Voltage Harmonic Effect of a Large-Scale Solar PV Plant on High-Voltage Transmission Network

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***Abstract*—Photovoltaic solar energy is one of the most cost-effective renewable technologies, driving significant global expansion. In Spain, renewable energy policies and environmental awareness have led to a rapid increase in photovoltaic plant installations. However, this growth poses challenges for power quality, particularly due to harmonic emissions that can affect grid stability and efficiency. This study analyses voltage harmonics in a 35 MW photovoltaic solar farm in south-east Spain, comparing harmonic levels before and after commissioning. Statistical analysis of harmonic percentiles and their relative variations reveals specific frequencies with significant deviations, potentially impacting grid stability. A categorisation of harmonics based on their response to the plant's operation is provided, highlighting those with extreme or irregular behaviour. These findings enhance the understanding of the effect of photovoltaic systems on voltage harmonics and offer guidance for mitigating harmonic emissions in future installations.**

***Keywords*—Electric power system, harmonics, string inverter, PV power plant, substation.**

I. Introduction

PHOTOVOLTAIC (PV) solar energy has emerged as one of the most cost-effective renewable generation technologies in recent years, driving the rapid expansion of PV power plants worldwide. According to [1], PV solar energy is the second cheapest option, only slightly surpassed by onshore wind. Furthermore, the International Renewable Energy Agency (IRENA) highlights that the levelised cost of energy (LCOE) for solar PV has significantly decreased, making it more affordable than traditional energy sources, such as coal and natural gas, in many markets [2]. Similarly, the International Energy Agency (IEA) underscores that PV solar energy is now considered the cheapest energy source in history [3].

This rapid growth has had a significant impact on the global energy landscape, particularly in countries such as Spain, where renewable energy policies and environmental awareness have fostered a remarkable increase in the installation of PV systems. Consequently, there has been a proliferation of PV solar farms, ranging from small self-consumption systems to large-scale power generation plants, including the solar farm analysed in this study, with a capacity of 35 MW and located in south-east Spain. According to [4], Spain reached a total of 25.1 GW of installed PV solar capacity by the end of 2023, with plans to expand the total installed capacity of this technology to 39.2 GW by 2030 [5].

While the expansion of PV energy provides countless benefits in terms of sustainability and carbon emission reductions, it also presents significant challenges in the field of power quality, particularly concerning harmonic emissions [6], [7], [8]. The presence of harmonics can significantly impact the stability and efficiency of the electrical system [9]. PV systems require power electronics equipment to convert the generated direct current (DC) into alternating current (AC), which generates harmonic signals that propagate throughout the electrical network. These harmonics can lead to various issues, including waveform distortion, excessive heating of equipment and interference with other devices connected to the grid [10], [11]. Therefore, understanding and mitigating the impact of harmonics generated by PV solar farms is essential to ensuring the stability and reliability of the electricity supply.

For this reason, various studies have been conducted on the analysis of harmonic emissions in PV solar farms. However, most of these studies have been carried out through simulations, using laboratory-measured data or involving systems with very limited power capacities or observation periods. In [12], the authors studied the Total Harmonic Distortion (THD) using simulated data from a 1.2 MW PV energy system, analysing up to the 31st harmonic. Similarly, the study in [10] simulated a 4 MW PV installation and analysed harmonics up to the 15th order. Other studies, such as those presented in [13], [14], [15], used simulated data and focused on harmonics up to the 29th order, along with the THD. In [16], a simulation-based study was carried out, while in [17], both simulation and real data were used. The latter involved a 1.4 MW PV installation at the University of Florida, with measurements taken over a single day, comparing current THD under varying irradiance levels. Another common approach for analysing harmonic and interharmonic distortion is to test different laboratory conditions, as described in [18], [7], [19].

It is also well established that the current and voltage harmonics in an electricity generation installation are strongly correlated [20], [21], [22]. Existing studies in the scientific literature on voltage harmonics predominantly focus on analysing operating conditions at the Point of Common Coupling (PCC), primarily due to regulatory standards concerning voltage levels. The UNE-EN 50160 standard [23]

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specifies the characteristics of voltage supplied at the PCC by distribution networks up to 150 kV. Standards EN IEC 61000-3-2 [24] and EN IEC 61000-3-12 [25] define the requirements for voltage harmonics at the PCC to ensure accurate measurements of current harmonics. Similarly, the IEEE Std 519 standard, EN IEC 61000-3-6 and EREC G5 set voltage harmonic limits at the PCC [26], [27], [28]. Nevertheless, to the best of the authors' knowledge, studies comparing voltage levels before and after the commissioning of a large PV power plant are scarce, especially those focusing on voltage harmonics on the generation side of photovoltaic power plants. Such analyses could provide the scientific community with insightful information.

In this context, this study analyses the influence of a 35 MW solar PV plant in Spain on voltage harmonics at the PCC. To this end, voltage measurements, based on real field data, were taken from the fundamental harmonic to the 50th harmonic (H50) before and after commissioning the installation, at the PCC in the high voltage (HV) side at 132 kV. Firstly, the evolution of each voltage harmonic is compared both during the day and at night. Subsequently, the harmonics mainly affected by the installation are identified and grouped according to their evolution, with the aim being to identify the main cause of these variations. This approach aims to provide a deeper understanding of the relationship between the plant and the network.

II. Database

A comprehensive measurement campaign was conducted at a 35 MW grid-connected PV power plant in Spain. The plant comprises seven distinct zones, each equipped with a Smart Transformer Station (STS) with capacities ranging from 3 MW to 6 MW, depending on the number of String Inverters (STI) connected. Each STI has a rated power of 185 kW. Additionally, the plant features single-axis solar trackers, which adjust the orientation of the panels to follow the suns path throughout the day. These trackers are particularly active during sunrise and sunset, repositioning the panels to capture optimal sunlight. Voltage harmonic measurements were performed at the PCC on the high-voltage (HV) side, connected to a 132 kV transmission network.

The measurements were taken over a nine-month period: four months before commissioning (April 28, 2021 - August 6, 2021) and five months after commissioning (August 9, 2021 - December 9, 2021). Data were recorded at the PCC using a Fluke 1760 Class-A Power Quality (PQ) Analyser, in compliance with IEC 61000-4-30:2015+A1:2021 standards [29]. This analyser features an intrinsic error of 1% and a phase error of 0.5ř, ensuring precise harmonic measurements. Measurements at 132 kV were performed using an inductive voltage transformer (IVT) rated for 132 kV, designed for energy distribution and substation applications. The transformer has a class 0.2 accuracy, ensuring a maximum voltage magnitude error of ś0.2%. While higher-order harmonic measurements are less precise, this voltage transformer can provide reasonable accuracy for measurements up to its first resonance, which can vary significantly for each individual inductive voltage transformer, but expected to be in the low kHz range as a generic value [30]. The transformed voltage was then measured using a Fluke TPS VOLTPROBE 1000 V, which has an intrinsic uncertainty of ś0.1%. Flexible current probes (Fluke TPS FLEX 24) were used, operating within a measuring range of 48 to 65 Hz at 23řC ś 2 K. Voltage and current data were sampled at intervals of 3 seconds, with harmonic calculations performed using a 200 ms averaging window (10/12 cycle), as specified in IEC 61000-4-7:2002+A1:2009 standards [31].

The dataset includes voltage and current harmonics from the fundamental harmonic (H1) to H50, recorded for daytime and nighttime conditions. Additional parameters, such as active power, reactive power, power factor, and apparent power, were also collected as 10-minute and 1-minute mean values. Figure 1 illustrates the layout of the plant, highlighting the location of the PCC between the transmission network and the utility transformer (where the measurements were taken) with a red mark.

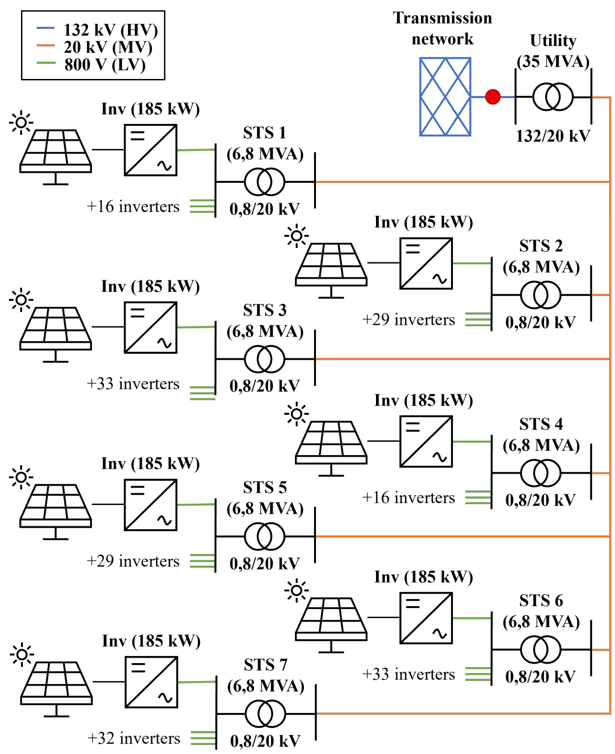


Fig. 1: Utility-scale PV plant layout.

From the beginning of the measurement campaign, the plant remained energised, although not operational. Moreover, the plant did not inject power into the grid during the nighttime period. The influence of the substation transformer on specific frequencies during this energised state cannot be dismissed. These conditions provide a unique opportunity to compare harmonic behaviour before and after commissioning under real-world conditions.

III. Methodology

This study analyses the voltage harmonic behaviour of a 35 MW PV power plant, focusing on its impact at the

PCC before and after commissioning. The methodology is structured as follows:

A. Analysis of Voltage Harmonic Standards

In the context of voltage harmonics within transmission networks, compliance with established standards is essential to ensure power quality and system reliability. While UNE-EN 50160 provides reference levels for voltage quality parameters in public supply networks [23], compliance with harmonic limits is typically governed by planning standards such as IEC 61000-3-6, IEEE 519, and EREC G5/5, depending on the country and specific grid requirements.

To ensure a comprehensive assessment, the most unfavorable measured values at the PCC were compared against the most restrictive limits specified by the four standard, as shown in Table I, both before and after the commissioning of the plant. For each harmonic order, the strictest limit among UNE-EN 50160, IEC 61000-3-6, IEEE 519, and EREC G5/5 was selected, guaranteeing that the comparison consistently considers the worst-case scenario for both the network conditions and the applicable standards.

It is important to note that these standards define limits based on different timeframes, such as highest daily or weekly values, and statistical parameters, such as 95% probability or 99th percentile values within the limits.

B. THD U Analysis

THD U was calculated for each phase, both before and after the plant's start-up, to assess its overall influence on harmonic distortion. The THD U values were compared against the limits established in Table I to ensure compliance.

C. Voltage Harmonic Analysis

Voltage harmonic measurements were conducted for frequencies ranging from H1 to H50. For each harmonic, data were segregated into daytime and nighttime periods based on sunrise and sunset times provided by the plant's operator. Voltage harmonics were statistically analysed using percentiles (1st, 5th, 25th, 50th, 75th, 95th, and 99th) to identify variations before and after the plants commissioning.

D. Voltage Harmonic Statistical and Graphical Analysis

The relative variation of each voltage harmonic percentile was calculated using Equation 1:

$$Var_P^{Hn} = \frac{V_{post,P}^{Hn} - V_{pre,P}^{Hn}}{V_{pre,P}^{Hn}} \tag{1}$$

where Var_P^{Hn} represents the relative variation of the percentile *P*-th percentile for the *n*-th harmonic [%], and $V_{pre,P}^{Hn}$ and $V_{post,P}^{Hn}$ denote voltage harmonic levels before and after commissioning, respectively [V].

These variations were visualised using heatmaps, with positive values indicating an increase in voltage harmonics and negative values representing reductions. The heatmaps distinguish between daytime and nighttime measurements across the three phases.

E. Classification and Behavioural Analysis

Harmonics were categorised based on their response to the plants operation:

- Improved behaviour: Those with reduced levels post-commissioning.
- Worsened behaviour: Those with increased levels.
- Either: Those with increased levels at some percentiles and decreased at others.
- Unaffected behaviour: Those showing minimal variation.

Additionally, harmonics exhibiting unbalanced phase behaviour were identified, suggesting potential influences from single-phase components within the system.

F. Extreme Variation Analysis

Harmonics displaying the most extreme variations between pre- and post-commissioning were further analysed using histograms and cumulative probability curves. In turn, correlation values between voltage harmonics and power were calculated for day periods and represented using heatmaps.

The correlation of variables is a statistical technique used to analyse the relationship between two or more variables, measuring the degree of association between them and their direction, thus obtaining a correlation coefficient that can vary between -1 and 1, using Equation 2

$$\rho_{xy} = \frac{Cov(x, y)}{\sigma_x \sigma_y} \tag{2}$$

where ρ_{xy} is the Pearson product-moment correlation coefficient, $Cov(x, y)$ is the covariance of variables x and y, σ_x is the standard deviation of x, and σ_y is the standard deviation of y.

These plots provided insights into potential grid stability issues caused by these variations, particularly for harmonics with significant deviations or irregular trends.

IV. Results

A. Compliance with Voltage Harmonic Standards

Figure 2 presents the maximum and 95th percentile values of each harmonic averaged over 10-minute and 3-seconds intervals, both before and after the commissioning of the plant. As indicated in Table I, all the observed values fall below the specified limits. This demonstrates that the harmonic levels of the system align with the established standards, ensuring high power quality.

		Order harmonic	50160 Uh (%)	EREC G5 Uh (%)	61000-3-6 Uh (%)	IEEE 519 Uh (%)	Minimum
Odd harmonics	**Non-Multiples of 3**	5	3.0	2.5	2	3.75	2
		7	2.5	2	2	2.25	2
		11	2.0	1.8	1.5	2.25	1.5
		13	1.5	1.5	1.5	2.25	1.5
		17	1.0	1.2	1	2.25	1
		19	1.5	1	1	2.25	1
		23	1.5	0.8	0.7	2.25	0.7
		25	0.5	0.8	0.7	2.25	0.7
		>25	0.5	0.6(25/h) + 0.2	0.5(25/h) + 0.2	2.25	0.5
	Multiples of 3	3	3.0	2	2	2.25	2
		9	1.5	1	1	2.25	1
		15	0.5	0.3	0.3	2.25	0.3
		21	0.5	0.3	0.2	2.25	0.2
		>21	0.3	0.2	0.2	2.25	0.2
Even harmonics		2	1.5	1	1.5	2.25	1
		4	1.0	0.8	1	2.25	0.8
		6	0.5	0.5	0.5	2.25	0.5
		8	0.3	0.4	0.4	2.25	0.4
		10	0.3	0.4	0.4	2.25	0.4
		≥12	0.3	0.2	0.2	2.25	0.2
THD		THD	3	2.5	3	3	2.5

TABLE I: Voltage harmonic limits according to different norms.

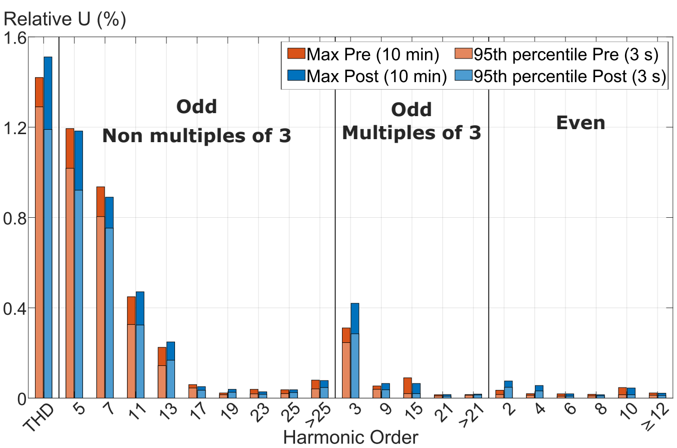


Fig. 2: Relative voltage harmonic values before and after commissioning.

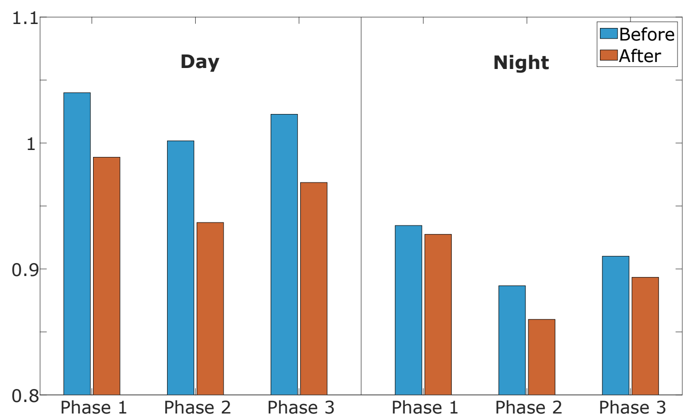


Fig. 3: Mean THD U (%) before and after commissioning.

B. General THD Improvement

THD U showed a general improvement across all phases after the commissioning of the PV plant. Figure 3 illustrates that post-commissioning mean THD U values remained below 1% for both daytime and nighttime conditions. These improvements suggest a filtering effect of the PV installation on harmonic distortions at the PCC.

C. Individual Harmonic Behaviour

Each harmonic from H1 to H50 was analysed to assess its behaviour before and after commissioning. Table II shows the harmonics categorised as improved, worsened, or irregular, during daytime and nighttime conditions, respectively. The findings are summarised as follows:

- Improved Harmonics: Several odd-order harmonics, such as H5, H9, H17, or H21, exhibited reductions during both day and night. Even-order harmonics, such as H10 and H14, also showed notable improvements.
- Worsened Harmonics: Harmonics such as H2, H4, H31, H35 or H47, showed increases, particularly during nighttime conditions. These increases were still within the acceptable limits specified by regulatory standards but highlight potential areas for future mitigation strategies.
- Either: Certain harmonics, such as H41, showed irregular behaviour, improving in some percentiles and worsening in others. This effect can be attributed to single-phase component connections in the system.

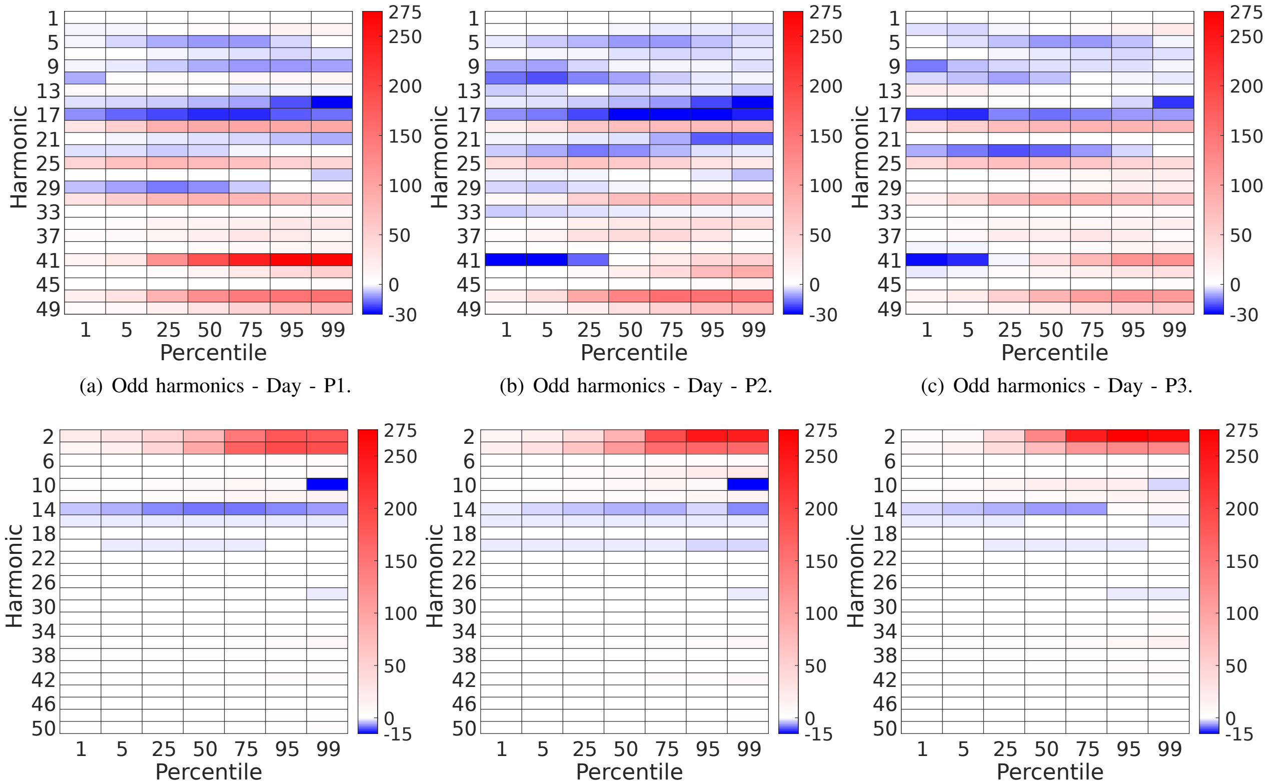
	Day		Night	
Effect	**Odd**	**Even**	**Odd**	**Even**
Improved	5, 9, 11, 15, 17, 21, 23, 27, 29	10, 14	5, 9, 17, 21, 23, 27, 33, 37, 43	10, 14
Worsened	19, 25, 31, 35, 37, 43, 47, 49	2, 4	11, 13, 31, 35, 47	2, 4, 12, 36
Either	41	-	3, 19, 41	-

TABLE II: Classification of voltage harmonics based on their variation behaviour.

In turn, harmonics that presented unbalanced phase behaviour in one or more phases are identified in Table III, such as H3, which shows improvements in phase 2 while phases 1 and 3 worsen, indicating single-phase component connections affecting that particular harmonic.

	Day		Night	
Effect	**Odd**	**Even**	**Odd**	**Even**
Unbalanced	21, 27, 29, 35, 37, 41, 43	-	3, 11, 19, 35, 43, 47	14

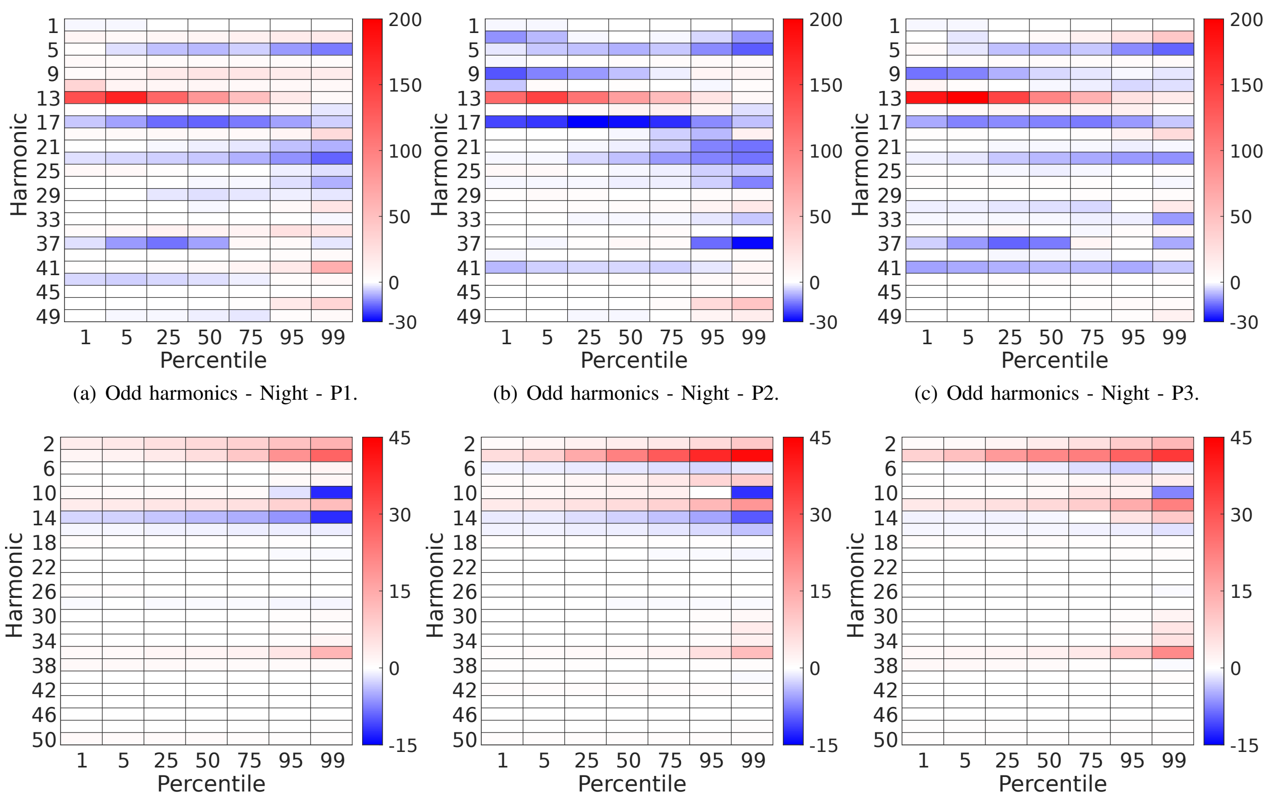
TABLE III: Identification of voltage harmonic orders with unbalanced variations.



(a) Odd harmonics - Day - P1. (b) Odd harmonics - Day - P2. (c) Odd harmonics - Day - P3.

(d) Even harmonics - Day - P1. (e) Even harmonics - Day - P2. (f) Even harmonics - Day - P3.

Fig. 4: Relative voltage harmonic percentile variation (%) during the day, before and after commissioning.



(a) Odd harmonics - Night - P1. (b) Odd harmonics - Night - P2. (c) Odd harmonics - Night - P3.

(d) Even harmonics - Night - P1. (e) Even harmonics - Night - P2. (f) Even harmonics - Night - P3.

Fig. 5: Relative voltage harmonic percentile variation (%) during the night, before and after commissioning.

D. Daytime and Nighttime Variations

Figures 4 and 5 depict heatmaps of relative harmonic variations during daytime and nighttime. Positive values (red tones) indicate increased harmonic levels, while negative values (blue tones) represent reductions. Notably:

- Daytime conditions showed more significant reductions in harmonics, likely due to active power output filtering effects.
- Nighttime conditions revealed increases in harmonics such as H13, linked to inverter behaviour during sunset transitions.

The reduction observed in odd-order harmonics (e.g., H5, H9) during daytime conditions can be attributed to the ability of the PV plant to maintain the bus voltage at the PCC, aiming to maintain levels as close as possible to 1 pu during active power generation. An increase in H1 voltage may lead to a relative decrease in harmonic magnitudes, provided that the absolute values of the harmonics do not increase proportionally. Conversely, increases in harmonics such as H19 and H25 may be linked to transient effects at the PCC or interactions with other grid-connected elements. Certain harmonics, such as H13, exhibited significant increases during sunrise and sunset. These variations are likely influenced by the single-axis tracking systems, which reposition the panels during these transitional periods. While these systems improve energy capture, their impact on harmonic behaviour warrants further investigation to optimise operational strategies and minimise grid disturbances.

These findings underscore the complexity of harmonic behaviour in large-scale PV systems and highlight the importance of phase-resolved analyses.

E. Extreme Harmonic Variations

Harmonics exhibiting extreme variations, such as H13 and H41, were further examined using histograms and cumulative probability curves. For instance:

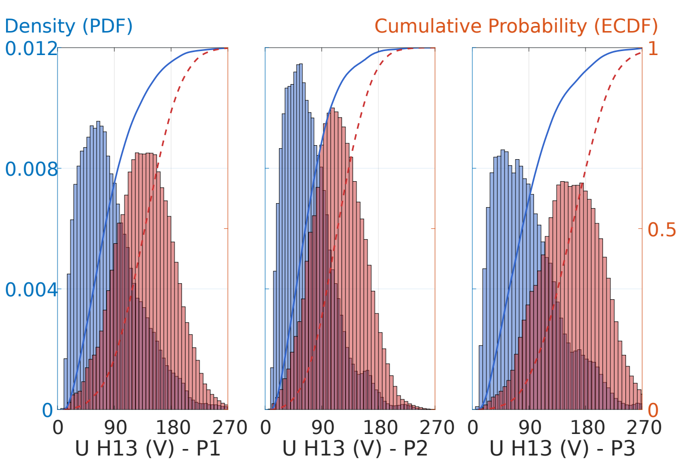


Fig. 6: Frequency histogram and probability density function of H13 during the night.

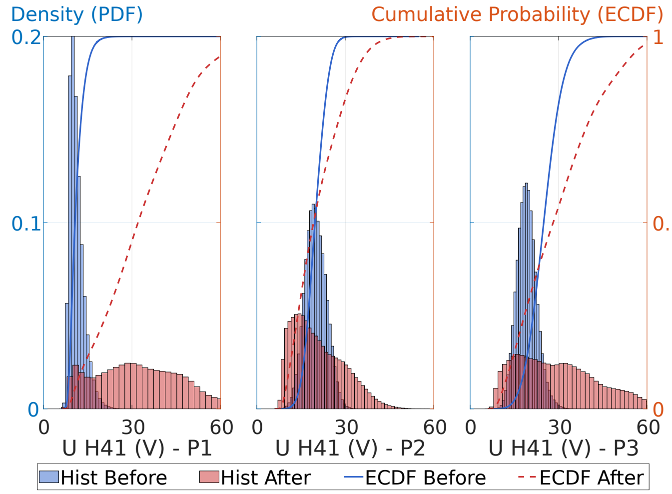
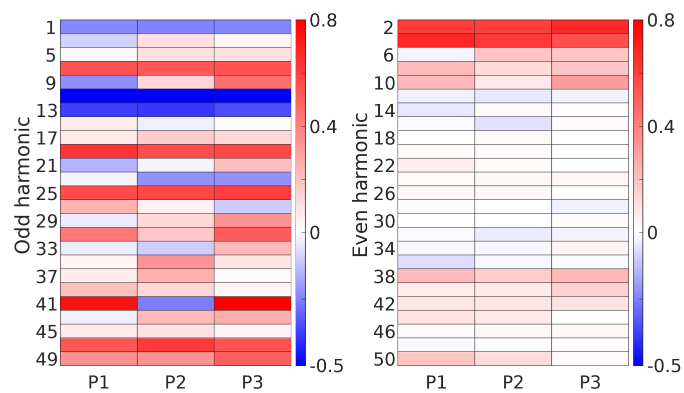


Fig. 7: Frequency histogram and probability density function of H41 during the day.

- H13 (Nighttime): This harmonic worsened significantly after sunset, with peaks corresponding to transient inverter activity (Figure 6).
- H41 (Daytime): Voltage levels for this harmonic increased with higher power output, as shown in Figure 7. The correlation matrix in Figure 8 indicates a strong relationship between power output and H41 voltage levels.

Figure 8 presents a correlation matrix between voltage harmonics and power output during daytime conditions. The matrix uses a colour scale where red indicates strong positive correlation, blue represents strong negative correlation and white denotes no correlation. Higher positive correlations (red regions) suggest that certain harmonics increase proportionally with power output, likely due to the active operation of the inverters and other plant components. This information is critical for identifying harmonics directly influenced by the plants power generation dynamics and could guide future optimisation strategies.



(a) Odd. (b) Even.

Fig. 8: Correlation factor of voltage harmonics with power during the day, after commissioning.

Additionally, the correlation observed for some harmonics explains the variations shown in Figure 4. Certain frequencies, however, exhibit results that are inconsistent with previous findings. This discrepancy suggests that factors other than power output may also influence voltage variations in the grid, warranting further investigation into these effects.

V. Discussion

This study elucidates the effects of a 35 MW PV power plant on voltage harmonic behaviour in a high-voltage transmission network, underlining both the positive impacts and challenges of integrating large-scale solar installations. The substantial reduction in Total Harmonic Distortion (THD U) across all phases post-commissioning highlights the plant's capacity to attenuate harmonic distortions, reinforcing the beneficial aspects of photovoltaic systems on power quality. However, specific harmonics, notably H13 and H41, exhibited worse behaviour, particularly under nighttime conditions, revealing the complexities of system interactions with the grid.

The persistence of all harmonics within the most restrictive limits established by UNE-EN 50160, IEC 61000-3-6, IEEE Std 519, and EREC G5/5 reflects the plant's compliance with stringent regulatory standards, suggesting no immediate risk to grid stability. Nonetheless, the variable behaviour of harmonics such as H13 and H41 under different operational states underscores the need for nuanced monitoring and tailored mitigation strategies to address these fluctuations effectively.

The application of percentile-based statistical analysis coupled with heatmap visualizations provides a detailed depiction of the harmonic dynamics, offering a replicable method for assessing the impacts of other renewable systems on power quality. This approach not only identifies key trends but also enhances the robustness of the analytical framework, facilitating its adaptation for broader applications.

VI. Conclusions

Our findings demonstrate a clear influence of the PV plant on improving voltage harmonic conditions, particularly during daylight, when active power generation is highest. The reductions observed in THD U and several odd-order harmonics signify the plants potential to maintain the bus voltage and reduce harmonic distortions. However, the variations in specific harmonics, notably during periods of low irradiance and nighttime, highlight the critical role of inverter control strategies and system configurations in mitigating harmonic emissions.

Future research should expand upon this study by further exploring the interactions between solar tracker activity and harmonic generation. It should also consider the impact of different plant sizes and configurations across various grid conditions to develop more generalized insights into the integration of PV systems into power networks. The ultimate goal is to balance the benefits of solar power against the potential challenges posed by harmonic disturbances, ensuring the reliable and efficient operation of the grid.

By adhering to these recommendations, stakeholders can better anticipate the complexities associated with large-scale renewable integrations and refine strategies for managing harmonic impacts, contributing to the broader goals of sustainable and stable power systems.

VII. Acknowledgment

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VIII. References

References

[1] Lazard, "Levelized Cost of Energy+ (LCOE+), June 2024," 2024.

[2] International Renewable Energy Agency (IRENA), Renewable Power Generation Costs in 2022. Abu Dhabi, UAE: International Renewable Energy Agency (IRENA), 2023.

[3] International Energy Agency (IEA), World Energy Outlook 2020. Paris, France: International Energy Agency (IEA), 2020.

[4] Unión Española Fotovoltaica (UNEF), Informe Anual UNEF 2023. Unión Española Fotovoltaica (UNEF), 2023.

[5] Ministerio para la Transición Ecológica y el Reto Demográfico (MITECO), Plan Nacional Integrado de Energía y Clima 2021-2030. Madrid, España: Ministerio para la Transición Ecológica y el Reto Demográfico, 2020.

[6] K. Peiris, S. Elphick, J. David, and D. Robinson, "Impact of multiple grid-connected solar pv inverters on harmonics in the high-frequency range," Energies, vol. 17, no. 11, 2024.

[7] X. Xu, A. Collin, S. Djokic, R. Langella, A. Testa, J. Meyer, and F. Möller, "Harmonic emission of pv inverters under different voltage supply conditions and operating powers," in 2016 17th International Conference on Harmonics and Quality of Power (ICHQP), 10 2016, pp. 373–378.

[8] A. Varatharajan, S. Schoettke, J. Meyer, and A. Abart, "Harmonic emission of large pv installations case study of a 1 mw solar campus," Renewable Energy and Power Quality Journal, vol. 12, pp. 701–706, 04 2014.

[9] D. Barkas, A. Menti, P. Pachos, and C. S. Psomopoulos, "Experimental investigation of the impact of environmental parameters on the supraharmonic emissions of pv inverters," AIMS Energy, vol. 12, no. 4, pp. 761–773, 2024.

[10] J. Sreedevi, N. Ashwin, and M. N. Raju, "A study on grid connected pv system," in 2016 National Power Systems Conference (NPSC), 2016, pp. 1–6.

[11] A. Chidurala, T. K. Saha, N. Mithulananthan, and R. C. Bansal, "Harmonic emissions in grid connected pv systems: A case study on a large scale rooftop pv site," in 2014 IEEE PES General Meeting | Conference & Exposition, 2014, pp. 1–5.

[12] A. Chidurala, T. Saha, and N. Mithulananthan, "Harmonic characterization of grid connected pv systems & validation with field measurements," in 2015 IEEE Power & Energy Society General Meeting, 2015, pp. 1–5.

[13] R. Sinvula, K. M. Abo-Al-Ez, and M. T. Kahn, "Total harmonics distortion (thd) with pv system integration in smart grids: Case study," in 2019 International Conference on the Domestic Use of Energy (DUE), 2019, pp. 102–108.

[14] R. R. Fortes, R. F. Buzo, and L. C. de Oliveira, "Harmonic distortion assessment in power distribution networks considering dc component injection from pv inverters," Electric Power Systems Research, vol. 188, p. 106521, 2020.

[15] S. Sakar, M. E. Balci, S. H. Abdel Aleem, and A. F. Zobaa, "Integration of large- scale pv plants in non-sinusoidal environments: Considerations on hosting capacity and harmonic distortion limits," Renewable and Sustainable Energy Reviews, vol. 82, pp. 176–186, 2018.

[16] F. Ruiz-Rodriguez, J. Full Professor, and F. Jurado, "Harmonic modelling of pv systems for probabilistic harmonic load flow studies," International Journal of Circuit Theory and Applications, vol. 43, 09 2014.

[17] S. Roy, A. Debnath, M. Tariq, M. Behnamfar, and A. Sarwat, "Characterizing current thds dependency on solar irradiance and supraharmonics profiling for a grid-tied photovoltaic power plant," Sustainability, vol. 15, no. 2, 2023.

[18] S. Djokic, J. Meyer, F. Möller, R. Langella, and A. Testa, "Impact of operating conditions on harmonic and interharmonic emission of pv inverters," in 2015 IEEE International Workshop on Applied Measurements for Power Systems (AMPS), 2015, pp. 1–6.

[19] R. Langella, A. Testa, J. Meyer, F. Möller, R. Stiegler, and S. Djokic, "Experimental-based evaluation of pv inverter harmonic and interharmonic distortion due to different operating conditions," IEEE Transactions on Instrumentation and Measurement, vol. 65, pp. 1–13, 05 2016.

[20] J. Schlabbach, A. Grob, and G. Chicco, "Influence of harmonic system voltages on the harmonic current emission of photovoltaic inverters," in 2007 International Conference on Power Engineering, Energy and Electrical Drives, 2007, pp. 545–550.

[21] A. Carretero-Hernandez, E. Artigao, S. Martin-Martinez, C. Alvarez-Ortega, M. Ochoa-Gimenez, and E. Gomez-Lazaro, "Comparison of harmonic emission in lv side of a large grid connected pv power plant," Electric Power Systems Research, vol. 223, p. 109586, 2023.

[22] K. Daniel, L. Kütt, M. N. Iqbal, N. Shabbir, and M. Jarkovoi, "Description of practical load harmonic current emission due to voltage harmonic variation," in 2021 IEEE 62nd International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), 11 2021, pp. 1–6.

[23] Asociación Española de Normalización y Certificación, "UNE-EN 50160:2010. Características de la tensión suministrada por las redes generales de distribución," Asociación Española de Normalización y Certificación (AENOR), Madrid, España, Tech. Rep., 2010.

[24] IEC, "EN IEC 61000-3-2:2019. Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions (equipment input current $\leq$ 16 A per phase)," Geneva, Switzerland, 2019.

[25] IEC, "EN IEC 61000-3-12:2011. Electromagnetic compatibility (EMC) - Part 3-12: Limits - Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current > 16 A and $\leq$ 75 A per phase," Geneva, Switzerland, 2011.

[26] IEEE Standards Association, "IEEE Std 519-2014. IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems," Piscataway, NJ, USA, 2014.

[27] IEC, "IEC 61000-3-6:2021. Electromagnetic compatibility (EMC) - Part 3-6: Limits - Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems," Geneva, Switzerland, 2021.

[28] Energy Networks Association (ENA), "Engineering Recommendation G5/5 - Harmonic emission limits for customer installations connected to the electricity supply system," London, UK, 2020.

[29] IEC, "IEC 61000-4-30:2015+A1:2021. Electromagnetic compatibility (EMC) - Part 4-30: Testing and measurement techniques - Power quality measurement methods - Class A," Geneva, Switzerland, 2021.

[30] IEC, "IEC TR 61869-103:2012. Instrument transformers - Part 103: The use of instrument transformers for power quality measurement," Geneva, Switzerland, 2012.

[31] IEC, "IEC 61000-4-7:2002. Electromagnetic compatibility (EMC) - Part 4-7: Testing and measurement techniques - General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto," Geneva, Switzerland, 2002.