee.ufmg.br)

Abstract: This paper presents an analysis of a working solar power plant in regards to power quality problem. Instead of focusing on power quality problems that can arise in the grid due to the connection to a photovoltaic power plant, the focus of this paper will be the devices of the power plant. The goal is to understand the impact of power quality events in them, particularly inverters, regardless of their origins - the main grid or the photovoltaic generation. This paper analyzes more than 100 voltage sag events and 30 voltage swell events detected during the operation. It also verifies measurement of voltage THD of approximately 2.2% against IEEE and ICE standards.

Keywords: solar power, power quality, harmonics, unbalance, voltage sag, voltage swell.

1. INTRODUCTION

The worldwide energy demand is deeply connected to population growth and technological development; as both of them rise so does the demand for energy. Statistics show that, in the next fifteen years, the demand for energy will increase by 41% (Bp Energy Outlook. 2020). In order to meet this rising demand and supply clean energy avoiding the environmental harm that fossil energy is linked to (Cabrera-Tobar et al. 2016), the investment in renewable energy sources, such as wind and solar, is rising. This investment led to a higher viability of building photovoltaic (PV) power plants, since the cost of production lowers with the development of the technology. Many countries today are stimulating the usage of renewable energy by its citizens and solar energy is the leading alternative in this area. Also financial incentives are given in order to increase the number of PV stations engaged in the energy generation (Ylmar et al. 2017).

Not only is the usage of solar energy increasing for low voltage consumption, such as houses, it has also been used in industries. Silva et al. (2019) analyses the possibility of usage of photovoltaic power plants as the main source in the production of ferroalloy in industries to meet its energy demands, since the unavailability and high costs of energy have a significant impact in the ferroalloy chain. Mekhilefa et al. (2011) shows that PV energy has been used for numerous industrial applications such as traffic lights, telecommunications and geographical-position systems for the last 20 years for complementing the energy demand or for reducing the production and maintenance costs of industry applications. In Lacerda et al. (2011), an alternative to feeding large DC loads using PV plants is presented. This one discusses that there are industrial processes that require DC current and the use of PV plants associated with DC/DC converters. In this type of process, losses are drastically reduced. For instance, electrolysis used for the production of metals requires high DC current that is usually obtained by using rectifiers in the grid. The paper argues that by using a DC/DC converter and injecting the solar generation directly into the electrolysis, the losses would be lowered. The case study of the paper is an example of industrial plant capability that has an electrolysis process. It was proved that, for processes fed in DC such as the ones present in mining and metal industries, employing a PV power plant associated with a DC/DC converter would be more economically feasible.

Due to the power inverters in the solar power plant, there can be a quality issue in regards to harmonic components in the AC current delivered to the final client and the injection of reactive power in the point of connection between the power plant and the main grid (Liu et al. 2019). Connecting more solar plants to the main grid means increasing the number of inverters involved in the power generation, augmenting the effects of the harmonic components in the overall power quality. In Chicco et al. 2009, it’s shown that if the power of the solar plant is low compared to the grid short-circuit power, the effects of the solar generation in the overall power quality are negligible. However, increasing the power of the solar plant (i.e. increasing the penetration level of the PV plant), the power quality is more affected by the harmonic content (Chicco et al. 2009).

Weaker grids, meaning grids more sensitive to small perturbations, pose challenges for connecting inverter-based sources, such as PV plants. Weak grids have high sensitivity of voltage in regards to changes in active and reactive power, i.e., high dV/dP and dV/dQ. This higher sensitivity leads to a higher risk of voltage collapse. Attempting to push active current during low voltage conditions could further degrade system voltage and result in collapse. Reactive current should be given priority during fault conditions in these weak grid conditions. However, studies should ensure that reactive current contribution during fault conditions does not cause voltage overshoot or other problems that could trip the inverters (North American Electric Reliability Corporation, 2017). In North American Electric Reliability Corporation, 2017, there are examples of real cases in North America of weaker grids connected to wind and solar plants, which experienced voltage and control instability, that led to inverter failures.

Due to its nature, the generation of energy in a solar plant is directly affected by the solar radiation in its PV panels, especially because the panels don’t have inertia (they track the changes in radiation). Depending on the day, the power generation can fluctuate during the operation hours; this fluctuation can compromise the levels of the AC voltage output (Urbanetz et al. 2012)-(Gao et al. 2017). This could also lead to a voltage unbalance, affecting the impedance of the transmission/distribution lines (Urbanetz et al. 2012).

The disturbances in the power quality of a PV plant are time-variant since they are dependent upon the solar radiation of the current instant. So the indices (harmonics, AC voltage output, voltage unbalance) should be studied for a predetermined period of time (Ortega et al. 2013a).

During the operation of the analyzed PV plant one of the solar inverters stopped working. It was a defect inside this inverter, arising from electrical disturbance, or in the path between the strings and the inverter.

During the almost four years of operation, there have been power outages that have compromised the operation of the power plant during operating hours. Some of these events will be shown in this paper aiming to enlighten electrical concerns over a PV electrical connection and its possible harm and possible events that may have caused the defect in the inverter. A weak grid may lead to a number of issues such as steady-state voltage instability that can damage the power inverters.

The goal of this paper is to analyze the AC grid in regards to power quality, focusing on three main parameters: harmonics, voltage unbalance and AC voltage output. This analysis is done with collected data in different points of the system over 3 years. In this paper, the analysis of the PQ (power quality) problems are done related to their impact in the inverters of the PV plant, instead of focusing on the impacts related to power quality that the solar power plant may cause in the main grid as other studies, as the ones seen in Ylmar et al. (2017), Mekhilefa et al. (2011), Urbanetz et al. (2012) and Ortega et al. (2013a).

Section 2 provides an overview of the power quality problems in a solar plant. Section 3 describes the studied power plant (Usina Experimental Fotovoltaica TESLA Engenharia de Potência, Experimental Photovoltaic Power Plant TESLA Power Engineering in free translation) - its operation, problems since the beginning of operation and its measurement system. Section 4 provides the results of the power quality assessment. Section 5 concludes this paper.

2. POWER QUALITY CHARACTERISTICS IN PHOTOVOLTAIC SYSTEMS

There are power quality problems that may arise due to external conditions, such as a weak grid, in the operation of a solar power plant that are able to damage its devices, particularly its power inverters. This section details the PQ indices of interest when analyzing a PV plant.

2.1 Harmonics

The power inverters used in the power plant to convert the DC power into AC power are responsible for injecting abundant harmonic content in the system due to the nonlinearity of the inverter (Liu et al. 2019).

The injected harmonic components can be separated into two groups: the low frequency harmonics (3rd, 5th and 7th) due to the dead time and the high frequency harmonics caused by the PWM modulation (components around the switching frequency). The output filter is generally used to eliminate the high frequency harmonics. The low-frequency harmonics are usually mitigated by installing a passive power filter at the low-voltage bus of the substation for harmonic suppression and reactive power compensation (Liu et al. 2019).

An effective method to assess the harmonic content of a PV plant is to use the THD indices for current and voltage. The harmonic measurements should be recorded continuously for a week and all measurements with no solar radiance should be deleted (Ortega et al. 2013b).

In Sidrach-de-Cardona et al. (2005), the experimental results of a grid connected photovoltaic system show that the current total harmonic distortion (THD) at the output of the power inverter depends strongly on the output power, which is determined by the size of the PV plant and the solar radiance. The results also show that the THD is the lowest when the power inverter works at its nominal power. To output power greater than 40% of the nominal value, the THD for current and for voltage are lower than established by the standard, 5% and 2% respectively. In Ortega et al. (2013a), the results show that for clear days (when the inverters are able to work at nominal power for longer periods of time), the THD is lower than 5%. For cloudy days, the THD is higher than 5%.

Urbanetz et al. (2012) shows the effects of the installation of a small grid-connected solar plant (12kWp), comparing the measurements of paraments of interest (harmonics, voltage and frequency) when the PV is connected and when it is not connected. For the analysis of harmonic content, the connection of the small PV plant improved the harmonic content, by decreasing the overall THD of the grid.

2.2 Voltage Unbalance

The integration of electric power generation by a solar plant can introduce a certain level of voltage unbalance in the grid. The voltage unbalance can be characterized by various indices such as the one seen in (1) defined in Rocha (2017).

$$FD\% \;=\; 100\sqrt{(1-\sqrt{3-6\beta})/(1+\sqrt{3-6\beta})}$$

(1) where $\beta = ({V_{ab}}^4 + {V_{bc}}^4 + {V_{ca}}^4)/(({V_{ab}}^2 + {V_{bc}}^2 + {V_{ca}}^2)^2)$ and FD is *fator de desequilíbrio de tensão* (voltage unbalance factor in free translation).

The voltage unbalance should be less than 2% (Urbanetz et al. 2012).

During unbalanced operation, large negative sequence currents flow in the system. The main issues related to voltage unbalance are the distortion on the DC side and the flow of large negative sequence currents between the output of the power inverters and the grid, potentially injecting low order harmonics on the AC side (Awadhi. 2017).

According to Zolkifri et al. (2017), the higher the penetration of PV plants the higher is the voltage unbalance. The paper suggests that the maximum PV penetration should not be more than 50% in a LV (low-voltage) system in order to avoid PQ problems regarding voltage unbalance.

2.3 AC Voltage Output

Urbanetz et al. (2012) shows a case study that tracks the fluctuation of the AC voltage of a grid when connected to a PV panel and when not connected; nominal voltage 220V. The voltage rose from 218V (not connected to PV plant) to 222V; meaning that when this grid is working below the nominal value, the PV plant affects it positively, increasing the voltage, providing a better voltage profile. However, when the grid is already operating in or close to nominal value, the connection to the PV plant can lead to voltage swell.

3. CASE STUDY

The PV plant analyzed in this paper is the Usina Experimental Fotovoltaica TESLA Engenharia de Potência (Experimental Photovoltaic Power Plant TESLA Power Engineering in free translation). The capacity of the power plant is 37kWp and it is located in Brazil. Fig. 1 shows the control room of the power plant. Fig. 2 is the single-line diagram of the solar plant.

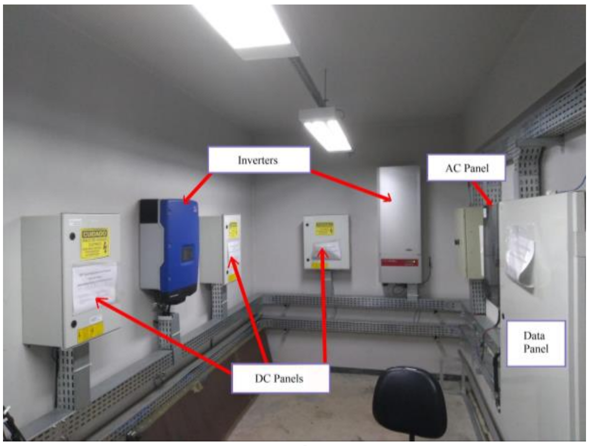

Fig. 1. Control Room

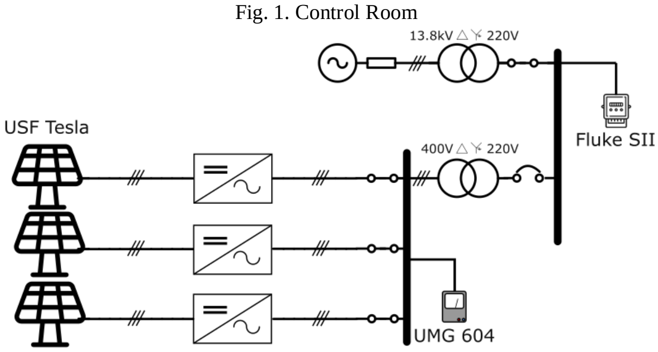

Fig. 2. Single-Line Diagram

There are three power inverters in the plant: a Jema IF - 15 n (15 kW) - the one that was damaged -, a Fronius IG Plus 150V-3 (10 kW) and a SMA Sunny Tripower 12000TL (12 kW). The power plant has 152 PV panels (Yingli 245P-32b, 245W.) divided in 3 groups that are divided in strings following the detailed scheme below seen in Fig. 3.

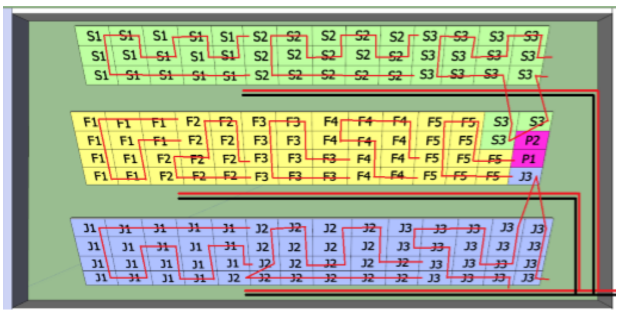
Fig. 3. Schematic of the Connection of the Panels

The output voltage of the power plant is 400Vac. There is 1 point of connection between the 13.8 kV main grid and the PV plant at 220V as seen in Fig. 2.

The loads fed by the solar power plant are illumination and computers.

2.3 Measurement System

All the power inverters are IoT (Internet of Things) ready. Using standard industrial TCP/IP Modbus protocol, the inverters are easy to be incorporated to the network and display their measurements in the Web when properly configured. They all communicate with a device that stores and makes the data available via a private portal. Every parameter related to each inverted can be recovered via this cloud.

There is also a Janitza energy meter, UMG 604, capable of measuring voltage, current, power and energy installed in the output of the power plant before the 400/220V transformer as seen in Fig. 2.

There is also a Fluke SII energy meter capable of measuring voltage, current, power, energy, frequency and harmonics installed in the 220V busbar before the 13.8k/220V transformer as seen in Fig. 2.

4. RESULTS AND ANALYSIS

For this study, the data analyzed here was stored by the aforementioned devices.

4.1 Measurement Devices

The UMG604 is seen in Fig. 2. The UMG604 meter records normal data every 15 minutes and is also able to record events - the value of the parameter, the time and its duration. For the data stored by the Janitza meter, three events are analyzed: voltage unbalance, voltage swell and voltage sag. The voltage unbalance is calculated by (1) and it considers line voltage. The configured limits for voltage swell and voltage sag are respectively 110% and 85% of nominal value (230V). It's important to notice that the events are monitored for phase voltages.

The inverters are represented by the 3-phase inverter in Fig. 2. The inverters SMA 12000TL and the Jema inverter record normal data every 5 minutes. For the data stored by the inverters, two events are analyzed: voltage swell and voltage sag. It's also important to mention that the Jema inverter only displays data until November, 2018, since it had a failure in November, 2018, and has been decommissioned since. For the analysis of voltage swell events, a 110% threshold was established to determine instants in which voltage swell happened.

4.2 Generation

Fig. 4 shows the generation of power from the beginning of the operation until March 04, 2020. This measurement is retrieved from the UMG604 meter. The drop of power generation from 2018 to 2019 and beyond can be explained by the failure and decommission of the Jema inverter on November/2018 and December/2018 respectively.

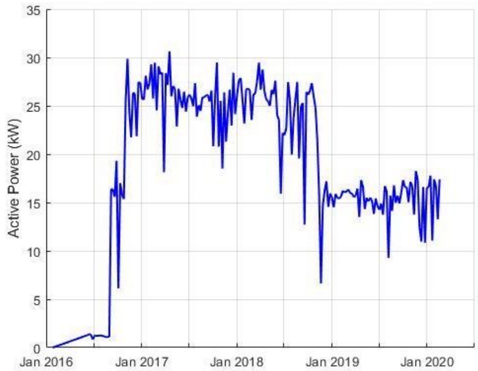

Fig. 4. Power generation

4.3 Voltage Unbalance

For voltage unbalance, all line voltage measurements (from June 3rd, 2016 until November 20, 2019) are recovered and used in the equation (1) seen in section III, subsection B, in order to calculate the voltage unbalance of every measured instant. To be considered a PQ problem, the FD should be higher than 2%. Fig. 5 shows a bar graph that depicts the occurrence of voltage unbalance from June 3rd, 2016, to November 20, 2019, following this limit.

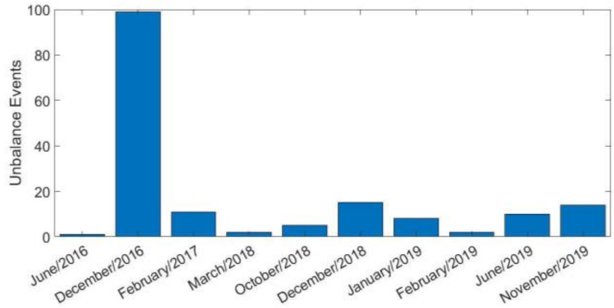

Fig. 5. Number of voltage unbalance occurrences in accordance to UMG604 measurements

Investigating December/2016, it's possible to notice that the events of voltage unbalance happened continuously between December 25th and December 26th as seen in Fig. 6. Investigating January/2019, it's possible to notice that the events of voltage unbalance happened continuously during the morning of January 17th as seen in Fig. 7.

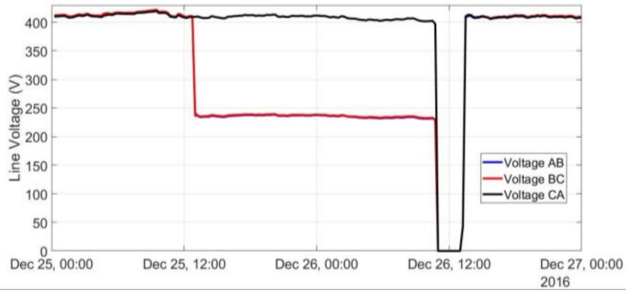

Fig. 6. Voltage unbalance on December/2016 registered by UMG604

Fig. 7. Voltage unbalance on January/2019 registered by UMG604

Analyzing the data, it's possible to conclude that, in this operation, the unbalance events are a product of voltage sag events (as seen in subsection E of this section) or power outages.

In order to understand the impacts of voltage unbalance in the lifespan of the inverters, the investigation focuses only on the event that happened in March 30th, 2018 since before and after the Jema inverter was not on commision and the SMA inverter didn't show signs of wear until the publication of the paper. Investigating this event, it was possible to see that the unbalance was detected due to a power outage that lasted 15 minutes. After, the Jema inverter resumed normal operation.

4.4 Voltage Swell

Fig. 8 shows the number of occurrences of voltage swell (voltage above 440V) events for the Jema inverter; there were no voltage swell events registered for the SMA inverter.

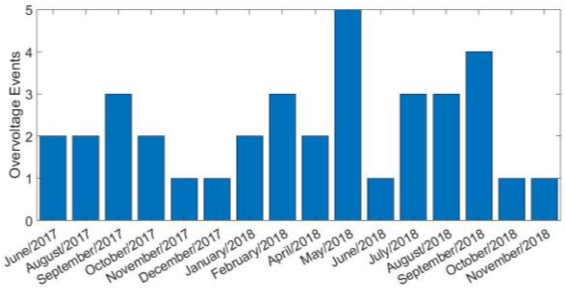

Fig. 8. Number of voltage swell occurrences registered by Jema inverter

Investigating the events, it's possible to see that the overvoltage events detected were only peaks, i.e., they weren't continuous events that could have caused permanent damages to the device when they were registered. An example is seen in Fig. 9. It's important to notice, though, that the output AC voltage was always above the nominal value (400V); this is true also for days with no overvoltage events as seen in Fig. 10.

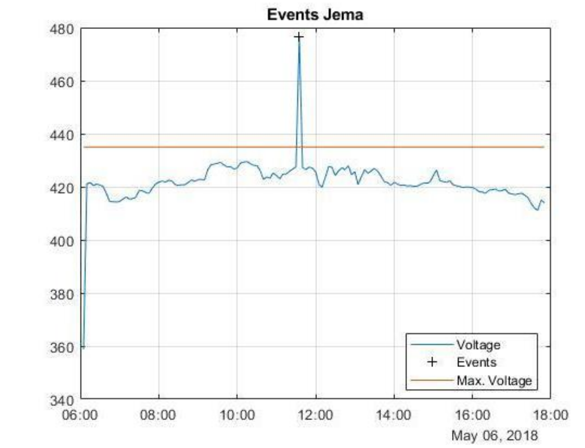

Fig. 9. Example of voltage swell registered by Jema inverter

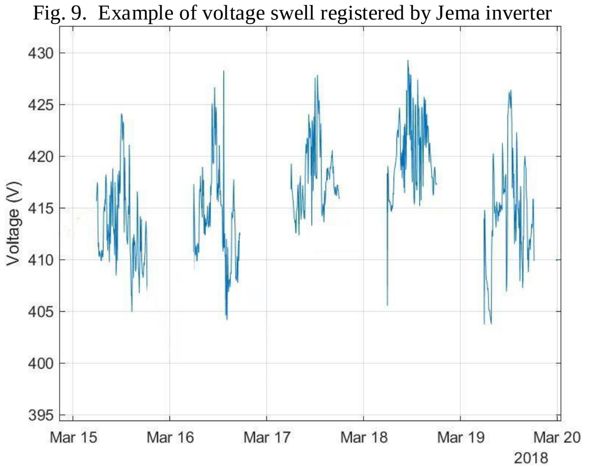

Fig.10. Normal operation - Jema inverter

This rise in voltage can lead to damages of the devices depending on its duration.

4.5 Voltage Sag

The UMG604 meter records every event regardless of its duration. In the events of voltage sag, the meter also registers as an event when there's a power outage of the main grid and these events are considered in the bar graph below.

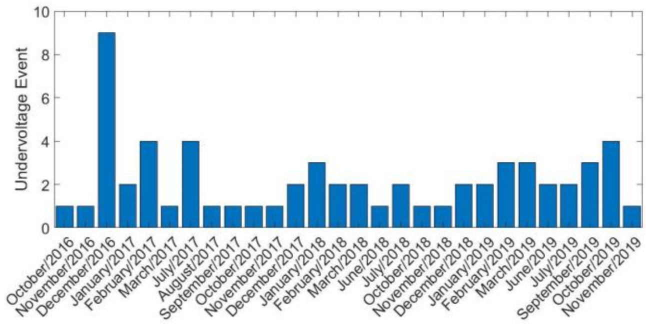

Fig. 11. Number of voltage sag occurrences registered by UMG604

During the operation, different types of voltage sags were detected: 1 phase, 2 phases and 3 phases. Some voltage sags lasted only milliseconds whereas others lasted for many seconds, even minutes. The fastest events lasted only 16.6ms - they happened during the morning and the afternoon - and the longest (not considering power outages) lasted 5 minutes and it also happened during the morning. The voltage drop varied between 15% and 70%.

Investigating December/2016, it's possible to see that the voltage sag events happened on 2 different days and the events in each day happened continuously in different phases as seen in Fig.12 - the events in each phase are counted separately.

Fig. 12. Voltage sag on December/2016

Investigating September/2017, it's possible to notice that the voltage sag happened on September 08 and the voltage drop was 61.35% for phase A, 43.2% for phase B and 52.69% for phase C. The voltage can be seen in Fig. 13.

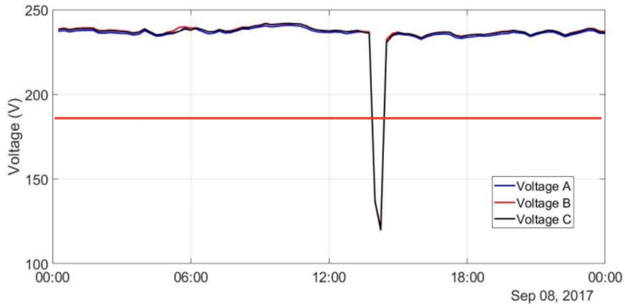

Fig. 13. Voltage sag on September/2017

For the analysis of voltage sag events detected by the inverters, a 90% threshold was established to determine instants in which voltage sag happened. Fig. 14 shows the number of occurrences of voltage sag events for the Jema inverter and Fig.15 shows the number of voltage sag events registered for the SMA inverter.

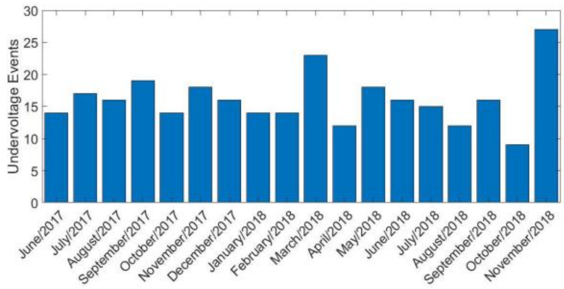

Fig. 14. Number of voltage sag occurrences - Jema

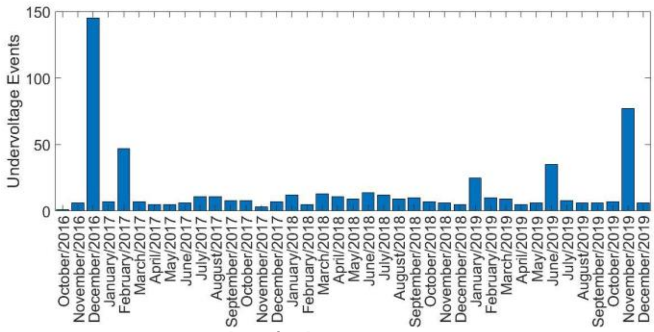

Fig. 15. Number of voltage sag occurrences - SMA

It's important to note that in the SMA and Jema measurements each instant in which the sag event is detected is counted in the bar graph. So, some events displayed in the bar graphs happened continuously. For example, in December/2016, almost 150 events were counted, because there was a power outage and almost 150 instances of measurement were detected to show a voltage lower than 90% the nominal voltage; it was at 0V. But it was a continuous singular event.

Investigating January 17, 2019, it's shown that there was a significant voltage drop detected by the SMA inverter as seen in Fig. 16 for almost 2 hours. The Jema inverter had already been decommissioned in January/2019.

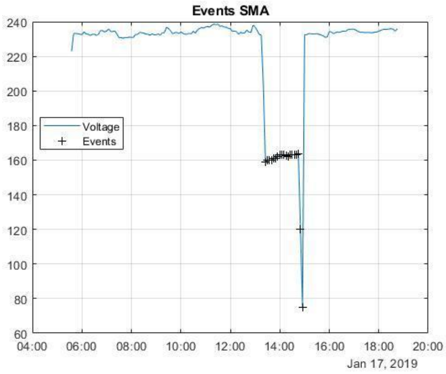

Fig. 16. Voltage sag on January 17, 2019.

In a previous subsection of this section, discussing voltage unbalance, it was seen that this voltage sag also triggered voltage unbalance. That means that, depending on the characteristics of the event (if it happened on all inverters or not, the percentage drop, the duration), an event can trigger other PQ problems as voltage unbalance. But there are voltage sag events that don't lead to other PQ problems, especially on the sag event which happens in all three phases.

Comparing the bar graphs in Fig. 14 and Fig. 15 with the bar graph in Fig. 13, it's possible to see that, as the voltage swell events, not every event detected by the inverters translates to events present in the line. In the months of August/2018 and September/2018 for example, the Jema and the SMA inverters detected voltage sag events. But, the UMG604 meter, which is installed down the line as seen in Fig. 3, didn't detect any events during these months.

Comparing the graphs in Fig. 14 and Fig.15, it's possible to see that the Jema inverter detects more sag events than the SMA inverter during the former's months of operation. November/2018 - the month the Jema inverter presented the failure, showed the most occurences of events, implying some connection between them both. The high number of voltage sag could be the reason or the consequence of a severe wear of the inverter, leading to its fatal failure.

All the events discussed - voltage unbalance, voltage sag and voltage swell - can be explained by faults in the distribution grid. Another possible cause for voltage sag can be the start of heavy loads in the grid. The start and movement of heavier loads require motors that have higher nominal power, leading to a higher startup current. However, the system - including the cabling - is designed for the lower nominal current. Therefore, this higher current at startup may lead to a voltage sag event in the grid. Voltage swell can happen due to the energization of capacitors. Another possible source of voltage swell may be the flow of single-phase sags through lagging transformers, that can lead to a voltage rise in one of the phases (Bollen. 2000).

4.5 Harmonics

Table 1 shows the measurements of voltage THD and current THD in percentage retrieved from the UMG604 meter. The measurements were taken on three different days in three distinct instances.

Table 1. THD Measurements - UMG604

	March 02, 2020			March 03, 2020			March 04, 2020		
	10h	12h	15h	10h	12h	15h	10h	12h	15h
Va	2.4	2.9	2.7	2.2	2.6	2.7	2.4	2.4	2.4
Vb	2.3	2.5	2.7	2.3	2.6	2.8	2.4	2.4	2.4
Vc	2.2	2.8	2.3	2.1	2.4	2.4	2.2	2.2	2.2
Ia	34	21	16	40	37	35	76	76	76
Ib	31	19	23	35	31	31	67	67	67
Ic	36	14	21	36	33	27	121	121	121

According to the IEEE 519 Standard, Recommended Practice and Requirements for Harmonic Control in Electric Power Systems, the voltage THD limit is 5% for voltage lower than 1kV (IEEE Std519-2014. 2014). As seen in Table 1, all THD measurements for every phase is well below this threshold.

For the current THD, it's important to notice that the standards supply limits for the nominal current; the limit seen in IEEE Std1547-2003, 2003 and Hall, 2004 is 5% for nominal current. The current is related to the solar irradiance in the photovoltaic cell - the higher the irradiance, the higher the current. The current measurements shown in Table 1 showed values lower than the nominal current, especially on March 04 - it was cloudy. And according to Castilla et al. 2013, the lower the current the higher the THD, which would explain the higher THD values seen in Table 1. This behavior of increasing the current THD whilst the current decreases can be seen in Fig. 17 throughout an afternoon (September, 11th – 09h30 AM to 05h30PM).

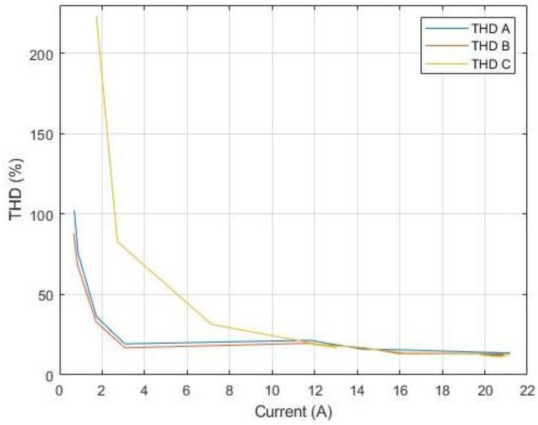

Fig. 17. Measurements of Current and Current THD in the Plant – Sunny Day

6. CONCLUSIONS

This paper provides further information and analysis in the PV power plant field, especially in regards to the impact of events related to power quality problems in the inverters of a PV plant.

In regards to the inverter that was damaged during operation, it's not possible to attribute the damage to the grid with the PQ information that was gathered along this paper since there could be a number of reasons. But, it can be said that, if this device were installed in a grid with more severe conditions as rural zones – weaker grids (meaning grids more sensitive to small perturbations) -, it would not operate correctly. That can be said because some severe events lead to current and voltage peaks that could damage the inverter if the duration was longer.

For future works, the plan is to investigate further the premature wear of the power inverters in regards to the endurance of the system to phenomena in the grid.

ACKNOWLEDGMENTS

The authors would like to thank UFMG, FAPEMIG, CNPq and CAPES for financial support.

REFERENCES

Awadhi, N. A. and Moursi, M. S. E. (2017) "A novel centralized PV power plant controller for reducing the voltage unbalance factor at transmission level interconnection," *IEEE Transactions on Energy Conversion*, vol. 32, no. 1, pp. 233-243.

Bollen, M. H. (2000) "Voltage sags characterization," in Understanding Power Quality Problems: Voltage Sags and Interruptions, IEEE, doi: 10.1109/9780470546840.

Bp Energy Outlook 2035. Technical Report. URL (http://www.bp.com); 2020.

Cabrera-Tobar, A., Bullich-Massagué, E., Aragüès-Peñalba, M. and Gomis-Bellmunt, O. (2016). "Topologies for large scale photovoltaic power plants", *Renewable and Sustainable Energy Reviews* [Online]. 59, pp. 309-319. Available: http://www.elsevier.com/locate/rser

Castilla, M., Miret, J., Camacho, A., Matas, J. and de Vicuna, L. G. (2013) "Reduction of current harmonic distortion in three-phase grid-connected photovoltaic inverters via resonant current control," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1464-1472, doi: 10.1109/TIE.2011.2167734.

Chicco, G., Schlabbach, J. and Spertino, F. (2009). "Experimental assessment of the waveform distortion in grid-connected photovoltaic installations", *Solar Energy* [Online]. 83(7), pp. 1026-1039. Available: https://www.sciencedirect.com/journal/solar-energy/vol/83/issue/7

Gao, Y., Xue, F., Yang, W., Sun, Y., Liang, H. and Li, P. (2017). "A three-part electricity price mechanism for photovoltaic-battery energy storage power plants considering the power quality and ancillary service", *Energies* [Online]. 10(1257), pp. 1-21. Available: https://doi.org/10.3390/en10091257

Hall, K. (2004) "EN/IEC 61000-3-2 harmonic analyzer evaluations," *2004 International Symposium on Electromagnetic Compatibility* (IEEE Cat. No.04CH37559), Silicon Valley, CA, USA, vol.1, pp. 153-156, doi: 10.1109/ISEMC.2004.1350016.

"IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems," *IEEE Std 519-2014* (Revision of IEEE Std 519-1992), vol., no., pp.1-29, 11 June 2014, doi: 10.1109/IEEESTD.2014.6826459.

"IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," *IEEE Std 1547-2018* (Revision of IEEE Std 1547-2003) , vol., no., pp.1-138, 6 April 2018, doi: 10.1109/IEEESTD.2018.8332112.

Lacerda, F. A. G., Gomes, R. A. M., Porto, M. P. and Cardoso, B. J. (2017) "Directly feeding large DC loads through PV power plants: A new concept applied to industry," *2017 IEEE Industry Applications Society Annual Meeting*, Cincinnati, OH, pp. 1-7.

Liu, Q., Li, Y., Luo, L., Peng, Y. and Cao, Y. (2019) "Power quality management of PV power plant with transformer integrated filtering method," *IEEE Transactions on Power Delivery*, vol. 34, no. 3, pp. 941-949.

Mekhilefa, S., Saidurb, R. and A. Safari. (2011) "A review on solar energy use in industries", *Renewable and Sustainable Energy Reviews* [Online]. 15(4), pp: 1777–1790. Available: https://doi.org/10.1016/j.rser.2010.12.018

North American Electric Reliability Corporation (2017), "Integrating inverter-based resources into low short circuit strength systems". URL (https://www.nerc.com/comm/PC_Reliability_Guidelines_DL/Item_4a._Integrating%20_Inverter-Based_Resources_into_Low_Short_Circuit_Strength_Systems_-_2017-11-08-FINAL.pdf)

Ortega, M. J., Hernández, J. C. and García, O. G. (2013a). "Measurement and assessment of power quality characteristics for photovoltaic systems: harmonics, flicker, unbalance, and slow voltage variations", *Electric Power Systems Research* [Online]. 96, pp. 23-35. Available: https://www.sciencedirect.com/journal/electric-power-systems-research/vol/96/suppl/C

Ortega, M. J., Hernández, J. C. and Medina, A. (2013b). "Statistical characterisation of harmonic current emission for large photovoltaic plants", *International Transactions on Electrical Energy Systems* [Online]. 24, pp. 1134-1150. Available: https://onlinelibrary.wiley.com/doi/abs/10.1002/etep.1767

Rocha, J. E. (2017) "Desequilíbrio de tensão" [Power Point Slides]. Retrieved from: http://paginapessoal.utfpr.edu.br/joaquimrocha/qualidade-da-energia-eletrica/Qualidade_09_Desequilibrio%20de%20tensao.pdf/at_download/file

Sidrach-de-Cardona, M. and Carretero J. (2005). "Analysis of the current total harmonic distortion for different single-phase inverters for grid-connected pv-systems", *Solar Energy Materials and Solar Cells* [Online]. 87(1-4), pp. 529-540. Available: https://www.sciencedirect.com/journal/solar-energy-materials-and-solar-cells/vol/87/issue/1

Silva, L., Dias, W., Vieira, C. and Assis, P. (2019). "Solar photovoltaic energy applied to ferroalloy industry", *REM - International Engineering Journal* [Online]. 72(2), pp. 251-255. Available: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S2448-167X2019000300251&lng=en&nrm=iso

Urbanetz, J., Braun, P. and Rüther, R. (2012). "Power quality analysis of grid-connected solar photovoltaic generators in Brazil", *Energy Conversion and Management* [Online]. 64, pp. 8-14. Available: https://www.sciencedirect.com/journal/energy-conversion-and-management/vol/64/suppl/C

Yilmaz, S. and Dincer, F. (2017). "Impact of inverter capacity on the performance in large-scale photovoltaic power plants – a case study for Gainesville, Florida", *Renewable and Sustainable Energy Reviews* [Online]. 79, pp. 15-23. Available: http://www.elsevier.com/locate/rser

Zolkifri, N. I., Gan, C. K., Khamis, A., Baharin, K. A. and Lada, M. Y. (2017) "Impacts of residential solar photovoltaic systems on voltage unbalance and network losses," *TENCON 2017 - 2017 IEEE Region 10 Conference*, Penang, pp. 2150-2155.