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Research article

Experimental investigation of the impact of environmental parameters on the supraharmonic emissions of PV inverters

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Abstract: Modern electricity networks are facing significant challenges in terms of power quality due to the increasing integration of power electronics. Even though low order harmonic control has largely been achieved, the emergence of supraharmonics is becoming a new cause for concern. This topic has gained interest in the past decade since power quality issues have become important due to the proliferation of highly sensitive electrical and electronic equipment. This special case of harmonics is mainly due to the power electronic converters utilized in industrial as well as residential applications, including electromobility, motor drive systems, and photovoltaic installations. While the adverse effects of supraharmonics have been pointed out in numerous studies and intensive research is underway on the crucial subject of supraharmonic measurements, the parameters affecting their levels have not received adequate attention. We attempted to shed more light on this important issue in the specific case of a small grid-connected PV system. In particular, the supraharmonic emission levels of the system were investigated through experimental measurements, and useful conclusions on the impact of specific environmental factors were derived.

Keywords: supraharmonics; environmental factors; photovoltaics; distributed generation; fourier transform

1. Introduction

Electrical power quality has been one of the major issues under investigation in the past decades. Electrical power quality is reflected on the electrical current and voltage waveforms. Ideal waveforms have a pure sinusoidal form with a standard frequency, depending on the country. For example, in Greece, the electrical current and voltage waveforms should present sinusoidal form with a frequency of 50 Hz. These waveforms deviate from the pure sinusoidal form due to many factors associated especially with power electronics. For this reason, quality indices have been introduced in order to characterize the purity of these waveforms. For the current and the voltage respectively, the Total Harmonic Distortion of the Current, THD_i, and the Total Harmonic Distortion of the Voltage, THD_v, are widely used. The massive penetration of PV generators, charging stations for electric vehicles and other similar electronic devices with high power content, resulted in an increment of the harmonic distortion and especially in the frequency band between 2 and 150 kHz. The term "supraharmonics" has been introduced from the scientific and engineering communities to characterize this particular frequency band.

Recent research work has proven that the existence of supraharmonics can have a negative impact on the operation of the electricity network [1,2]. For example, supraharmonics have been associated with acoustic noise. Coils, transformers and capacitors included in household devices constitute sources of mechanical oscillations which are transmitted on the surfaces of devices and detected as noise. Characteristic examples of devices that have been associated with acoustic noise resulting from supraharmonics are battery chargers for electronic equipment such as personal computers and smart phones [3].

Research on supraharmonics has recently intensified due to the increasing reports of disturbances attributed to them. Data from various sites in Europe and North America reveals that supraharmonic emission is affecting networks worldwide [4]. In North America, the problem of supraharmonic emission is stronger than in Europe, possibly because of a differentiation on the design of the two grids or due to the connection of more supraharmonic injecting devices to the North American electrical grid. Furthermore, according to [4], important problems for the correct measurement of supraharmonics are measuring instrument restrictions and the lack of standardization regarding measuring techniques.

Scientific research conducted on the electricity network in Germany [2] has revealed supraharmonic pollution in the electrical current and voltage waveforms associated with renewable energy sources. The existence of supraharmonics was the result of the utilization of frequency power converters. Additionally, according to this research, the supraharmonics can be transferred from the High Voltage network to the Medium Voltage and Low Voltage networks. In [5], an investigation on the supraharmonic interaction between an electrical vehicle and a photovoltaic inverter was conducted. The intermodulation distortion due to the interaction of different switching frequencies was highlighted. A typical domestic customer was also considered in this study to reveal the effect of intermodulation distortion on household equipment. Supraharmonic emissions from electric trains used in public transportation were investigated in [6]. The static frequency converters used in these railway systems seem to have an extra negative impact on suprahatmonic emissions. It was shown that the increase of frequency power converters in such railway systems lead to the increase of emissions in the 1–10 kHz band. A system built to measure supraharmonics in the range of 2 up to 300 kHz revealed the supraharmonic emission of Light Emitting Diodes (LEDs) and CFL lighting devices [7,8]. This system considers the measurement of the voltage as well as current spectra. The operation of Compact Fluorescent Lamps (CFL) was also investigated in [9]. Simulation results showed that the ballast circuit used in CFLs can be responsible for supraharmonic emissions. However, since the distribution system impedance is basically resistive, it was concluded that it is unlikely for the supraharmonic emission from CFLs to spread through the electricity network. On the other hand, as it was proved in [10], supraharmonics can, in fact, propagate through a Medium Voltage electrical network over several kilometers. Practical methods for the determination of the sources of supraharmonics were also introduced.

Apart from supraharmonic emission propagation toward the electrical grid, there is also the case of emission propagating toward a neighboring customer's installation. In fact, the latter seems to be more likely than the former. Moreover, supraharmonic emissions propagation seems to be strongly associated with the number and constellation of devices emitting supraharmonics, as well as the source impedance characteristics [11]. Furthermore, the flow of a large number of harmonics and supraharmonics may result in high frequency resonances in the grid. The change in the resonance characteristics of the power grid cannot be addressed with classical passive filters. For this reason, the use of active filters can significantly improve the performance of passive filters [12].

Regardless of the power rating of the devices, grid-connected inverters used for the conversion of DC current and voltage to AC are a common component. Even though the application of pulse width modulation techniques can significantly mitigate low order harmonic distortion, (< 2 kHz), the high switching frequency required in modulation techniques results in suprahamonic emission. For this reason, both harmonic and supraharmonic distortion have to be taken into consideration from the early design stage of power inverters [13,14].

Emission levels seem to depend on many factors. For example, in photovoltaic systems such factors are the DC input voltage, AC voltage level and fluctuation and power output of the inverter. It is observed that different inverter models, with different designs and control schemes, present supraharmonic emission to the grid [15]. However, due to the wide range of operating conditions of PV systems, their behavior has to be more rigorously studied. The acquisition of as much data as possible on the factors affecting this behavior can provide helpful guidance on the selection of suitable equipment or installation location. In [16], the supraharmonic emissions of a small-scale grid-connected PV system were studied by means of a dedicated simulation tool. The impact of specific PV system parameters, such as filter component values and the location of the system on the utility distribution feeder, was investigated. In this study, field measurements of the supraharmonic emissions of a grid-connected PV system are examined and important conclusions regarding the influence of environmental parameters on their levels are derived. A custom measuring procedure was designed in the frame of the paper. The existence of supraharmonics was confirmed with the supraharmonic distortion due to the inverter be worst at low solar irradiance and therefore at low output power. The supraharmonics seem to be straight correlated with the switching frequency of the inverter and its integer multiples. The above-mentioned important observations can open new horizons in the design of power inverters aiming to the limitation of the supraharmonics. Additionally, this paper can essentially contribute to the shaping of future legislation about the supraharmonics into the modern electrical networks.

2. Materials and methods

2.1. Measuring topology

Our aim of this article is to investigate the suprahamonics produced by the inverter of a typical small residential photovoltaic (PV) system. Furthermore, the association of supraharmonic emissions with environmental parameters is investigated aiming to identify potential relation between them. The PV system used in this work is installed in Athens, Greece, with a nominal power of 8 kWp, with a 3-phase inverter and no other PV in the same connection line up to the transformer. The PV is directly connected to the low voltage electrical grid, in a distance of 300 m from the distribution transformer. The installed inverter is an SMA Sunny Tripower. Figure 1 presents the wiring of the PV scheme.

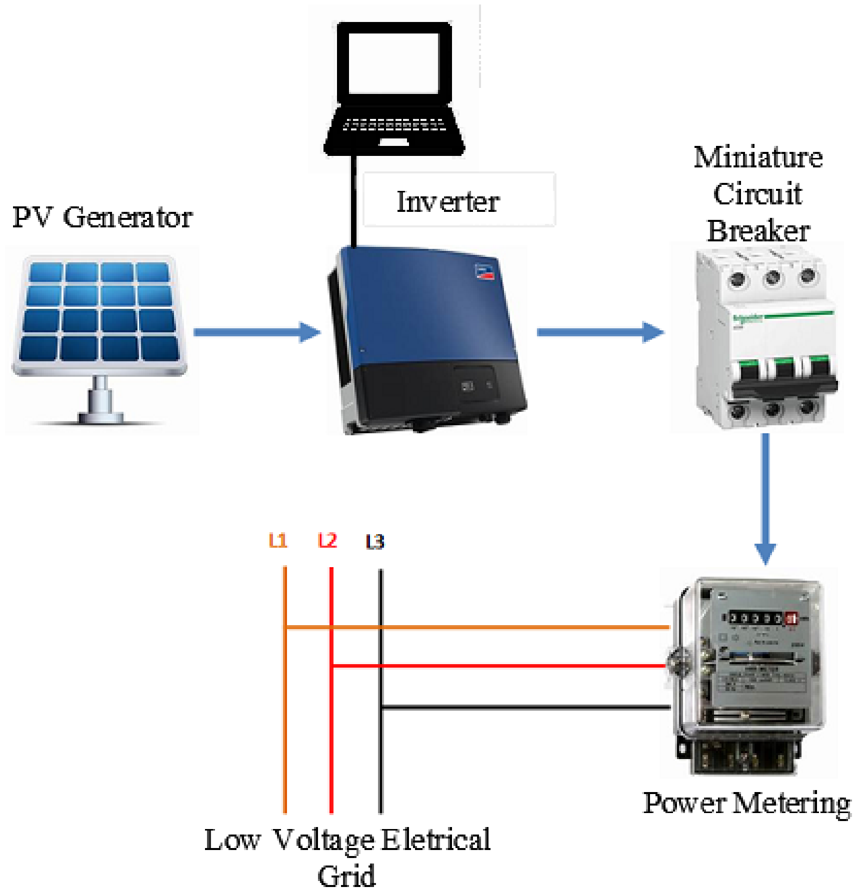


Figure 1. Home PV installation under investigation.

Table 1. Inverter specifications.

Parameter	Value
Nominal value at 230 V and 50 Hz	10 kW
Apparent Power with cosφ = 1	10 kVA
Nominal Grid Voltage	~3/N/PE, 230 V/400 V
Nominal Current @ 220 V	14.5 A
Nominal Current @ 230 V	14.5 A
Nominal Current @ 240 V	13.9 A
THDi when THDv <2% and AC Power >50% of nominal value	≤3%

Table 1 presents the AC output characteristics of the inverter. It is worth noting that the THDi value, which is ≤3%, requires the THDv to be <2% and the AC output power to be >50% of nominal power. The THDi and THDv indices given for the inverter have been calculated without taking into consideration the supraharmonics band, due to the fact that supraharmonics are not addressed by international standards.

Figure 2 illustrates the measuring topology used in this paper. Temperature measurements are conducted on the frame and protected glass of the photovoltaic (no. 1 in Figure 2) using a laser thermometer. Ambient temperature and humidity are measured (no. 2) by means of a hand measuring device and solar irradiance is measured by means of a pyranometer (no. 3). Furthermore, a personal computer is used to obtain power measurements (no. 4) and three current probes in combination with a digital oscilloscope are used for the measurement of the three phase currents at the AC side of the inverter.

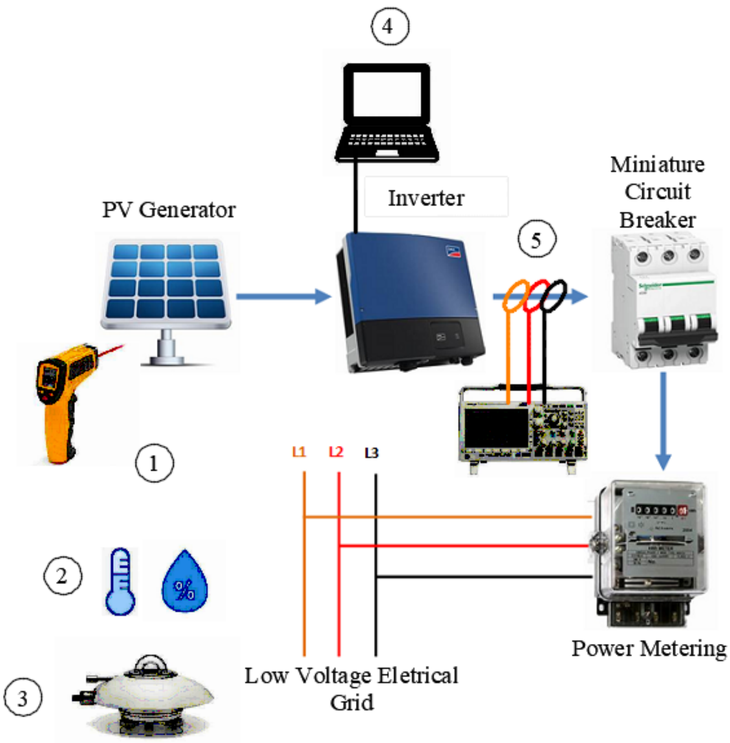


Figure 2. Measuring topology.

2.2. Measuring devices

As mentioned, a laser thermometer was used for the temperature measurement on the glass of the photovoltaic panels and for the temperature on the corresponding frame of the photovoltaic panels. This laser thermometer (Type UNI-T UT303B IR) has a temperature range of –32 ~ 850 ℃. The response is 250 msec and the accuracy is ±1.8%.

The solar irradiance was measured by means of the solar irradiance sensor (pyranometer) DeltaOHM LP471PYRA.03 and a digital measuring device of type HD2102.2. The data sheet of the two measuring devices employed in the measurement of solar irradiance can be found in reference [17].

Three current transformers were used for the detection of the three phases of the current at the AC side of the inverter (Type ELDITEST CP6220 [18]). Their basic technical specifications are presented in Table 2. In addition, a four-channel digital oscilloscope (Type SDS2304X [19]) was used for the capture and measurement of the three electric currents. The current probe measuring bandwidth is DC up to 300 kHz. This range covers the supraharmonics located in the range of 2–150 kHz. The sampling rate of the oscilloscope is 2 Gsa/sec. This speed is adequate for the accurate detection and measurement of supraharmonics.

Table 2. Basic technical specifications for the current probe ELDITEST CP6220.

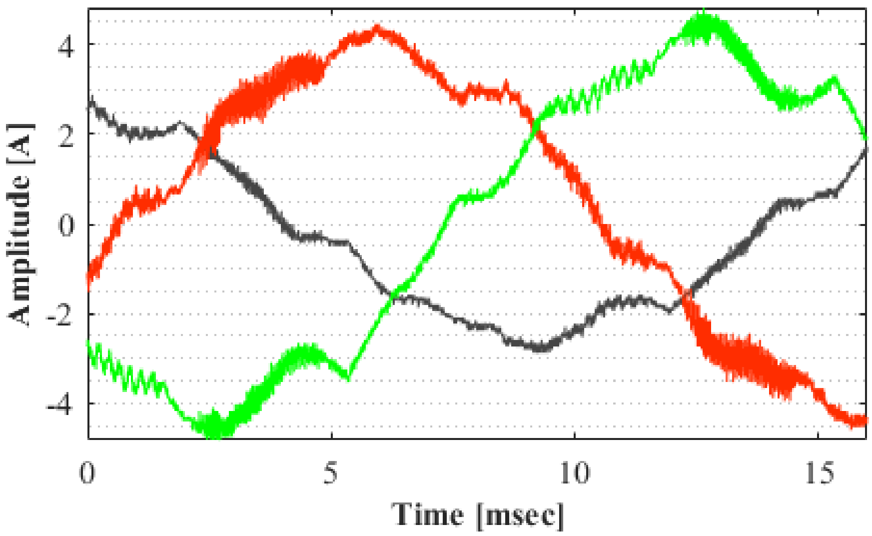
Parameter	Value
Measurement ranges	100–10 mV/A
Current (DC + peak AC)	10–100 A
Bandwidth	DC–300 kHz
Rise and fall time	1.2 μs (typ.)
Max. working voltage	600 VAC RMS CAT II / 300 VAC RMS CAT III
Max. floating voltage	600 VAC RMS CAT II / 300 VAC RMS CAT III
Operating Temp.	0 to 50 ℃ (32 to 122 °F)
Max. operating humidity	0 to 95% (0 to 40 ℃; 32 to 104 °F) 0 to 45% (40 to 50 ℃; 104 to 122 °F)

3. Measurements and results

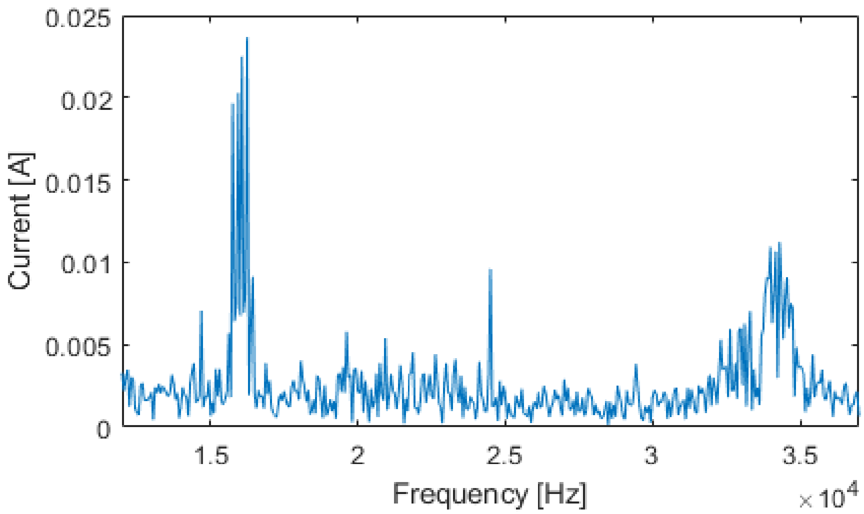
Our aim is to investigate the possible relation and potential correlation of specific environmental parameters with the supraharmonics produced at the inverter output of a small-scale residential PV installation. For this reason, two different sets of measurements are taken into consideration. The two sets were conducted on different days and hours of the year. The first measurement set was conducted on the 4th of September and in the time slot of 12.30 to 14.00. The second measurement set was conducted on the 17th of August and in the time slot of 16.00 to 18.15. The measured parameters were the solar irradiance in [W/m^2], the PV glass temperature and PV panel frame temperature in [℃], the ambient temperature and humidity in [℃] and [%], respectively, the inverter AC output in [kW], and the three electric currents for the three phases at the inverter output in [A].

The electric current measurements for the three phases were conducted by means of the digital oscilloscope in combination with the current probes mentioned in the previous section. Their analysis for the existence of supraharmonics was done using Fourier transform with MATLAB code written by the authors.

Figure 3 presents the 3-phase electric currents at one measurement instance. The waveform is not a pure sinusoidal wave. The existence of harmonics is proven in Figure 3a. Additionally, Figure 3b shows the Fourier Transform analysis which was conducted in the band area from 10 up to 40 kHz. The Fourier analysis confirms the existence of supraharmonics.



(a)



(b)

Figure 3. Measurement of three phase currents (a) In the Time domain; (b) In the Frequency domain (for one phase).

During the measurement procedure six different parameters were measured, namely the three phase currents, the ambient temperature and humidity, the glass and frame temperature of the photovoltaic panels and the solar irradiance. Two measurement sets were obtained, corresponding to the two different days and time slots. Figure 4 presents the correlation of the THDi versus the inverter power output and the solar irradiance for the measurements of the first day. This figure presents the resulting THDi at 16 kHz (Figure 4a,b) and the resulting THDi at 32 kHz (Figure 4c,d). Quite expectedly, as the solar irradiance increases, so does the power output. However, it can also be deduced that as the solar irradiance increases, the THDi decreases. This is also evident from the results obtained on the second day, which are presented in Figure 5.

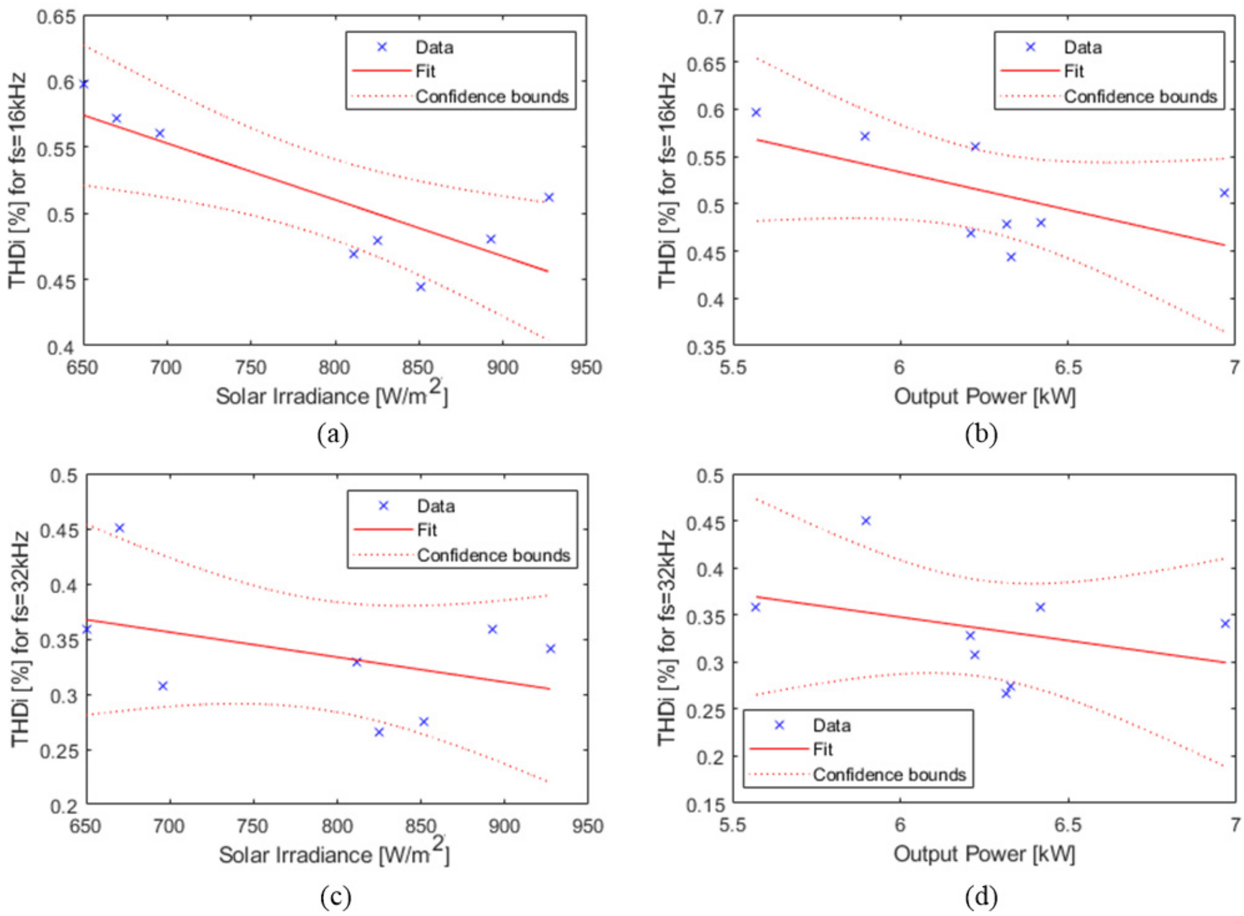


Figure 4. THDi values correlated with solar irradiance and inverter power output for the first measurement set (first day).

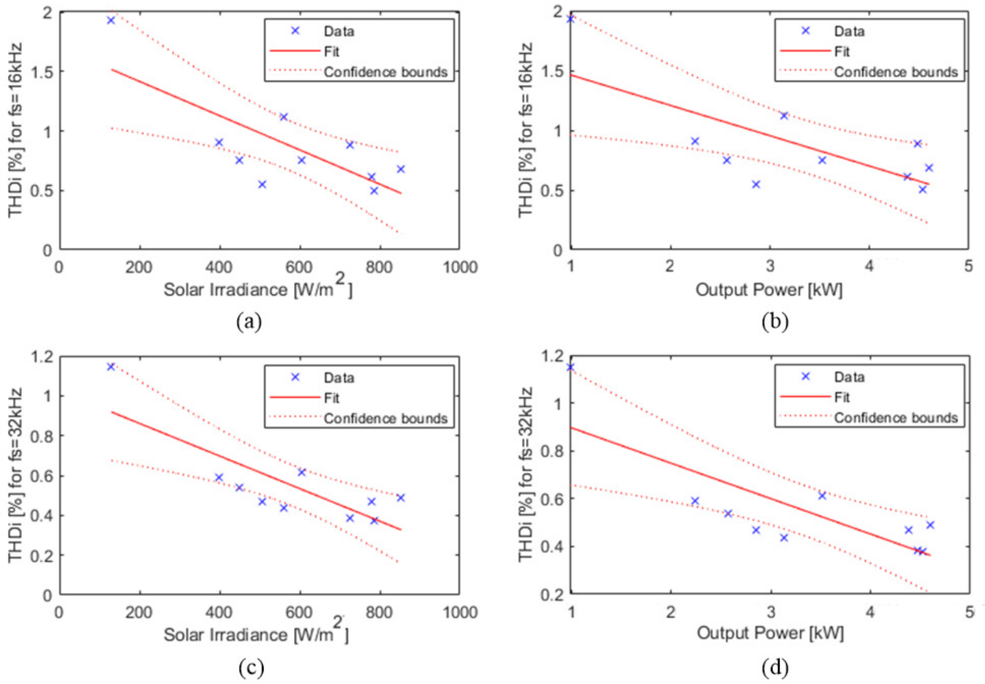


Figure 5. THDi values correlated with solar irradiance and inverter power output for the second measurement set (second day).

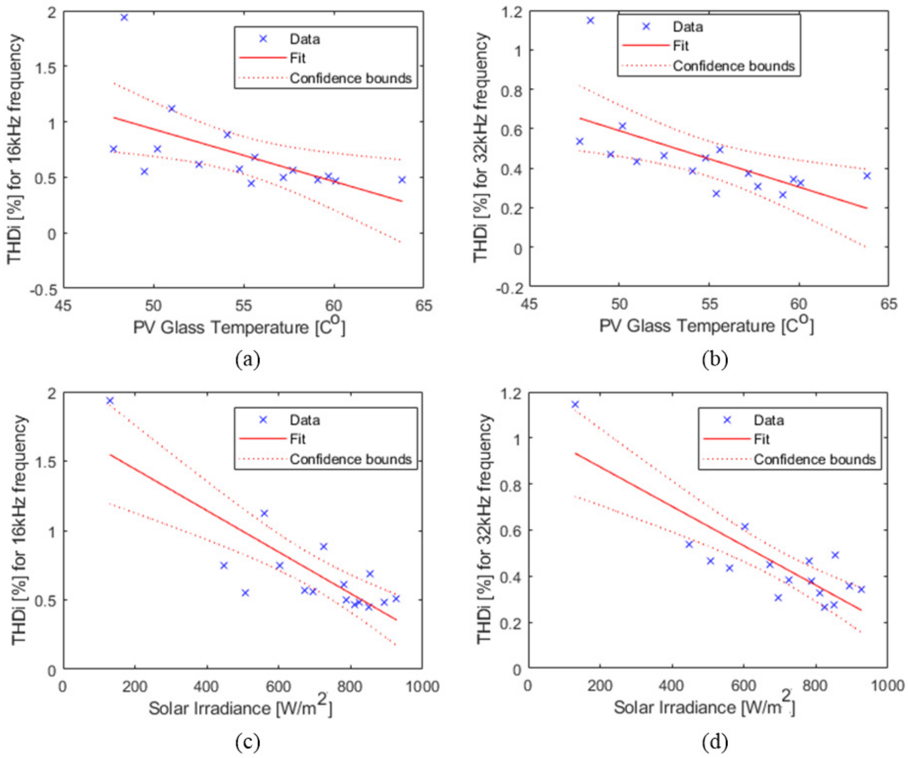


Figure 6. THDi values correlated with PV Glass Temperature and solar irradiance.

Figure 6 presents the correlation of THDi for the supraharmonic components of 16 and 32 kHz with the PV glass temperature and the solar irradiance. The increase of the solar irradiance results to an increase of the power output from the inverter. Moreover, the increase of the solar irradiance is associated with the increase of the PV glass temperature. On the other hand, the THDi for the supraharmonics seems to decrease.

4. Discussion

Supraharmonics distortion is a power quality disturbance that has only been under study for the past few years. The results of the presented research confirm the presence of supraharmonics at the output of the power inverter of a small grid-connected PV system. The mean THDi value turned out to be quite significant and cannot be ignored. The correlation of the THDi with environmental parameters such as PV glass temperature and solar irradiance had not been examined up to this point. Most of the existing studies are based on the correlation of the AC power output quality with the THDi. From the presented measurements it can be deduced that the solar irradiance, which affects the AC power output, has an impact on the THDi. The decrease of the solar irradiance leads to an increase of the supraharmonics.

Even though many parameters have been taken into consideration in the current study, the investigation of additional operation conditions is of high priority. All the measurements presented in this study were taken during three different summer days with constantly high ambient temperatures. It is proposed that multiple sets of measurements are obtained, under different environmental conditions and seasons of the year. Moreover, in addition to the supraharmonic emissions of small-scale 3-phase PV inverters examined in this study, an extensive investigation of the supraharmonic emissions of power inverters included in large-scale PV installations should also be conducted. Additionally, standards on supraharmonics must be introduced as soon as possible, since PV inverters are only a portion of the supraharmonic emitting devices. Other well-established applications of inverter technology include motor control drives in industrial installations, wind farms and quick chargers for electrical vehicles.

5. Conclusions

We examined the correlation between the supraharmonic current emission of a residential PV inverter and environmental conditions. Two supraharmonic areas centered around 16 and 32 kHz were considered, since these areas demonstrated the greatest impact during the measurement procedure. The presented graphs separately displayed the THDi at 16 and 32 kHz. The total supraharmonic-related THDi is the sum of the corresponding indices at 16 and 32 kHz. This results in THDi values ranging from 2.5% at low solar irradiance (about 150 W/m^2) to 0.8% at maximum solar irradiance (about 800 W/m^2). The presented THDi is a mean value of the THDi of the three phases. It should be noted that in some cases with low solar irradiance the THDi of one phase was exceeding the value of 10%. There seems to be no correlation between the PV glass temperature and the THDi of the supraharmonics. It is our opinion that the investigation of the correlation of solar irradiance with the THDi must be extended to include the total harmonic range from fundamental to 150 kHz, and an overall THDi including the harmonic and supraharmonic bands should be calculated and regulated, because the supraharmonics do not have regulated limits. This will allow to identify the true THDi in the networks and will reduce the stress in the existing network equipment which is not designed to operate in such rich in harmonics environment. Additional measurements should be taken considering different locations, PV systems orientation, and different operational and weather conditions, allowing a better understanding of the magnitude of supraharmonics emitted to the networks from the PV operation. This will allow the proper regulation of the limits for supraharmonics emission to the grids.

Use of AI tools declaration

The authors declare that they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

Constantinos S. Psomopoulos is an editorial board member for AIMS Energy and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

Author contributions

Dimitrios Barkas: Investigation, Formal analysis, Data Curation, Writing—Original draft. Anthoula Menti: Writing—Review and Editing. Pavlos Pachos: Writing—Review and Editing, Funding acquisition. Constantinos Psomopoulos: Conceptualization, Writing—Review and Editing, Supervision.

References

1. Novitskiy A, Westermann D (2017) Time series data analysis of measurements of supraharmonic distortion in LV and MV networks. *52nd International Universities Power Engineering Conference (UPEC)*, Heraklion, Greece, 1–6. https://doi.org/10.1109/UPEC.2017.8231921
2. Novitskiy A, Schlegel S, Westermann D (2019) Measurements and analysis of Supraharmonic influences in a MV/LV network containing renewable energy sources. *2019 Electric Power Quality and Supply Reliability Conference (PQ) & 2019 Symposium on Electrical Engineering and Mechatronics (SEEM)*, Kärdla, Estonia, 1–6. https://doi.org/10.1109/PQ.2019.8818259
3. Körner PM, Stiegler R, Meyer J, et al. (2018) Acoustic noise of massmarket equipment caused by supraharmonics in the frequency range 2 to 20 kHz. *18th International Conference on Harmonics and Quality of Power (ICHQP)*, Ljubljana, Slovenia, 1–6. https://doi.org/10.1109/ICHQP.2018.8378856

4. Rönnberg SK, Gil-De-Castro A, Medina-Gracia R (2018) Supraharmonics in European and North American low-voltage networks. *2018 IEEE International Conference on Environment and Electrical Engineering and IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe),* Palermo, Italy, 1–6. https://doi.org/10.1109/EEEIC.2018.8493930
5. Abid F, Busatto T, Rönnberg SK, et al. (2016) Intermodulation due to interaction of photovoltaic inverter and electric vehicle at supraharmonic range. *17th International Conference on Harmonics and Quality of Power (ICHQP),* Belo Horizonte, Brazil, 685–690. https://doi.org/10.1109/ICHQP.2016.7783471
6. Lennerhag O, Dernfalk A, Nygren P (2020) Supraharmonics in the presence of static frequency converters feeding a 16⅔ Hz railway system. *2020 19th International Conference on Harmonics and Quality of Power (ICHQP),* Dubai, United Arab Emirates, 1–6. https://doi.org/10.1109/ICHQP46026.2020.9177901
7. Agudelo-Martínez D, Limas M, Pavas A, et al. (2016) Supraharmonic bands detection for low voltage devices. *17th International Conference on Harmonics and Quality of Power (ICHQP),* Belo Horizonte, Brazil, 1003–1009. https://doi.org/10.1109/ICHQP.2016.7783327
8. Martínez DA, Pavas A (2015) Current supraharmonics identification in commonly used low voltage devices. *IEEE Workshop on Power Electronics and Power Quality Applications (PEPQA),* Bogota, Colombia, 1–5. https://doi.org/10.1109/PEPQA.2015.7168230
9. Agudelo-Martínez D, Pavas A (2017) Simulation of supraharmonics: A Compact Fluorescent Lamp (CFL) in single operation. *IEEE Workshop on Power Electronics and Power Quality Applications (PEPQA),* Bogota, Colombia, 1–6. https://doi.org/10.1109/PEPQA.2017.7981682
10. Novitskiy A, Schlegel S, Westermann D (2018) Analysis of supraharmonic propagation in a MV electrical network. *19th International Scientific Conference on Electric Power Engineering (EPE)*, Brno, Czech Republic, 1–6. https://doi.org/10.1109/EPE.2018.8396041
11. Espín-Delgado Á, Busatto T, Ravindran V, et al. (2020) Evaluation of supraharmonic propagation in LV networks based on the impedance changes created by household devices. *2020 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe)*, The Hague, Netherlands, 754–758. https://doi.org/10.1109/ISGT-Europe47291.2020.9248928
12. Xu LY, He YJ, Lei C, et al. (2020) Research on active filter for supraharmonics suppression of power grid. *2020 IEEE 3rd Student Conference on Electrical Machines and Systems (SCEMS)*, Jinan, China, 735–740. https://doi.org/10.1109/SCEMS48876.2020.9352290
13. Rönnberg SK, Gil-de Castro A, Moreno-Munoz A, et al. (2017) Solar PV inverter supraharmonics reduction with random PWM. *11th IEEE International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG)*, Cadiz, Spain, 644–649. https://doi.org/10.1109/CPE.2017.7915248
14. Moreno-Munoz A, Gil-de Castro A, Romero-Cavadal E, et al. (2015) Supraharmonics (2 to 150 kHz) and multi-level converters. *2015 IEEE 5th International Conference on Power Engineering, Energy and Electrical Drives (POWERENG)*, Riga, Latvia, 37–41. https://doi.org/10.1109/PowerEng.2015.7266293
15. Klatt M, Meyer J, Schegner P, et al. (2016) Characterization of supraharmonic emission caused by small photovoltaic inverters. *Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MedPower)*, Belgrade, 1–6. https://doi.org/10.1049/cp.2016.1067

16. Menti A, Barkas D, Kaminaris S, et al. (2021) Supraharmonic emission from a three-phase PV system connected to the LV grid. *Energy Rep* 7: 527–542. https://doi.org/10.1016/j.egyr.2021.07.100
17. DeltaOhm pyranometer data sheet. Available from: https://environmental.senseca.com/wp-content/uploads/document/DeltaOHM_HD2102.1_2_datasheet_ENG.pdf.
18. ELDITEST CP6220 current probe data sheet. Available from: https://ctemedia.s3-us-west-1.amazonaws.com/public/attachments/CP6000_series_datasheet.pdf.
19. Siglent SDS2304X 300 MHz four channel oscilloscope data sheet. Available from: https://www.siglent.eu/product/1139355/siglent-sds2304x-300mhz-four-channel-oscilloscope.