Article **Journal Electrical Engineering**
June 2021, Vol.5 No.14 20-31

Analysis of power quality in photovoltaic systems interconnected to the grid

Análisis de calidad de la energía en sistemas fotovoltaicos interconectados a la red

DIBENE-ARRIOLA, Luis Martin†*´, FLETES-CAMACHO, Noé Guadalupe´, PAREDES-VAZQUEZ, César Paul´ and MARROQUÍN-DE JESÚS, Ángel´´

´Universidad Tecnológica de Bahía de Banderas, Engineering Division Renewable Energies and Industrial Maintenance, Nayarit 63732, Mexico.
´´Universidad Tecnológica de San Juan del Río, Chemistry and Renewable Energy Division, Querétaro, Mexico.

ID 1st Author: *Luis Martin, Dibene-Arriola* / **ORC ID:** 0000-0002-1906-4528, **CVU CONACYT ID:** 412156

ID 1st Co-author: *Noé Guadalupe, Fletes-Camacho* / **ORC ID:** 0000-0002-2435-6971. **Researcher Thomson ID:** U-9488-2018. **arXiv Author ID:** 2839471

ID 2nd Co-author: *César Paul, Paredes-Vazquez* / **ORC ID:** 0000-0002-4408-9487, **arXiv Author ID:** 284265, CVU CONACYT ID: 890844

ID 3rd Co-author: *Ángel, Marroquín-De Jesús* / **ORC ID:** 0000-0001-7425-0625, **CVU CONACYT ID:** 81204

DOI: 10.35429/JEE.2021.14.20.31 Received January 25, 2021; Accepted June 30, 2021

Abstract

A lot of authors are concluded that photovoltaic systems distort the waveform of voltage and current, the evaluation of these distortion indices is carried out in accordance with IEEE Std 519-2014, equipment sensitive to variations in the voltage wave, are affected in their operation, causing a rise in temperature, a decrease in speed in rotating machines, among others, these variations are accentuated by low irradiance values. In this work, the results of the online monitoring of electrical parameters are shown, when connecting a network analyzer Hioki® model PQ3198, class A, in the terminals of the alternating current side of the Fronius® inverter, SYMO 10.0-3 208 / 240V of a 10 kWp commercial photovoltaic system and a GOODWE® inverter, model GW-2000-NS with 220 output voltage in a 2 kWp home photovoltaic system; The measurement period was one week, the analyzer was programmed to sample every 5 minutes. Finding effects on voltage and current harmonics greater than 5% established in the IEEE 1100-1999 standard, but less than 10% established in the Mexican legal framework, in accordance with CFE Specification L0000-45 "Permissible deviations in waveforms of voltage and current in the supply and consumption of electrical energy" the values of the harmonic distortion indices have a variation of 8%.

Photovoltaic systems, Disturbances, Power quality

Resumen

Diversos autores concluyen que los sistemas fotovoltaicos distorsionan la forma de onda de voltaje y corriente, la evaluación de estos índices de distorsión se realiza de conformidad con el IEEE Std 519-2014, equipos sensibles a variaciones en la onda de voltaje, son afectados en su funcionamiento, ocasionando elevación de temperatura, disminución de la velocidad en máquinas rotativas, entre otras, estas variaciones se acentúan más ante bajos valores de irradiancia. En el presente trabajo se muestran los resultados del monitoreo en línea de parámetros eléctricos, al conectar un analizador de redes Marca Hioki® modelo PQ3198, clase A, en las terminales del lado de corriente alterna del inversor Fronius®, SYMO 10.0-3 208/240V de un sistema fotovoltaico comercial de 10 kWp y de un inversor GOODWE®, modelo GW-2000-NS de 220 volts de salida en un sistema fotovoltaico doméstico de 2 kWp; El período de medición fue de una semana, se programó el analizador para que realizará un muestreo cada 5 minutos. Encontrándose afectaciones de voltaje y armónicos de corriente mayores al 5% establecidas en el estándar IEEE 1100-1999, pero menores al 10% establecido en el marco legal mexicano, de conformidad con la Especificación CFE L0000-45 “Desviaciones permisibles en las formas de onda de tensión y corriente en el suministro y consumo de energía eléctrica” los valores de los índices de distorsión armónica tienen una variación del 8%.

Sistemas fotovoltaicos, Perturbaciones, Calidad de la energía

Citation: DIBENE-ARRIOLA, Luis Martin, FLETES-CAMACHO, Noé Guadalupe, PAREDES-VAZQUEZ, César Paul and MARROQUÍN-DE JESÚS, Ángel. Analysis of power quality in photovoltaic systems interconnected to the grid. Journal Electrical Engineering. 2021. 5-14:20-31.

* Correspondence to Author (Email: ldibene@utbb.edu.mx)
† Researcher contributing as first author.

Introduction

This topic arises from an investigation about greenhouse gas (GHG) emissions from beach hotels; when in an interview with a hotel maintenance manager, he states that he is not interested in the use of Photovoltaic Systems (PV) to reduce GHG emissions into the atmosphere since, according to him, PV burn the electronic cards of the equipment laundry and air conditioning by affecting the quality of electrical energy.

Electricity consumption in hotels is generally used for lighting, use of elevators, water pumping, air conditioning, electrical kitchen machinery, kitchen equipment, electric heat pumps, etc. Additionally, hotels consume some fuel, such as LP gas, diesel or natural gas, for the generation of sanitary hot water, pool water heating and for cooking (SEMARNAT, 2020).

Electronic equipment is damaged by any of the following causes: Overvoltages, overcurrents (overloads, short circuits and ground faults), electromagnetic and electrostatic interference, contamination, heating and by problems associated with power quality, such as resonance (Ruelas, 2021). This work will try to answer the question: Do photovoltaic systems cause damage to the electronic boards of air conditioning and laundry equipment? The afore mentioned, he worried us since it is currently considered very important to reduce these emissions and that type of comments can influence the interest in the VFs of other hotels.

Background:

(Favuzza, Graditi, Spertino, & Vitale, 2004) They investigated the impact of SFVs on the quality of the power of the network. Their results show that the level of harmonic distortion at the point of common coupling **(**PCC) is comparable to levels of distribution networks without distributed generation and that there are no critical consequences in terms of voltage distortion at the PCC. The results obtained show that the impact of photovoltaic inverters on the quality of the energy of the network depends on the impedance of the electrical network and that investors with different types, connected to the urban network, have indicated a very similar behavior.

On the other hand, (Hernández & Medina, 2006) state that the fundamental aspects of supply quality that must be evaluated in the PCC are: voltage and frequency variation, voltage dips and overvoltage intervals, flicker, unbalance, harmonic distortion, power factor and reactive power. They indicate that photovoltaic generators that have inverters with PWM technology inject minimal harmonic currents into the grid with little effect on supply quality and that flickers and voltage imbalances are comparable to those existing in the electricity grid (low voltage) without photovoltaic generation.

Finally, they conclude that the photovoltaic inverter plays a fundamental role in the operation of the photovoltaic generator in relation to the quality of supply parameters. (González-Castrillo, Romero-Cadaval, González-Romera, Barrero-González, & Guerrero-Martínez, 2007), show results of the measurement of power quality parameters carried out in a rural distribution network in two periods of time, previous and after the connection to the line of a photovoltaic plant and also present the same parameters registered in the PCC and recognize a slight impact of the photovoltaic subsystems on the harmonic voltage distortion. (Patsalides, et al., 2007) considered 14 different grid-connected photovoltaic systems in Cyprus and conducted online monitoring of electrical parameters.

They found that low solar irradiance has a significant impact on the quality of the output power of the photovoltaic system. The electrical parameters recorded were: active power, reactive power, voltage and current for each harmonic frequency. They also measured power factor and total harmonic distortion for voltage and current for two weeks. They found that the power factor is greater than 80% for irradiances greater than 300 W/m^2 and falls below that value with lower irradiances. That the reactive power varies significantly during the day of and that the rapid variations of the reactive power supplied by the photovoltaic systems, assuming very high densities of such systems, can cause a fast switching of the capacitor and that due to these oscillations and transients of voltage can occur with unpredictable amplitude and duration.

That these transients can cause failures in sensitive electronic equipment or minimize the life expectancy of network elements, if the amplitude of a transient exceeds the limits of the IEEE Std 1159-1995 (R2001) Recommended Practice for Monitoring Electric Power Quality, the Limit values for transients are (Table 2):

IEEE
Std 1159-1995 IEEE RECOMMENDED PRACTICE FOR

Table 2—Categories and typical characteristics of power system electromagnetic phenomena

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1.0 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5 ns rise	< 50 ns	
1.1.2 Microsecond	1 μs rise	50 ns–1 ms	
1.1.3 Millisecond	0.1 ms rise	> 1 ms	
1.2 Oscillatory			
1.2.1 Low frequency	< 5 kHz	0.3–50 ms	0–4 pu
1.2.2 Medium frequency	5–500 kHz	20 μs	0–8 pu
1.2.3 High frequency	0.5–5 MHz	5 μs	0–4 pu

Therefore, it is desirable to reduce the existence of such transients. Finally, they found that current harmonics are very sensitive to changes in incident radiation. (Çelebi & Çolak, 2011) investigated the effects of harmonic distortion in electrical networks, depending on the location and number of photovoltaic systems, using the simulation program Pspice®.

They found that harmonic currents generated by photovoltaic systems can degrade the quality of the electrical grid and alter the performance of other electrical equipment. According to the simulation results, the harmonic distortion generated by the photovoltaic generators is below the standards in a distribution network that only has domestic loads and that if the photovoltaic generators are located close to the transformer, the harmonic distortion becomes even lower.

In addition, the installation of photovoltaic systems close to the transformer helps to control the increase in voltage in the distribution lines. They found that the inverters used in the simulation circuit affect the harmonic levels, so their quality properties are important for the network. (González, Romero-Cadaval, E., & Guerrero, 2011) carried out measurements on power quality parameters (PQ) carried out in a radial distribution network in two periods of time, before and after connecting a photovoltaic plant to the network at the common coupling point of the grid and the photovoltaic plant.

Some measured values are compared to the limits established in IEEE Std 519-2014. The measurements carried out in the network showed that the insertion of the photovoltaic plant causes changes in the measured quality parameters and operational characteristics that do not seriously affect the operation of the network. (Bouchakour, Chouder, Cherfa, Abdeladim, & Kerkouche, 2012) analyzed and evaluated the measurements of the photovoltaic array under test to observe the general effect of solar irradiance on the operation of the systems connected to the grid under test.

They found that solar irradiance has a significant impact on the quality of the output power of the photovoltaic system as the active power and power factor go down, while the reactive power goes up. In addition, a TRMS voltage drop is observed in the range of 210-220V, contrary to that observed for the case of average irradiance in the range of 220-230V. Gallo et al. (2013) carry out an analysis of the common indices of energy quality in steady and transient state, both on the AC and DC sides from experimentally recorded data in a medium-scale photovoltaic system that is connected to the grid, in order to understand and explore the nature of the electricity generation patterns of photovoltaic plants.

They find that the steady state indices during a sunny day are: plants at fundamental frequency behave as an ideal source with an almost unity power factor. That the total harmonic distortion of voltage (THDV) as a function of the active power is practically uncorrelated with the output power of the system and that the total harmonic distortion of current (THDI) is high for low active power, since the inverter does not work in its nominal operating conditions, generating a highly distorted current waveform at certain times of the day (for example, at sunrise and sunset). That the voltage imbalance is not correlated with the active power. That the maximum and average values of the groups of voltage and current harmonics at low frequency (50-2500 Hz) measured throughout the day have notable amplitudes in the 3rd, 5th and 11th order. That the eleventh harmonic has a high value in both voltage and current and that it could provide useful information about the state of the network. (Lu, Wang, Ke, Chang, & Yang, 2014) found that the power quality of an PV system complies with the Taiwan Power Company grid code.

ISSN-2523-2517

During one-week electrical parameter measurements were made on a connected 70.38 kW SFV at the National University of Science and Technology Peng-Hu, Taiwan and the recorded results include three-phase voltages, currents, active power, reactive power, power factor, frequency, current harmonics, voltage flickers and voltage variations. (Misak, Prokop, & Bilik, 2014) mention that energy quality problems may arise due to the use of renewable sources in active distribution networks and that these problems are caused by the decrease in the short-circuit power of local renewable sources, the stochastic supply of electrical energy from renewable sources and the operation of the active distribution network in autonomous mode without connection to the external distribution system. In the case of these conditions, the mutual interference between sources and loads is relevant and the quality parameters of electrical energy can be exceeded (Niitsoo, Jarkovoi, Taklaja, Klüss, & Palu, 2015) analyze the harmonic content of photovoltaic generation and the influence on power quality indicators in residential distribution networks. They found moderate additional harmonic distortion in the residential load current and voltage distortion in the substation busbar when photovoltaic panels were added. (Caballero, Cortez, Muñoz, & Castañeda, 2016) mention that the biggest problem in photovoltaic supply is harmonics, due to the waveform delivered by the inverter. That to solve harmonic problems in the network, signal conditioners are used, ranging from tuned passive filters to active filters.

That the former is cheaper, but their selectivity does not allow them to compensate beyond their tuned frequency, while the active filters present a dynamic solution that adjusts to the compensation needs. That they used the active series filter for its main objective of eliminating voltage harmonics, which achieves that both the current and the voltage are sinusoidal. As a result of the implementation of the active filter, the reduction of the harmonic content from 48.3% originally to 2.61% was demonstrated in simulation (this harmonic content must be current), thus complying with the IEEE 519-1992 and CFE L0000- 45 Mexican. (Durán, Raggio, Socolovsky, Videla, & Plá, 2016) analyze energy quality: (i) at the connection point of a 40 kWp PV system installed in the Scientific and Technological Pole, and (ii) in one of the the electrical circuits of a single-family home.

They found that the harmonic components of current injected into the network by the SFV are clearly below the limits established by the IEC 61000-3-2 standard and that the harmonic components of current emitted by household appliances are significantly higher than the harmonics injected by a typical power PV inverter for a single-family home so the connection of PV systems to the electrical grid does not affect the quality of service in terms of harmonic distortion. (Afonso, de Arruda Bitencourt, Fortes, Gomes, & Maciel, 2018) analyzed the harmonics generated in a system when there are different levels of photovoltaic solar generation penetration. They simulated a real system in the city of Buzios (Brazil) in the HarmZs® program with measured values from existing panels and evaluated the total harmonic voltage distortion.

They observed that in the scenarios with massive penetration of photovoltaic generators, the established limits were violated, so the insertion of new (small) renewable sources connected to the grid must be discussed in the context of energy quality to avoid large distortions in the electrical systems so that they are adequate and comply with the existing regulations for energy distribution. (Spertino, et al., 2018) mention that in the case of PV systems, harmonic injection and unbalance are due to pulse width modulation (PWM) switched transistors inside the converters, therefore quantified the impact of harmonic distortion on disequilibrium. They then tested a photovoltaic system with a multi-inverter configuration and made power quality measurements of the worst and best converters to finally compare with the overall power quality measurements of all inverters.

From the review of publications on the subject, the following results were found:

1. Publications that mention that photovoltaic systems do not significantly affect the quality of electrical energy at the PCC and that the level of harmonic distortion is comparable to the levels of distribution networks without distributed generation and that there are no critical consequences in terms of distortion in the PCC (Favuzza, Graditi, Spertino, & Vitale, 2004), (Hernández & Medina, 2006), (González-Castrillo, Romero-Cadaval, González-Romera, Barrero-González, & Guerrero-Martínez, 2007), (González, Romero-Cadaval, E., & Guerrero, 2011), (Lu, Wang, Ke, Chang, & Yang, 2014), (Niitsoo, Jarkovoi, Taklaja, Klüss, & Palu, 2015) y (Durán, Raggio, Socolovsky, Videla, & Plá, 2016).

2. Publications that state that the harmonic currents generated by photovoltaic systems can degrade the power quality grid and alter the performance of other electrical equipment and that the inverters used affect harmonic levels, so their quality properties are important for the network since the quality parameters of the electrical energy can be exceeded. (Çelebi & Çolak, 2011), (Misak, Prokop, & Bilik, 2014) y (Afonso, de Arruda Bitencourt, Fortes, Gomes, & Maciel, 2018).

3. Publications that mention that low solar irradiance has a significant impact on the quality of the output energy of the photovoltaic system (Patsalides, y otros, 2007), (Bouchakour, Chouder, Cherfa, Abdeladim, & Kerkouche, 2012) y (Gallo, Landi, Luiso, & Edoardo, 2013), a situation that occurs at dawn and dusk of the day.

4. That the biggest problem in the photovoltaic supply are harmonics, due to the waveform delivered by the inverter. That to solve the harmonic problems in the network, signal conditioners are used, ranging from tuned passive filters to active filters (Caballero, Cortez, Muñoz, & Castañeda, 2016).

In addition to the above results, the fundamental aspects of supply quality that must be evaluated in the PCC are: voltage and frequency variation, voltage dips and overvoltage intervals, flicker, unbalance, harmonic distortion, power factor and reactive energy (Hernández & Medina, 2006).

It is clear from the previous review that there are different results in the studies about the effect on the quality of electrical energy when using VFS. Therefore, this study seeks to determine for a 2 kW domestic PV system installation and a 10 kW commercial one how the power quality is affected and if this affectation can damage the electronic boards of the devices of a given installation.

Materials and methods

Measurements were made at a 10kWp commercial PV system and also at a 2 kWp domestic SFV; located in Puerto Vallarta, Jalisco and Nuevo Vallarta, Nayarit respectively, both interconnected to the grid of the basic service provider under the Net Metering contract scheme, Net Metering or Net Metering is a form of billing in which the consumer generates and consumes electrical energy in the same supply contract. The systems present differences in marks, inclinations, orientations and the electrical installation. Even the network, although it can be interpreted that it depends on the same source of public generation, the network behaves with different parameters adding that the commercial system corresponds to a three-phase system and the residential one to a single-phase 2-phase system.

The only common thing is that the two systems were monitored by the same instrument, a Hioki® model PQ3198 power quality analyzer, current sensors calibrated at 500A for the commercial system and 50A for the residential system and a range of 5-minute record for both systems, it is important to mention that the equipment used for the measurements is calibrated by the company Welsh Instrumentation Electronic Measurement and Control Equipment. Considering the above, the two monitoring have different dates and times, but even so the results can be conclusive.

The characteristics of both systems are shown in tables 1 and 2 below:

Capacity	10 kWp
Number of panels	40
Peak power of each panel	265 W
Panel brand	SOLAREVER®
Panels model	SE-156*156-P-60
Inversor brand	Fronius®
Inverter model	SYMO 10.0-3 208/240
Maximum power output	13 kW

Table 1 10 kWp photovoltaic system

Capacity	2 kWp
Number of panels	6
Peak power of each panel	330 W
Panel brand	Risen Solar Technology
Panels model	RSM72-6-330P
Inversor brand	GOODWE
Inverter model	GW-2000-NS
Maximum power output	2.6 kW

Table 2 2 kWp photovoltaic system

The following figures 1 and 2 show the arrangement of both systems:

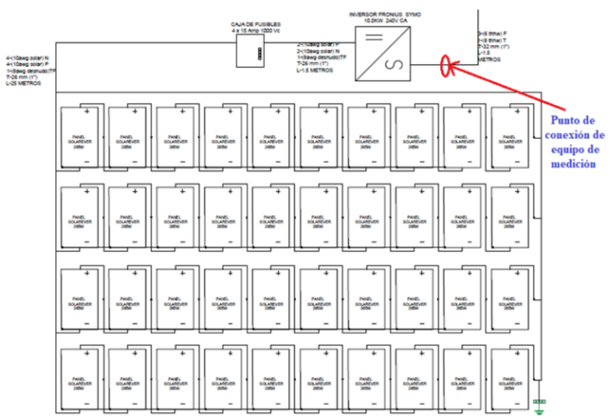

Figure 1 10 kWp Commercial PV system connection diagram

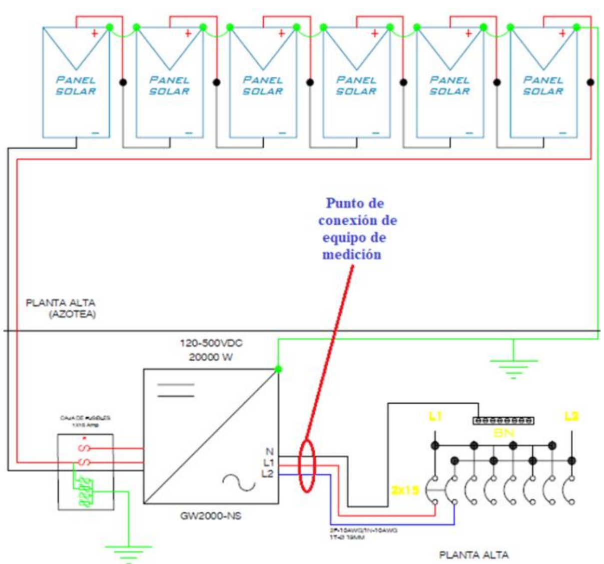

Figure 2 2 kWp domestic PV system connection diagram

Results

10 kWp commercial photovoltaic system

The analysis of the electrical monitoring carried out at the facilities of the company construction materials La Vena S.A. de C.V., located in Puerto Vallarta, Jalisco. The electrical installation is of the commercial type, designed for office equipment, home and power equipment for a semi-automatic block machine. It presents a main board of 20 branch circuits 120/240 V, 3 phases – 4 wires (3F-4H) Model QO1201125 Square D®, it houses inside: 15 thermomagnetic switches of 1 x 20 A, 1 thermomagnetic switch of 2 x 20 A and a 3 x 50 Amp thermomagnetic switch, 4 secondary load centers; offices, block, large house and office expansion.

In the office charging center is the interconnection point of a 10 kWp PV system, at that point the Hioki® power quality analyzer model PQ3198, class A was connected to monitor the electrical parameters, in the period of time from November 4 to 11, 2020.

2 kWp residential photovoltaic system

The photovoltaic system supplies electricity to a house of approximately 98 m^2 of construction, located on Valle del Bambú street number 305 of the Los Encantos neighborhood in Nuevo Vallarta, Nayarit. The house has; three bedrooms, two bathrooms upstairs, living room, kitchen, dining room and service yard. Unlike the commercial service, this has a photovoltaic system in the same scheme (Net metering) but with a lower power system, 2kWp. The system's interconnection point is located in the only load center, it receives a power supply from the basic service provider 2 phase-3-wire (3F-3H) 220 V. At this point, the Hioki® power quality analyzer model PQ3198, class A was connected to monitor electrical parameters, in the period of time from December 3 to 11, 2020.

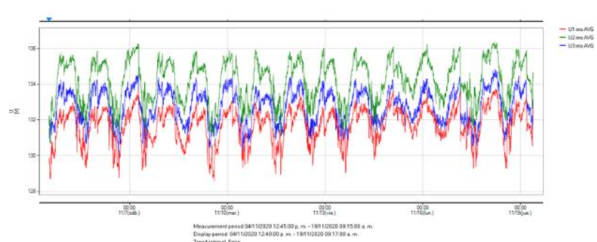

Figure 3 10 kWp PV system voltage profile graph

ISSN-2523-2517

In general, the 3 phases presented instantaneous variations (Figure 3). The values were compared with the IEEE 1100-1999 standard, variation not greater than 5% and the regulation of the law of the public electricity service, which in its chapter V article 18 indicates that the supplier must offer and maintain the service in the form of Alternating current in one, two or three phases, at high, medium or low voltages, available in the area in question, observing the following: I. II. That the frequency is 60 Hertz, with a tolerance of 0.8 percent more or less, and that the tolerances on high, medium or low voltage do not exceed ten percent more or less and tend to be reduced progressively.

Phase	Nominal phase-to-neutral voltage	Phase-to-neutral voltage (V) Mínimum	Average	Maximum	Limits	IEEE Std 1100-1999
1	127 V	130.80	131.71	131.97	± 5%	Complies
2	127 V	133.45	134.22	134.55		Complies
3	127 V	132.09	132.77	133.11		Complies

Table 3 Measurement values obtained compared to IEEE Std 1100-1999

Phase 1 presents an average 3.76% above the nominal value, phase 2 presents an average of 5.61% above the nominal value and phase 3 presents an average value of 4.59% above the nominal value (Table 3).

Current profile

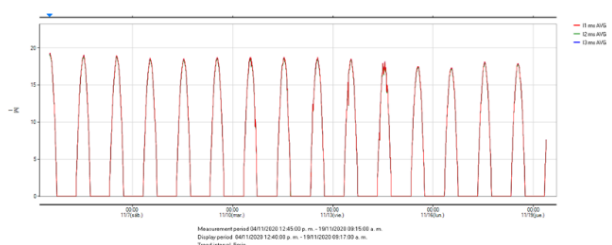

Figure 4 Graph of current profile in PV system of 10 kWp

In general, the 3 phases present a balanced behavior, registering average values of 19.5 A per phase at 1:00 p.m. The variation in amperage is not periodic and is caused by variations in solar irradiance in the solar panels. Throughout the monitoring period, there were no other disturbances that affect the quality of energy due to the effect of the current.

Power profile

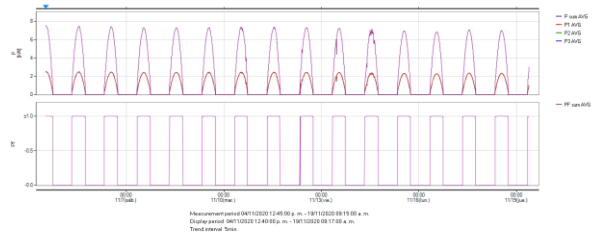

Figure 5 Graph of the power profile in PV system of 10 kWp

In general, in figure 5, the 3 phases presented a maximum individual real power (kW) of 2.4 kW and a total of 7.31 kW. The values are reasonable considering that it has an installed photovoltaic capacity of 10 kWp. Since it is not an efficiency study, the comparative alternating current power versus photovoltaic power is not made.

The lower part of the graph shows the behavior of the power factor throughout the measurement period. Due to the type of system in question, electricity generation from a linear signal in this case, the average value of the power factor throughout the measurement time was 0.99. Measurements were made with original factory settings (Table 4).

Power	Power values Minimum	Average	Maximum	Inverter power in kWp
Apparent (kVA)	7.53	7.56	7.59	
Real (kW)	7.52	7.55	7.57	13
Reactive (kVAR)	-0.75	-0.36	0.51	

Table 4 Measurement values obtained

Harmonic component profile of voltage and current

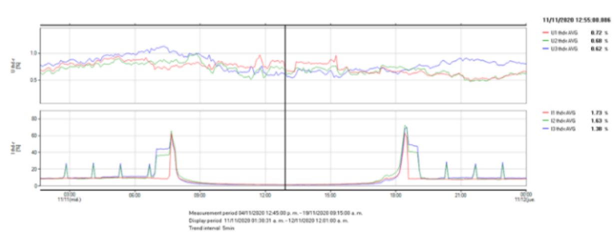

Figure 6 Graph of voltage and current profile in PV system of 10 kWp

Figure 6 shows the behavior of the inverter, with early morning being the left side and nighttime being the right side, the upper part shows THDv and lower part of current THDi. In graph 4 it can be seen that during the operation of the inverter it shows average THDi values of 1.6% in each phase and a practically periodic voltage harmonic distortion behavior of 0.6% of THDv. This is due to the fact that all the time the inverter is receiving a potential difference at the measurement point and this will be the value of the grid, as opposed to the current. This only shows reading when the inverter is injecting energy into the grid and is capable of controlling the harmonic contribution, at night, as it does not have a generation and the equipment goes to "rest state" there is no current circulation so that the reading you have may be due to interference or noise due to a zero value or milliamp readings. The manufacturer of the inverter in its technical sheet shows a THDv of 1.5%, according to the registered data they are under that margin.

For THDv, the maximum value reached in the measurements is approximately 1.2%, comparing the values with table 1 of IEEE Std 519-2014, it is observed that it complies with this total harmonic distortion index in voltage.

Table 1—Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV < $V \leq 69$ kV	3.0	5.0
69 kV < $V \leq 161$ kV	1.5	2.5
161 kV < V	1.0	1.5[a]

[a]High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

Source: https://edisciplinas.usp.br/pluginfile.php/1589263/mod_resource/content/1/IEEE%20Std%20519-2014.pdf

Phase	THDV Máx.	Maximum limit (%)	Std. IEEE 519-2014
1	0.69	8%	Complies
2	0.66		Complies
3	0.55		Complies

Table 5 Measurement values obtained compared to IEEE 519-2014

Calculation of Total Demand Distortion (TDD)

Total Demand Distortion or TDD evaluates the harmonic currents that occur between the user and the power supply.

Harmonic values are based on a common point of coupling (PCC), which is a common point from which each user receives power from the power supply.

The power meter uses the following equation to calculate TDD,

$$TDD = \left(\frac{\sqrt{(HCIA)^2+(HCIB)^2+(HCIC)^2}}{(ILOAD)*100}\right)$$

Where ILoad equals the maximum demand load of the power system. Source: https://www.productinfo.schneider-electric.com/pm5300/5be97f3b347bdf0001d99c87/PM5300%20User%20Manual/Spanish/BM_PM5300UserManual_EAV15107_Spanish_Castilian_es_0000237456.ditamap/$/C_PQ_TDDCalculations_Spanish_Castilian_es_0000076995

Frequency profile

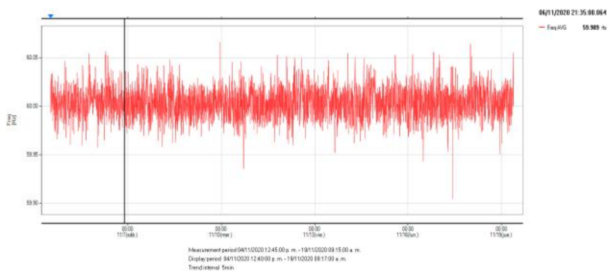

Figure 7 Maximum and minimum frequency profile

The graph shows the profile of the maximum and minimum frequency. The behavior of the average frequency is 60,004 Hz, minimum value 59,959 Hertz and its maximum value 60,049 Hertz. The average value is 0.006% above the value of the fundamental frequency of 60 Hertz. The variation window presents a maximum 0.08% above the value of the fundamental. The maximum values were presented instantaneously, however, these values do not affect the loads.

Measurements in the residential photovoltaic system

Voltage profile

In general, the 2 phases presented instantaneous variations (figure 8). The values were compared with the standard IEEE 1100-1999 variation not greater than 5% and with the regulation of the law of the electric power public service, chapter V article 18 variation not greater than 10%;

Phase 1 presents an average 6.6% above the nominal value (127 V), phase 2 presents an average 7.62% above the nominal value (127 V), the two phases can be classified as out of range under the IEEE 1100- standard 1999 but within the regulations of the law of the electric power public service.

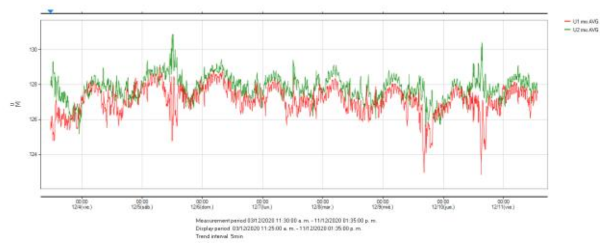

Figure 8 Graph of voltage profile in PV system of 2 kWp

Phase	Nominal phase-to-neutral voltage	Phase-to-neutral voltage (V) Minimum	Average	Maximum	Limits	IEEE Std 1100-1999
1	127 V	107.57	127.12	127.53	± 5%	No complies
2	127 V	127.22	127.83	128.43		Complies

Table 6 Voltage limits

Note: In phase 1 the minimum value marks 107.57 on December 4, 2020 at 1:50 p.m., this value was caused by a CFE failure.

Current profile

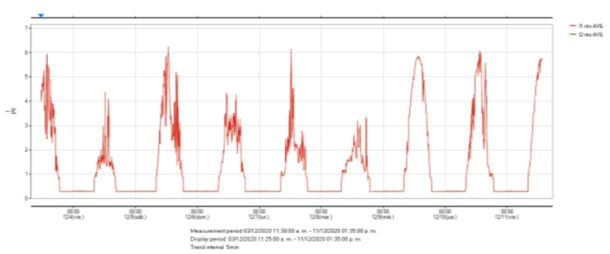

Figure 9 Graph of current profile in PV system of 2 kWp.

Graph 9 shows the behavior of the 2 phases, which present a balanced behavior, registering maximum values of 6.25 A per phase in the period of time between 12h00 and 13h00. The variation in amperage is not periodic and is caused by variations in solar irradiance in the solar panels. Throughout the monitoring period, there were no other disturbances that affect the quality of energy with reference to the current.

Power profile

In general, in graph 8, the 2 phases presented a maximum individual real power (kW) of 0.7 kW and a total of 1.5 kW. The values are reasonable considering that it has an installed photovoltaic capacity of 2 kWp.

Since it is not an efficiency study, the comparative alternating current power VS photovoltaic power is not made.

The lower part of the graph shows the behavior of the power factor throughout the measurement period. Due to the type of system in question, electricity generation from a linear signal can have a power factor of practically 1, in this case, its average value was oscillating throughout the operation time from 0.8 to 0.99. Most brands allow you to adjust the power factor by limiting other parameters. Measurements were made with original factory settings.

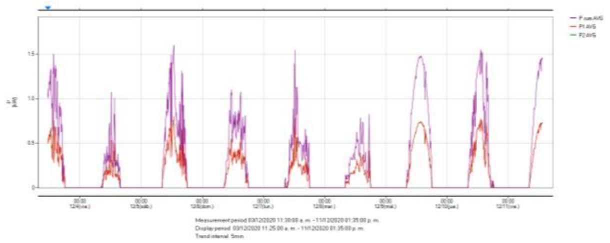

Figure 10 Graph of the power profile in PV system of 2 kWp

Phase	Nominal phase to neutral voltage	Phase-to-neutral voltage (V) Mínimum	Average	Máximum	Límits	IEEE Std 1100-1999
1	127 V	107.57	127.12	127.53	± 5%	Fails
2	127 V	127.22	127.83	128.43		Complies

Table 7 Measured values obtained

Harmonic component profile of voltage and current

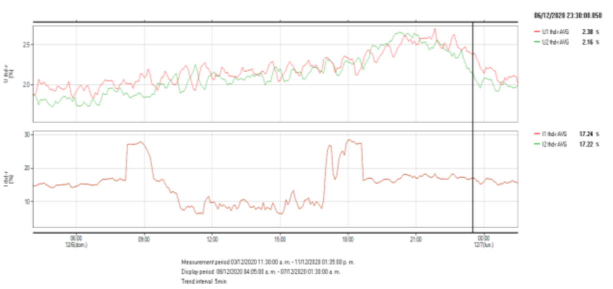

Figure 11 Profile graph of the harmonic component of voltage and current in PV system of 2 kWp.

Graph 11 shows the behavior of the inverter, with early morning being the left side and nighttime being the right side, the upper part of the graph shows the total harmonic distortion of voltage THDv and the lower part the total harmonic distortion in current THDi. In graph 8 you can see that during the operation of the inverter it shows average THDi values of 6.23% in each phase and a practically periodic voltage harmonic distortion behavior of 2.42% of THDv.

This is due to the fact that all the time the inverter is receiving a potential difference at the measurement point and this will be the value of the grid, as opposed to the current. This only shows reading when the inverter is injecting energy into the grid and is capable of controlling the harmonic contribution, at night, as it does not have a generation and the equipment goes to "rest state", there is no current flow through what the reading you have may be due to interference or noise due to a zero value or milliamp readings. The manufacturer of the inverter in its data sheet shows a THDv of <3%, for the THDv the maximum value reached in the measurements is approximately 2.5%, comparing the values with table 1 of the IEEE Std 519-2014, it is observed that it complies with this index of total harmonic distortion in voltage.

Table 1—Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV < $V \leq 69$ kV	3.0	5.0
69 kV < $V \leq 161$ kV	1.5	2.5
161 kV < V	1.0	1.5[a]

[a]High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected.

Source: https://edisciplinas.usp.br/pluginfile.php/1589263/mod_resource/content/1/IEE%20Std%20519-2014.pdf

Phase	THDV Máx.	Maximum limit (%)	Std. IEEE 519-2014
1	2.42	8%	Complies
2	1.93		Complies
3	N/A		N/A

Table 8 Measurement values obtained compared to IEEE 519-2014

Frequency profile

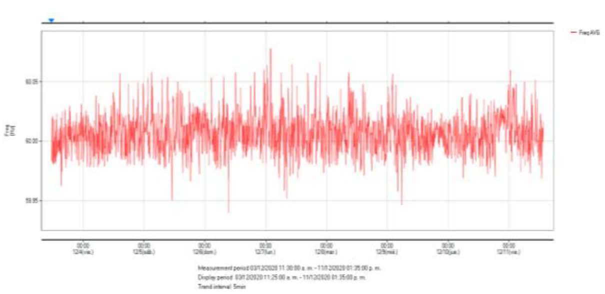

Figure 12 Frequency profile

The graph shows the profile of the maximum and minimum frequency. The behavior of the average frequency is 60,078 Hz, minimum value 60,039 Hertz and its maximum value 60,273 Hertz. The average value is 0.12% above the value of the fundamental frequency of 60 Hertz.

The variation window presents a maximum 0.45% above the value of the fundamental. The maximum values were presented instantaneously, however, these values do not affect the loads.

Discussion

According to the data recorded in the commercial photovoltaic system using a Fronius® inverter of Austrian origin, acceptable values were found in voltage, current, power, PF and harmonics. Although it has a harmonic distortion, it is low and the individual contribution it can make is 0.05 Amp. Harmonic orders do not represent a possibility of damage to specific loads connected to the network. Graph 12 shows the behavior of the voltage waveform, the THDV is 1.52%. No other disturbances affecting power quality are observed during the measurement period.

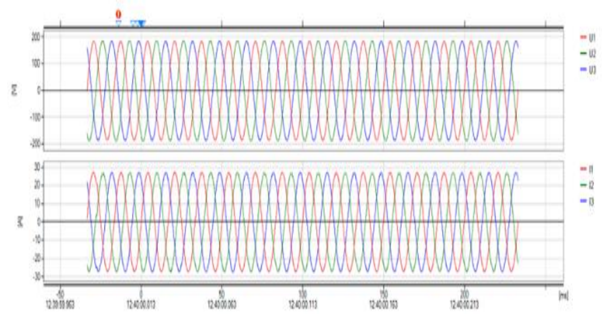

Figure 14 Waveform of a commercial photovoltaic system

On the other hand, the residential photovoltaic system uses a GOODWE® inverter made in Shanghai meets off-grid values, but these are not attributable to the inverter, but to the grid. The current behavior is stable as is the power. Harmonics are integer multiples of the fundamental frequency, this disturbance that affects the quality of power, the presence of harmonics in residential, commercial and industrial electrical systems, causes heating of conductors, tripping of protections and the effects are maximized when the voltage occurs. series or parallel resonance which contributes to the damage of sensitive electronic equipment. It is necessary to know the response of the industrial electrical system, which can be known by performing a frequency sweep to know the frequency at which the series or parallel resonance could occur.

The individual contribution continues to be low, during the measurement period harmonics of 3rd order (3.05%), 5th order (1.82%), 7th order (1.7%) and with a higher contribution of 9th order (4.25%) were identified. Figure 10 shows the waveform of the residential inverter, a distorted wave can be seen on the crest and this distortion is caused by the afore mentioned harmonics.

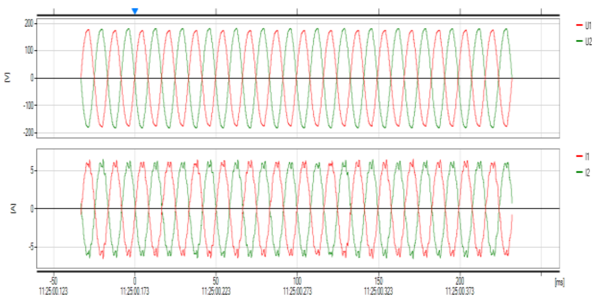

Figure 13 Waveform of a domestic photovoltaic system

Conclusions

The degree to which harmonics can be tolerated is determined by the susceptibility of the load (or power source) to them. The least susceptible type of equipment is one in which the main function is in heating, such as in an oven. In this case, harmonic energy is generally used and is therefore completely tolerable. The most susceptible type of equipment is that whose design or constitution assumes a (almost) perfect sinusoidal fundamental input.

This equipment is frequently found in the categories of communication or data processing equipment. One type of load that normally falls between these two extremes of susceptibility is motor load. Most motor loads are relatively tolerant of harmonics. Even for the least susceptible equipment, harmonics can be damaging. In the case of a furnace, for example, they can cause thermal dielectric stress or stress, which causes premature aging of the electrical insulation.

Broadly speaking, it can be concluded that a photovoltaic system can deliver a different quality of energy between inverter manufacturers and this could be directly related to the price. The better power quality you deliver, the more specific electronics you will need, increasing your cost.

Now, this power quality cannot be enough to say that it will cause failures in the grid or electrical appliances, these damages are associated with a combined situation between the inverter, the grid and electrical appliances, that is, resonance. These impact studies are recommended to be done in photovoltaic systems connected to industrial electrical installations.

In the two cases studied, we found effects greater than 5% established in the IEEE 1100-1999 standard, but less than 10% established in the Mexican legal framework, in accordance with CFE Specification L0000-45 "Permissible deviations in waveforms of voltage and current in the supply and consumption of electrical energy, which do not cause damage to the electronic cards of the equipment used in the Mexican hotel industry".

Acknowledgments

The authors are grateful for the facilities provided by the company "MATERIALES LA VENA", as well as the owner of the house to carry out the analysis within their PV system interconnected to the grid, they also thank the Technological University of Bahía de Banderas, Nayarit and Technological University of San Juan del Río, Querétaro for its willingness to do so loan of Hioki® power quality analyzer equipment.

References

Afonso, T., de Arruda Bitencourt, L., Fortes, M., Gomes, J., & Maciel, R. (2018). Impact Analysis on Power Quality of a Small Distributed Generation. *American Journal of Renewable and Sustainable Energy, 4*(3), 56-63.

Bouchakour, S., Chouder, A., Cherfa, F., Abdeladim, K., & Kerkouche, K. (2012). The First Grid-Connected Photovoltaic System in Algeria: Power Quality Observation. *The Second International Days on Renewable Energies & Sustainable Development*, (págs. 1-6). Argelia.

Caballero, C., Cortez, L., Muñoz, G., & Castañeda, J. (2016). Filtro activo de potencia para compensar la distorsión armónica de un sistema fotovoltaico autónomo. *Tecnología e Inovación, 3*(9), 76-84.

ISSN-2523-2517

Çelebi, A., & Çolak, M. (2011). The effects of harmonics produced by Grid connected photovoltaic systems on electrical networks. . *Universities Power Engineering Conference (UPEC) Proceedings of* , (págs. 1-8). Izmir.

Durán, J. C., Raggio, D., Socolovsky, H. P., Videla, M., & Plá, J. (2016). Evaluación de la calidad de la energía en dos casos de estudio: distorsión armónica inyectada por un sistema fotovoltaico de 40 kw y emitida por las cargas de una vivienda unifamiliar. . *Avances en Energías Renovables y Medio Ambiente-AVERMA*(20), 1-12.

Favuzza, S., Graditi, G., Spertino, F., & Vitale, G. (2004). Comparison of power quality impact of different photovoltaic inverters: the viewpoint of the grid. *IEEE International Conference on Industrial Technology, 2004.*, (págs. 542-547).

Gallo, D., Landi, C., Luiso, M., & Edoardo, F. (2013). Analysis of a photovoltaic system: AC and DC power quality. *WSEAS Transactions on Power Systems, 8*(4), 45-55.

González, P., Romero-Cadaval, E., G. E., & Guerrero, M. A. (2011). Impact of grid connected photovoltaic system in the power quality of a distribution network. (págs. 466-473). Springer.

González-Castrillo, P., Romero-Cadaval, E., González-Romera, E., Barrero-González, F., & Guerrero-Martínez, M. A. (2007). Influencia de una Instalación Fotovoltaica Conectada a Red sobre la Calidad de Potencia de una Red de Distribución. Extremadura, España.

Hernández, J. C., & Medina, A. (2006). Conexión de sistemas fotovoltaicos a la red eléctrica: calidad de suministro. *Sumuntán*(23), 33-44.

Lu, S. Y., Wang, L., Ke, S. C., Chang, C. H., & Yang, Z. H. (2014). Analysis of measured power-quality results of a PV system connected to Peng-Hu Power System. *IEEE Industry Application Society Annual Meeting* , (págs. 1-7).

Misak, S., Prokop, L., & Bilik, P. (2014). Power quality analysis in off-grid power system. *ELEKTRO*, 337-342.

Niitsoo, J., Jarkovoi, M., Taklaja, P., Klüss, J., & Palu, I. (2015). Power quality issues concerning photovoltaic generation in distribution grids. *Smart Grid and Renewable Energy*, 1-6.

Patsalides, M., Evagorou, D., Makrides, G., Achillides, Z., Georghiou, G. E., Stavrou, A., & Werner, J. H. (2007). The effect of solar irradiance on the power quality behaviour of grid connected photovoltaic systems. *RE&PQJ*, 1-7.

Ruelas, R. (12-26 de abril de 2021). Sistemas de Puesta a Tierra [Curso de Capacitación]. . Querétaro, Querétaro, México: Instituto de Ingenieros en Electricidad y Electrónica IEEE PES Querétaro-Guanajuato.

SEMARNAT. (2020). *Guía de eficiencia energética en el diseño, construcción y operación de hoteles en climas cálidos.* Obtenido de https://www.gob.mx/semarnat/documentos/guia-de-eficiencia-energetica-en-el-diseno-construccion-y-operacion-de-hoteles-en-climas-calidos

Spertino, F., Chicco, G., Ciocia, A., Malgaroli, G., Mazza, A., & Russo, A. (2018). Harmonic distortion and unbalance analysis in multi-inverter photovoltaic systems. *2018 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)* (págs. 1031-1036). IEEE.

ISSN-2523-2517