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ASSESSMENT OF HARMONIC DISTORTION IN SCHOOL BUILDINGS EQUIPPED WITH GRID-CONNECTED PV SYSTEMS

Professional Article

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Abstract The integration of photovoltaic systems into power grids can impact power quality, particularly concerning voltage and current harmonics. This study investigates the power quality of a photovoltaic system integrated into the electrical system of an educational facility, focusing on harmonic distortion in both voltage and current. Comprehensive measurements were conducted across three phases and analysed according to the EN 50160 and IEEE 519 Standards. The results demonstrated that, while the voltage quality meets EN 50160 requirements consistently, indicating stable voltage levels, the current measurements revealed significant harmonic distortion. Notably, Phase 2 exhibited Total Harmonic Distortion values substantially above the acceptable limits, with Phase 1 and Phase 3 also showing elevated Total Harmonic Distortion. To address these issues, the study recommends the implementation of advanced harmonic filters and optimisation of inverter technologies. These measures are crucial for enhancing power quality, and ensuring compliance with the industry Standards in high photovoltaic penetration scenarios.

Keywords
power quality analysis, grid-connected PV systems, EN 50160 standard, IEEE 519 Standard, IEC 61000 standard, voltage harmonics, current harmonics, harmonic distortion, renewable energy integration, compliance assessment

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1 Introducton

The integration of photovoltaic (PV) systems into building infrastructures has seen a significant increase, driven by the need for sustainable energy solutions and the declining cost of solar technology. However, while PV systems offer substantial environmental benefits, their integration poses challenges related to power quality, particularly concerning voltage harmonics and current distortion.

The impact of PV systems on power quality has been studied widely. Various research works have highlighted the issues and proposed solutions to mitigate them. For instance, harmonic resonance, which can arise from the interaction between the PV inverters and the grid, has been a focal point. Studies have shown that using LCL filters and advanced impedance modelling techniques can suppress harmonic resonance effectively and enhance system stability [1 – 6].

Moreover, the integration of PV systems often leads to the generation of harmonics at the point of common coupling (PCC). [7] This issue is exacerbated by fluctuations in solar irradiance, which can cause significant variations in power quality parameters. Research has demonstrated that sophisticated control strategies, such as zero sequence current adjusters and hybrid optimisation techniques, can mitigate these effects. [5-10]

Experimental evaluations of distortion effects in grid-connected PV systems have provided valuable insights into the behaviour of these systems under different conditions. For example, studies have utilised real-time simulation platforms to analyse the impact of solar radiation levels and controller tuning on harmonics, revealing that proper system design and control can improve the power quality significantly [11,12]. Additionally, the use of various harmonic compensation strategies, including the proportional-integral resonance controllers with harmonic and lead compensators, has shown promising results in reducing total harmonic distortion (THD) and improving the overall performance of grid-connected PV systems [13-16].

Studies have also addressed the impact of high PV penetration on power quality, finding that the current harmonics generated by PV systems can exceed the thresholds set by Standards like IEEE 519. This can lead to issues such as overheating of transformers and increased losses in the distribution network [17].

EN 50160 outlines the voltage characteristics of electricity supplied by public distribution systems, and defines acceptable limits for voltage variations and harmonic distortion. On the other hand, IEEE 519 provides guidelines for harmonic control in electrical power systems, specifying acceptable limits for current and voltage harmonics in different types of electrical systems. For compliance in Europe, the IEC 61000-3-6 Standards are also highly relevant for managing current harmonics in PV systems.

In educational buildings the integration of PV systems presents unique challenges, due to variable load profiles and the influence of student activities on power consumption patterns. Research suggests that tailored solutions, including the use of passive and active filtering techniques, are essential for mitigating harmonic issues in such environments. [18, 19]

Compliance with the EN 50160 and IEEE 519 Standards is crucial for ensuring the safe and efficient operation of PV systems. EN 50160 focuses on the quality of voltage supplied by the public distribution system, specifying limits for parameters such as voltage magnitude, frequency and harmonics. IEEE 519, on the other hand, sets standards for harmonic distortion in electrical power systems, providing limits for both voltage and current harmonics based on the size of the electrical system and the point of common coupling (PCC). The IEC 61000-3-6 standards are also applicable in Europe for managing the current harmonics in PV systems. These standards are essential for mitigating the adverse effects of harmonics, such as equipment overheating, reduced efficiency and potential damage to sensitive electronic devices. [20,21]

Given the rigorous nature of these Standards, they are appropriate for current harmonics analysis in PV systems. However, continuous monitoring and adaptive control strategies are necessary to maintain compliance, especially in environments with fluctuating power demands, such as school buildings. Future research might also explore additional Standards and Guidelines that could complement EN 50160 and IEEE 519, enhancing the power quality in systems with high PV penetration further.

This study investigates the power quality of a school building with an integrated PV system, focusing on voltage harmonics and current distortion. The measurements were taken over a one-week period with a ten-minute interval recording, providing a detailed insight into the power quality dynamics of the building. The primary objective was to assess the compliance of voltage harmonics with the EN 50160 standards and identify the extent of current distortion present.

The findings revealed that, while the voltage harmonics are within acceptable limits, there is a severe current distortion issue. By providing empirical data and analysis, the study aims to offer practical insights and recommendations for improving the integration of PV systems in similar settings.

2 Materials and Methods

The study analyses the measurement results for a school building located in Slovenia (EU). While specific details about the building, such as its surface area, are not relevant to this study, key details include the installed photovoltaic (PV) power on the rooftop (50 kW) and the nominal current rating of the building's circuit breakers (160 A). The school building is shown in Figure 1.

Figure 1: School building
Source: own.

The measurements were conducted in accordance with the EN 50160 Standard, with data collected at 10-minute intervals over a one-week period. The Metrel MI2892 instrument was used and connected at the point of common coupling (PCC) to the main distribution board, where the 3x160 A circuit breakers are installed. Measurements were taken for both the photovoltaic (PV) system and the school building. The data were analysed using the Metrel PowerView software (version 3.0.0.5936, 64-bit). The instrument is shown in Figure 2.

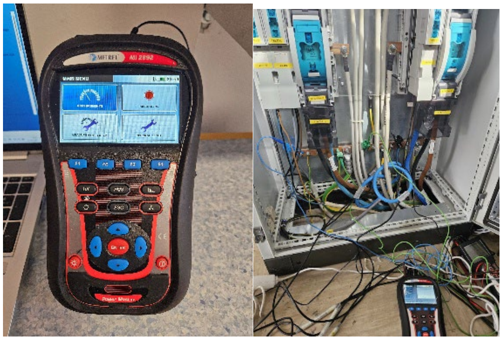

Figure 2: Measuring equipment and the setup: (a) Metrel MI 2892 Power Master Measuring instrument; (b) Connection setup at the point of common coupling (PCC) at the main distribution board.

Source: own.

Although the building has 3x160A circuit breakers the fundamental current harmonic does not go over 75A (as the results will show), so the current harmonics are analysed by the IEC 61000-3-6 Standard.

2.1 Standards for Power Quality in School Buildings with Integrated PV Systems

When integrating photovoltaic (PV) systems into school buildings, ensuring compliance with power quality standards is crucial to maintain a stable and efficient electrical system. Three primary Standards provide guidelines for voltage and current harmonics: EN 50160, IEEE 519, and IEC 61000. This section of the article reviews these Standards in the context of PV integration in school buildings, providing a comparative analysis and highlighting the relevant requirements.

Meeting the power quality Standards is essential for ensuring the reliability, safety, and efficiency of the electrical systems in the school building. It protects equipment, enhances energy efficiency, ensures regulatory compliance, and supports the effective integration of renewable energy sources. By adhering to these Standards, the school can provide a safe and conducive learning environment, while also achieving financial and environmental benefits.

2.1.1 EN 50160: Voltage Characteristics

EN 50160 specifies the voltage characteristics of electricity supplied by public distribution networks. It addresses primarily the voltage quality parameters, including frequency, magnitude, waveform, symmetry and the presence of disturbances. [20]

The integration of photovoltaic (PV) systems into buildings such as schools has become increasingly prevalent, due to the push for sustainable energy solutions. However, this integration brings challenges, particularly in maintaining power quality. The European Standard EN 50160 is pivotal in defining the voltage characteristics for electricity supplied by public distribution systems, ensuring stability and reliability. This chapter explores EN 50160's relevance in the context of our study, which examines the power quality of a school building with a grid-connected PV system.

EN 50160 covers the voltage characteristics of low, medium and high voltage public distribution systems. It applies to various buildings, including residential, commercial and educational institutions like the school in our study. The Standard provides a comprehensive framework for assessing and maintaining power quality, crucial for the seamless operation of electrical systems, especially when integrating renewable energy sources.

To evaluate compliance with EN 50160, we conducted measurements over a one-week period at 10-minute intervals. This methodology provides a detailed analysis of the voltage characteristics, identifying any deviations from the Standard. Our findings help in assessing whether the school's electrical system, influenced by the grid-connected PV system, meets these stringent requirements.

Key Requirements:

- Voltage Frequency: 50 Hz ± 1% for 95% of a week.

- Voltage Level: ±10% of the nominal voltage for 95% of a week.
- Voltage Harmonics: Total harmonic distortion (THD) should not exceed 8% for 95% of a week.
- Voltage Fluctuations: Voltage deviations should not exceed ±5%.
- Voltage Unbalance: Should not exceed 2% for 95% of a week.

Table 1 shows the voltage harmonic limits by the EN50160 Standard.

Table 1: Voltage Harmonic Limits (EN50160)

Harmonic Order	Maximum Individual Harmonic Voltage (% of fundamental)
1st	-
3rd	5
5th	6
7th	5
9th	1.5
11th	3.5
13th	3
15th	0.5
THD	8% (95% of the time)

Source: EN 50160: Voltage characteristics of electricity supplied by public distribution networks. European Committee for Electro-technical Standardization (CENELEC).

2.1.2 IEC 61000: Electromagnetic Compatibility

IEC 61000 series address the electromagnetic compatibility (EMC) requirements. IEC 61000-3-6, titled "Electromagnetic compatibility (EMC) – Part 3-6: Limits – Limits for harmonic currents," is a key Standard developed by the International Electrotechnical Commission (IEC) to regulate the harmonic distortion in electrical systems. This Standard is crucial for ensuring that the harmonic currents generated by electrical equipment do not affect the quality of the power supply and the operation of other equipment adversely. It limits the harmonic current emissions of equipment connected to public low-voltage systems with a rated current ≥ 16 A and ≤ 75 A. [21]

IEC 61000-3-6 sets out limits for harmonic currents in electrical systems, with a primary focus on controlling harmonic currents at various orders. The Standard targets specifically:

- The 5th Harmonic: typically, the permissible limit for the 5th harmonic current is around 20% of the fundamental current.
- The 7th Harmonic: the limit for the 7th harmonic current is generally about 14% of the fundamental current.

The Standard emphasises odd harmonics, because they are generated more commonly by typical non-linear loads, and can have a more significant impact on power systems. In contrast, even harmonics (such as the 2nd, 4th, and 6th) are addressed less frequently, as they are less prevalent in systems with standard non-linear loads. Detailed limits for harmonic currents are specified in the Standard, including in Table 2.

Table 2: Harmonic Current Limits (IEC 61000-3-6) for Equipment Rated Up to 75A

Harmonic Order	Current Limit (% of fundamental)
3rd	5
5th	20
7th	14
9th	7
11th	6
13th	5
15th	4
17th	4
19th	3
21th	3

Source: ELECTROMAGNETIC COMPATIBILITY (EMC) – Part 3-6: Limits – Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems

2.1.3 IEEE 519: Harmonic Control

IEEE 519 provides recommended practices for harmonic control in electrical power systems. It sets limits for both voltage and current harmonics, to minimise interference and ensure compatibility with sensitive electronic equipment. [22]
Key Requirements:

Voltage Distortion Limits:

- Systems below 69 kV: THD should not exceed 5%.
- Systems between 69 kV and 161 kV: THD should not exceed 2.5%.

– Systems above 161 kV: THD should not exceed 1.5%.

Current Distortion Limits:

– Vary depending on the short-circuit ratio (I_{sc}/I_L), ranging from 4% to

20% for individual harmonics and 5% to 20% for THD.

IEEE 519 is critical for managing the harmonic currents generated by PV inverters, ensuring that they do not exceed acceptable limits and affect other devices connected to the same grid.

Table 3 shows the general harmonic current limits by the IEEE 519 Standard.

Table 3: General Current Harmonic Limits (IEEE 519)

Short-Circuit Ratio I_{sc}/I_L	Maximum Individual Harmonic Current (%) h < 11	Maximum Total Harmonic Current (%)	Total Demand Distortion (TDD) (%) 11 ≤ h ≤ 17
<20	4	5	2.0
20 - 50	7	8	3.5
50 -100	10	12	4.5
100 - 1000	12	15	5.5
>1000	15	20	7.0

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

Table 4 shows the specific values for harmonics (used for the I_{sc}/I_L<20).

Table 4: General Current Harmonic Limits (IEEE 519)

Harmonic Order	Current Limit (%)	Harmonic Order	Current Limit (%)
2	5	8	4
3	4	10	4
4	2	11-16	2
5	4	17-22	1.5
6	2	23-34	0.6
7	4	35-50	0.3

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

Adhering to these Standards is essential for the effective integration of PV systems in school buildings. EN 50160 ensures voltage quality, IEEE 519 provides comprehensive guidelines for controlling harmonic distortions, and IEC 61000 addresses the EMC requirements. Together, these Standards help maintain a reliable and stable power supply, ensuring the safety and performance of electrical systems in educational facilities.

2 Results

In this section we present the measured results for current and voltage, including their waveforms and harmonic content. These results are then compared with the relevant Standards: EN 50160, IEEE 519, and IEC 61000-3-6.

2.1 Current and Voltage Measurements

The measured voltage was within the limits specified by the EN 50160 Standard consistently. This result aligns with expectations, as the voltage waveform was observed to be a stable sinewave across all three phases, with no significant fluctuations, as illustrated in Figure 3.

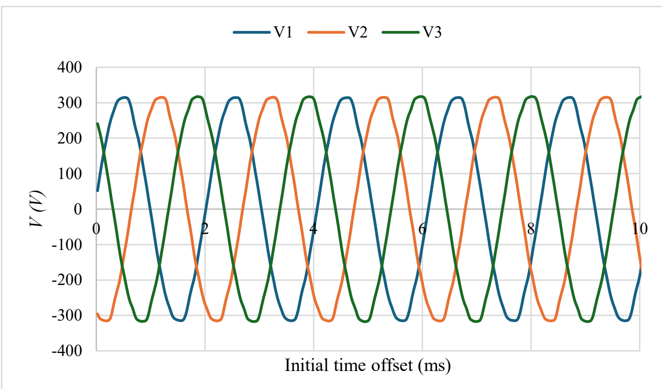

Figure 3: Measured voltage waveform.
Source: own.

Figures 4-6 illustrate the voltage Total Harmonic Distortion (THD) for each day of the week, separately for all three phases. These Figures confirm that the THD values remained within acceptable limits throughout the week, supporting the overall compliance with the EN 50160 requirements.

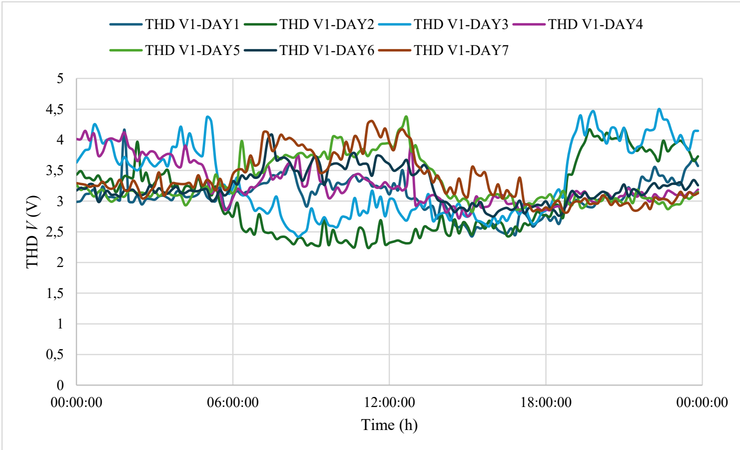

Figure 4: Voltage THD in phase 1.

Source: own.

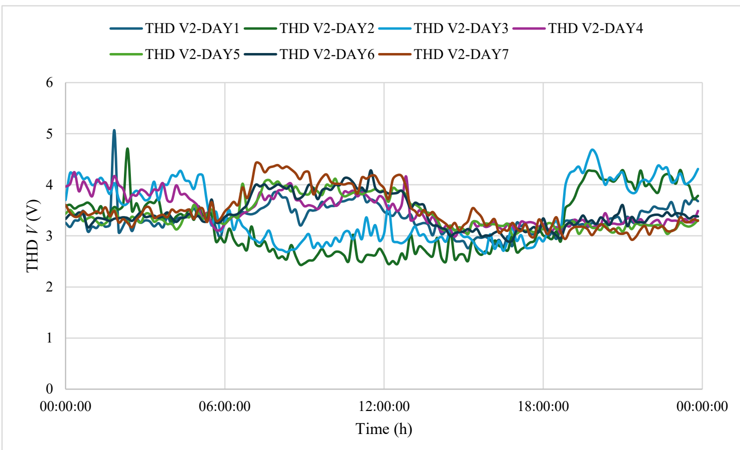

Figure 5: Voltage THD in phase 2.

Source: own.

THD was minimal throughout the measurement period. Based on these results, we limited our comparison of voltage harmonics to the EN50160 requirements up to the 10th harmonic, as detailed in Table 5.

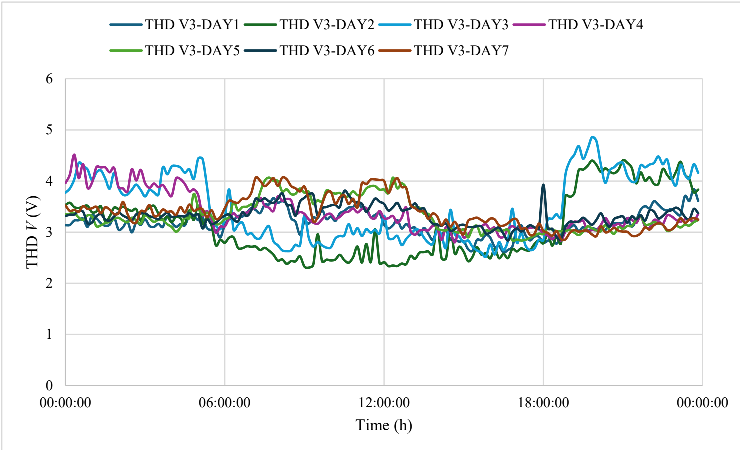

Figure 6: Voltage THD in phase 3.

Source: own.

Table 5: Voltage Harmonic Comparison to the EN50160 requirements

		PHASE L1		PHASE L2		PHASE L3	
Harmonic	Limit	Measured	Status	Measured	Status	Measured	Status
THD	< 8.00 %	1.62 %	Passed	1.64 %	Passed	1.63 %	Passed
2	< 2.00 %	0.05 %	Passed	0.05 %	Passed	0.05 %	Passed
3	< 5.00 %	0.59 %	Passed	0.70 %	Passed	0.54 %	Passed
4	< 1.00 %	0.04 %	Passed	0.04 %	Passed	0.04 %	Passed
5	< 6.00 %	0.93 %	Passed	0.90 %	Passed	0.95 %	Passed
6	< 0.50 %	0.04 %	Passed	0.03 %	Passed	0.04 %	Passed
7	< 5.00 %	1.11 %	Passed	1.07 %	Passed	1.17 %	Passed
8	< 0.50 %	0.03 %	Passed	0.03 %	Passed	0.03 %	Passed
9	< 1.50 %	0.74 %	Passed	0.80 %	Passed	0.71 %	Passed
10	< 0.50 %	0.02 %	Passed	0.02 %	Passed	0.02 %	Passed

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

The harmonic analysis reveals that all the measured values are well within the EN50160 limits. Key results include that the THD was well below the 8.00% limit (1.62% - 1.64% across all phases) and all measurements (2nd to 10th harmonics) were significantly below their respective limits. Overall, the voltage quality is excellent, with all the harmonics meeting or exceeding the regulatory Standards.

The current measurement displayed a distorted waveform, as illustrated in Figure 7, with a clear presence of significant harmonics.

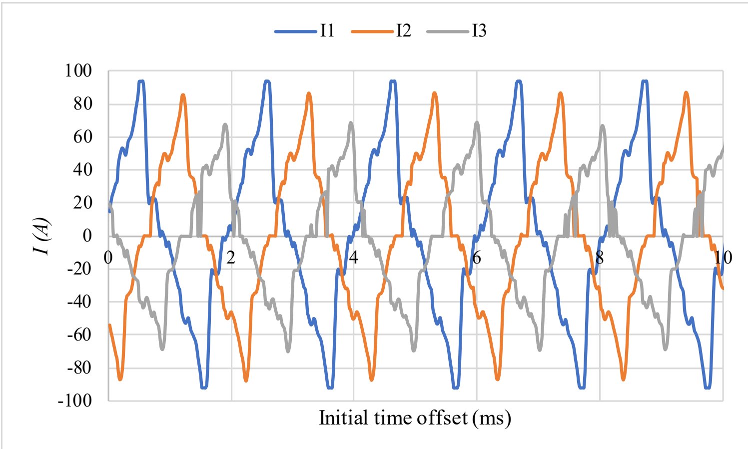

Figure 7: Measured current waveform.
Source: own.

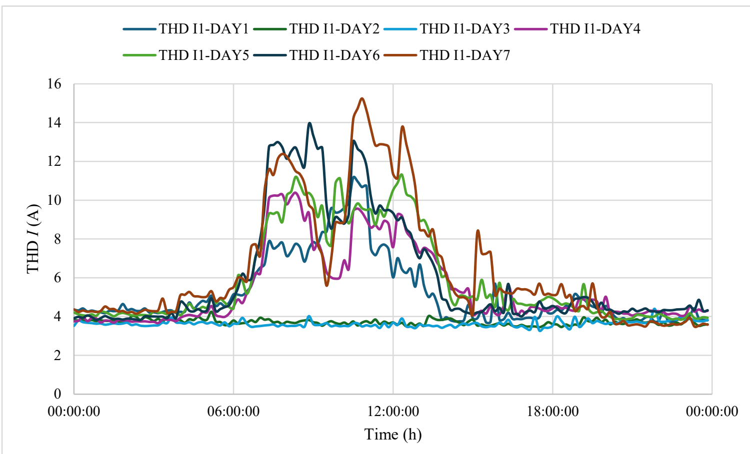

Figure 8: Current THD in phase 1 (A)
Source: own.

Figures 8-10 present the Total Harmonic Distortion (THD) in (A) for each day of the week, while Figures 11-13 show the THD in percentage, separately for all three phases. These Figures confirm that the THD values were consistently high.

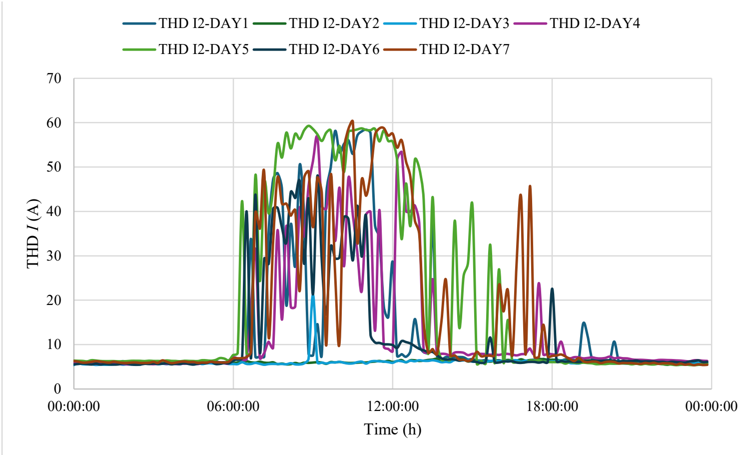

Figure 9: Current THD in phase 2 (A)
Source: own.

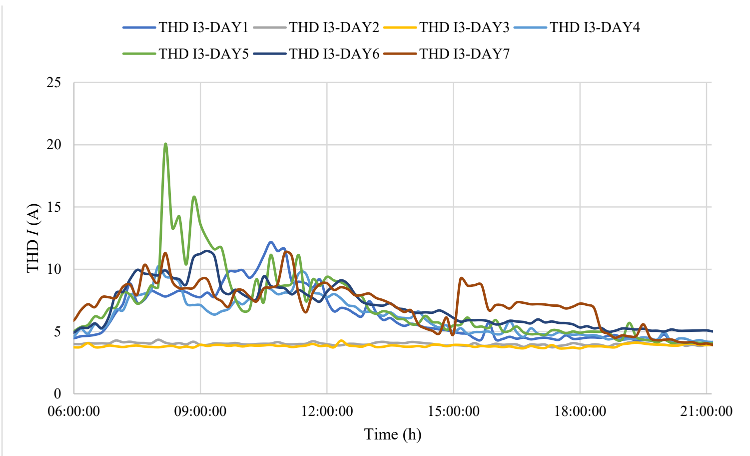

Figure 10: Current THD in phase 3 (A)
Source: own.

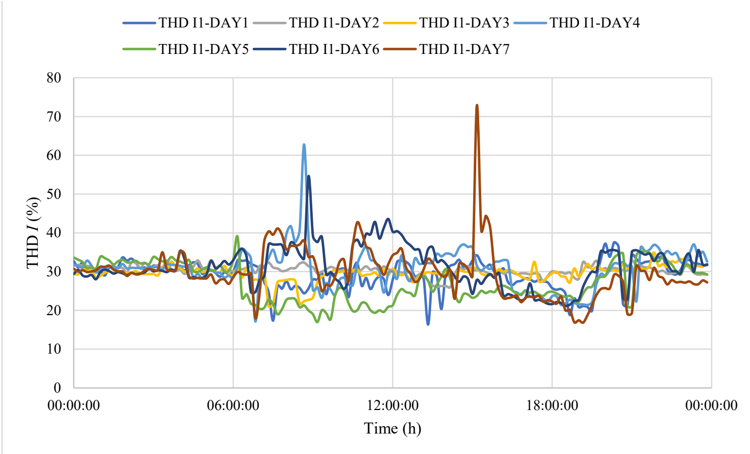

Figure 11: Current THD in phase 1 (%)
Source: own.

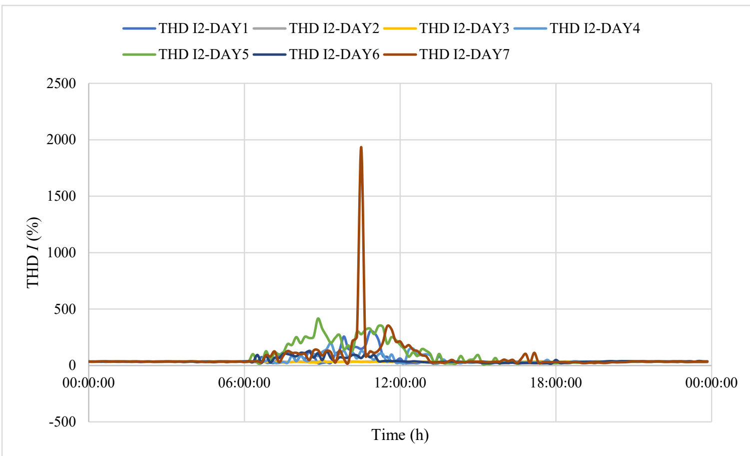

Figure 12. Current THD in phase 2 (%)
Source: own.

Figures 14 and 15 display the Total Harmonic Distortion (THD) in both amperes (A) and percentage (%) for all the phases combined. These Figures reveal a significant level of distortion, with Phase 2 showing particularly high levels of harmonic distortion.

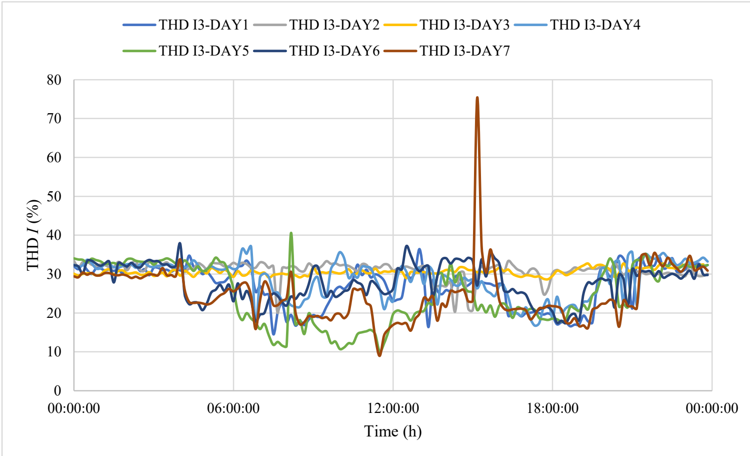

Figure 13: Current THD in phase 3 (%)

Source: own.

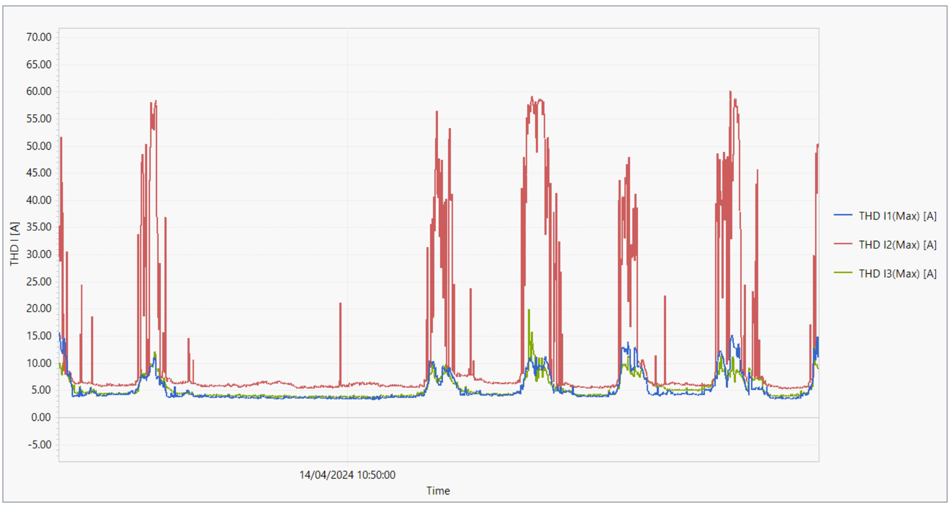

Figure 14: Current THD for all phases (A)

Source: own.

Figures 14 and 15 illustrate clearly that Phase 2 exhibited the highest levels of current harmonics. To address this, the measured harmonic data for each phase have been compared to the Standards outlined in IEEE 519. The detailed comparison of individual phases is presented in Tables 6-8.

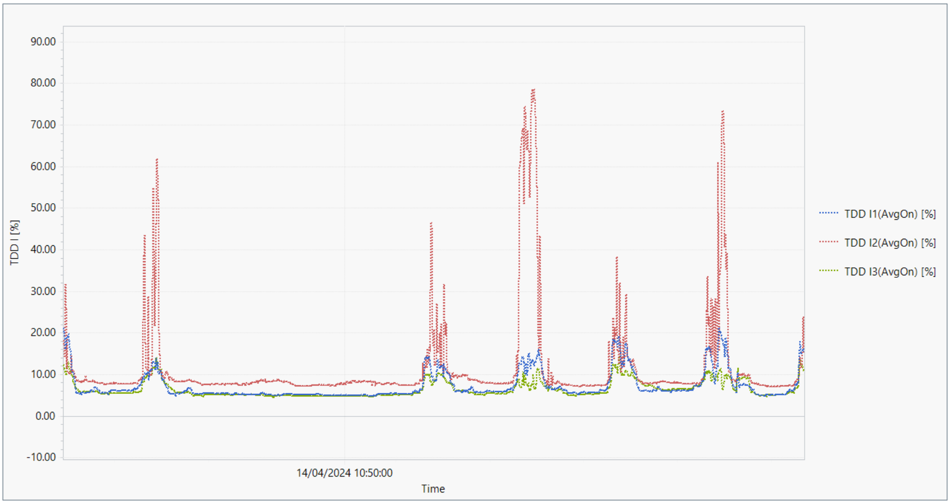

Figure 15: Current THD for all phases (%)
Source: own.

Table 6: Current Harmonic Comparison to the IEEE 519 requirements – Phase 1

h	Limit (%)	Measured (%)	Status
TDD	5.00	9.97	Failed
2	2.00	0.40	Passed
3	4.00	6.93	Failed
4	2.00	0.18	Passed
5	4.00	4.66	Failed
6	2.00	0.11	Passed
7	4.00	3.68	Passed
8	4.00	0.09	Passed
9	4.00	3.24	Passed
10	4.00	0.07	Passed
11	2.00	2.09	Failed
12	2.00	0.07	Passed
13	2.00	1.33	Passed
14	2.00	0.06	Passed
15	2.00	0.95	Passed

Table 7: Current Harmonic Comparison to the IEEE 519 requirements – Phase 2

h	Limit (%)	Measured (%)	Status
TDD	5.00	24.46	Failed
2	2.00	9.24	Failed
3	4.00	8.78	Failed
4	2.00	8.13	Failed
5	4.00	7.04	Failed
6	2.00	6.73	Failed
7	4.00	5.54	Failed
8	4.00	5.19	Failed
9	4.00	4.24	Failed
10	4.00	3.95	Passed
11	2.00	3.75	Failed
12	2.00	3.48	Failed
13	2.00	3.27	Failed
14	2.00	3.12	Failed
15	2.00	3.26	Failed

Table 8: Current Harmonic Comparison to the IEEE 519 requirements – Phase 3

h	Limit (%)	Measured (%)	Status
TDD	5.00	8.31	Failed
2	2.00	0.40	Passed
3	4.00	5.75	Failed
4	2.00	0.19	Passed
5	4.00	3.71	Passed
6	2.00	0.12	Passed
7	4.00	2.93	Passed
8	4.00	0.10	Passed
9	4.00	2.78	Passed
10	4.00	0.07	Passed
11	2.00	1.47	Passed
12	2.00	0.08	Passed
13	2.00	1.77	Passed
14	2.00	0.06	Passed
15	2.00	0.90	Passed

The Total Harmonic Distortion (THD) for Phase 1 measured at 9.97%, which is notably above the allowable limit of 5.00%. This indicates a severe level of distortion in this phase, leading to potential issues such as increased heating and energy losses in the electrical equipment. For Phase 2, the THD was even higher at 24.46%, exceeding the limit by a substantial margin. This extreme level of distortion suggests significant harmonic interference, which could cause operational problems and reduce the lifespan of connected devices.

The THD for Phase 3 stood at 8.31%, which is also above the permissible limit of 5.00%. This indicates that, while not as severe as Phase 2, Phase 3 still experiences considerable harmonic distortion that could impact system performance.

The harmonic measurements for lower-order harmonics showed varying results. For instance, the 2nd harmonic was significantly high in Phase 2 (9.24%), indicating potential issues with non-linear loads or rectifiers in this phase. Similarly, the 3rd harmonic, which is often associated with non-linear devices, was elevated across all the phases, suggesting widespread harmonic distortion sources.

The higher-order harmonics (e.g., the 5th, 7th, and above) generally exhibited lower percentages, but still presented some level of distortion, particularly in Phase 2, where the 5th harmonic was at 7.04%, and the 7th was at 5.54%. The higher percentage of these harmonics contributes to the overall THD, and underscores the need for corrective measures.

Phase 1 shows mostly passed measurements for the individual harmonics but failed in the overall THD. This indicates that, while individual harmonics may be within acceptable limits, their cumulative effect leads to excessive THD.

Phase 2 failed to meet harmonic limits consistently across several orders and the overall THD. This phase is the most problematic, suggesting significant sources of harmonic generation or inadequate filtering.

While having some passed measurements for individual harmonics in Phase 3, the overall THD was still above the limit, pointing to potential issues that, although less severe than in Phase 2, still warrant attention.

The measurements revealed that harmonic distortion is a prevalent issue across all the phases, with Phase 2 experiencing the most significant distortion. The overall THD values exceeding the permissible limits in all phases indicate a need for harmonic mitigation strategies, such as installing filters, or improving power factor correction, to ensure system reliability and compliance with the Standards.

Comparison of the measured current harmonics was compared to the IEC 6100-3-6 requirements and is presented in Table 9.

Table 9: Current Harmonic Comparison to the IEC 6100-3-6 requirements

Harmonic Order	Limit (%)	Measured (L1, L2, L3)	Status (L1, L2, L3)
3	5	6.93%, 8.78%, 5.75%	Failed (L1, L2), Passed (L3)
5	20	4.66%, 7.04%, 3.71%	Passed (L1, L3), Failed (L2)
7	14	3.68%, 5.54%, 2.93%	Passed (L1, L3), Failed (L2)
9	7	3.24%, 4.24%, 2.78%	Passed (L1, L3), Failed (L2)
11	6	2.09%, 3.75%, 1.47%	Failed (L1, L2), Passed (L3)
13	5	1.33%, 3.27%, 1.77%	Passed (L1, L3), Failed (L2)
15	4	0.95%, 3.26%, 0.90%	Passed (L1, L3), Failed (L2)
17	4	0.60%, 2.71%, 0.64%	Passed (L1, L3), Failed (L2)
19	3	1.15%, 2.49%, 1.19%	Failed (L1, L2, L3)
21	3	0.71%, 2.17%, 0.44%	Passed (L1, L3), Failed (L2)

Overall, the measured harmonics for some orders are significantly above the specified limits in one or more phases, especially for the 3rd, 5th, 7th, 9th, 11th, 13th, 19th, and 21st harmonics. These discrepancies suggest that corrective actions or mitigation strategies are required, particularly for the phases exceeding the harmonic limits. Addressing these issues can improve the overall power quality and system performance.

4 Discussion

The results of this study provide a comprehensive analysis of the power quality in a school building equipped with a grid-connected photovoltaic (PV) system. Our findings revealed a dual scenario: while the voltage quality adheres to the EN 50160 Standards, the current quality exhibits significant deviations from the IEEE 519 and IEC 61000-3-6 Standards.

4.1. Voltage Quality Analysis

The voltage measurements throughout the study period showed consistent compliance with the EN 50160 Standard. The Total Harmonic Distortion (THD) in voltage was well within the acceptable limit of 8%, and the individual harmonic components were below the specified thresholds. This stability in voltage quality suggests that the integration of the PV system has not affected the voltage characteristics of the building's power supply adversely. The results indicate that the voltage harmonics introduced by the PV system are managed effectively, aligning with the European Standard for Voltage Quality.

4.2 Current Quality Analysis

Conversely, the current measurements revealed notable issues with harmonic distortion. The THD values for current were significantly higher than the limits set by IEEE 519 and IEC 61000-3-6. Particularly in Phase 2, the distortion was pronounced, with the Total Demand Distortion (TDD) exceeding the permissible limit of 5%. This elevated level of distortion is a concern, as it can lead to potential operational issues such as overheating of transformers, increased losses in distribution networks, and potential interference with sensitive electronic equipment.

The elevated harmonic distortion in current, especially in Phase 2, suggests that the PV system's inverters may be introducing harmonics that are not mitigated adequately by the existing filtering mechanisms. This could be due to a variety of factors, including the inverter design, the interaction of multiple inverters, or the characteristics of the load profile in the school building.

4.3 Implications for Power Quality Management

The discrepancy between voltage and current quality highlights the need for a more nuanced approach to power quality management in systems with high PV penetration. While the voltage quality remains within acceptable limits, the current distortion underscores the necessity for continuous monitoring and adaptive control strategies.

The installation of advanced harmonic filters could help in mitigating the excessive current harmonics. Both passive and active filters can be employed to address specific harmonic orders that exceed acceptable levels.

The optimisation of inverter settings and possibly employing more sophisticated inverter technologies with better harmonic suppression capabilities could be beneficial. Ensuring that the inverters are sized and configured properly to match the load characteristics can also help reduce harmonic generation.

Implementing a real-time monitoring system to track the power quality parameters continuously can facilitate early detection of issues and enable timely corrective actions. Regular maintenance and calibration of equipment are crucial to ensure ongoing compliance with the power quality Standards.

4.4 Educational Facility Considerations

Educational buildings, with their variable load profiles and frequent fluctuations in power demand, present unique challenges for power quality management. The study underscores the importance of tailored solutions that consider the dynamic nature of these environments. Strategies such as load management, peak shaving, and integration of energy storage systems, may also contribute to more stable power quality.

5 Conclusions

This study provides valuable insights into the power quality implications of integrating grid-connected PV systems in educational facilities. While the voltage quality in the school building adheres to the EN 50160 Standards, significant challenges were identified with current harmonic distortion. The findings emphasise the need for a comprehensive approach to power quality management, including advanced filtering solutions, optimised inverter configurations and continuous monitoring.

Future research should focus on exploring additional strategies and Standards that could enhance power quality further in high-PV penetration scenarios. By addressing the identified issues and implementing recommended measures, educational institutions can integrate renewable energy systems better, while maintaining stable and reliable power quality.

Overall, the study underscores the importance of ongoing evaluation and adaptation in managing the interplay between PV systems and power quality, ensuring that the benefits of renewable energy integration are realised without compromising system performance or equipment safety.

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Povzetek v slovenskem jeziku

Ocena harmonskega popačenja v šolskih stavbah s fotonapetostnimi sistemi. Integracija fotonapetostnih sistemov v elektroenergetska omrežja lahko vpliva na kakovost električne energije, zlasti glede napetostnih in tokovnih harmonikov. Ta študija obravnava kakovost električne energije v šolski stavbi z integriranim fotonapetostnim sistemom, s poudarkom na harmonskem popačenju napetosti in toka. Izvedene so bile obsežne meritve v vseh treh fazah, analiza pa je potekala v skladu s standardoma EN 50160 in IEEE 519. Rezultati kažejo, da kakovost napetosti dosledno izpolnjuje zahteve standarda EN 50160, kar potrjuje stabilne napetostne ravni, medtem ko meritve toka razkrivajo izrazito harmonsko popačenje. Posebej izstopa faza 2, kjer vrednosti celotnega harmonskega popačenja bistveno presegajo dovoljene meje, povišane vrednosti pa se pojavljajo tudi v fazi 1 in fazi 3. Za obvladovanje teh težav študija priporoča uporabo naprednih harmonskih filtrov in optimizacijo pretvornikov. Ti ukrepi so ključni za izboljšanje kakovosti električne energije in zagotavljanje skladnosti s strokovnimi standardi v scenarijih z visokim deležem obnovljivih virov energije.