

HARMONIC ANALYSIS OF DISTRIBUTED ENERGY SOURCES USING SLIDING FFT AND IEC 61000-4-7

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This paper presents the results of harmonic analysis of the current and voltage signals measured at the points of common coupling (PCC) to the distribution networks of several distributed energy sources. One small hydro (HPP) and four small photovoltaic (PV) power plants are considered. Voltage and current harmonics are calculated in two ways: 1) as per standard IEC 61000-4-7, and in accordance with IEEE 519 and EN 50160, and 2) by sliding fast Fourier transform (SFFT), which is applied to calculate time-varying current and voltage harmonics in the specific recorded signals. Application of IEEE 519 and EN 50160 yields different results and conclusions due to different calculation procedures and limiting values. PV power plants can generate almost sinusoidal currents when operating with high power, while the HPP can generate currents with strongly distorted waveshapes when supplying large nonlinear loads. As a result, all four PV power plants meet the requirements for current and voltage harmonics, whereas the analyzed HPP does not meet some of the defined limits. The SFFT analysis confirms the feasibility of dynamic real-time harmonic monitoring, which can play a crucial role in modern distribution networks.

1. INTRODUCTION

In recent decades, many distributed energy sources, such as small hydropower plants (HPP) and photovoltaic (PV) power plants, have been built and integrated into electrical distribution networks worldwide. HPP generates almost sinusoidal currents when supplying linear loads since their generators are almost linear sources of electric power. Some distortion of the current and voltage waveshapes appears due to the nonlinear magnetizing curve of the generator iron core. On the other hand, PV and wind power plants are connected to the distribution networks by using power converters, which are nonlinear equipment. Due to that, these power plants have much more distorted current waveshapes in comparison with traditional electrical energy sources based on synchronous and asynchronous generators [1, 2]. Large nonlinear loads such as electric vehicle charging stations, regulated electric drives, and many others strongly impact the generation of current harmonics and the distortion of voltage waveshape [3]. Because of that, analysis of power quality has become a very important topic in modern distribution networks [4]. European norm (EN) 50160 [5] is widely applied to check the power quality in distribution networks. This norm considers only the quality of supply voltage. The current quality and control of current harmonics in the distribution networks are frequently done based on the standard IEEE 519 [6].

Harmonic analysis of the voltage and current waveshapes at the points of common coupling (PCC) of distributed energy sources is important to keep power quality within proposed limits [4–7] and to enable wide-scale integration of renewables into the distribution networks [8]. PV and wind power plants (WPP) are especially interesting since they are nonlinear sources of electric power [7–12]. Good exploitation characteristics of modern PV power plants and their inverters are reported, proving that it is possible to do wide-scale integration of renewables into the grid without compromising power quality criteria [8–13].

The main objectives of this paper can be listed as follows:

- To investigate the harmonic impact of large, time-varying nonlinear industrial loads and PV power plants on distribution network power quality through detailed field measurements and numerical analyses.
- To evaluate the effectiveness of the sliding fast Fourier

Transform (SFFT) method for real-time harmonic analysis, especially in capturing transient events caused by sudden or intermittent operation of nonlinear loads, and to compare its performance with the aggregation approach defined in IEC 61000-4-7.

- To analyze and compare the applicability of the IEEE 519 and EN 50160 under identical network conditions, identifying potential inconsistencies and highlighting the need for harmonized interpretation of power quality criteria.
- To assess the harmonic performance of PV power plants under various operating conditions and in different distribution networks, and to determine their suitability for large-scale integration into modern distribution networks without degrading power quality.

2. MEASUREMENT OF THE POWER QUALITY IN THE REAL DISTRIBUTION NETWORKS

Power quality measurements are conducted at five locations over five seven-day periods, as suggested in EN 50160 and IEEE 519, and as in [9, 12, 13]. Measurements are conducted with an industrial class A three-phase power quality analyzer [15]. Locations for measurement are marked in Fig. 1 and have the following parameters:

- PV1: $P_n=150$ kWp, built in a rural area, close to two other PV power plants with a total installed capacity of 383 kWp. Connection of the PV power plants to the main substation (MSS₁), with short circuit power (SSC) of 80 MVA, is done using a 4.2 km long 10 kV overhead line (OHL) and a 17 km long 35 kV OHL.
- PV2: $P_n=150$ kWp, built in a rural area. Connection to the MSS₁ is made via 3.8 km of 10 kV OHL and 17 km of 35 kV OHL.
- PV3: $P_n=250$ kWp, built in an urban area. Connection to the MSS₁ is via a 3.4 km 10 kV OHL. In cases PV1, PV2, and PV3, local consumption consists mainly of households.
- PV4: $P_n=15.6$ kWp, built on the rooftop of the university building (UB), and connected by an 80 m long low voltage cable (LVC) to the main distribution board. The 10/0.4 kV/kV transformer placed in the UB is supplied from the MSS₁ by a 1.5 km long 10 kV underground cable line (UCL) and by a 1 km long 35 kV UCL.

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- HPP: $P=850$ kW, built in a rural area. About 1 km from the HPP (500 m of OHL and 500 m of UCL, at 10 kV voltage level, both), there is a quarry with many large nonlinear loads (NLL). Quarry is supplied from the MSS₂ by the 4.5 km long 10 kV OHL. The NLL includes three 250 kW induction motors equipped with soft starters (each operating at up to 50% load) and several 50 kW induction motors controlled by thyristor-based variable frequency drives (VFDs).

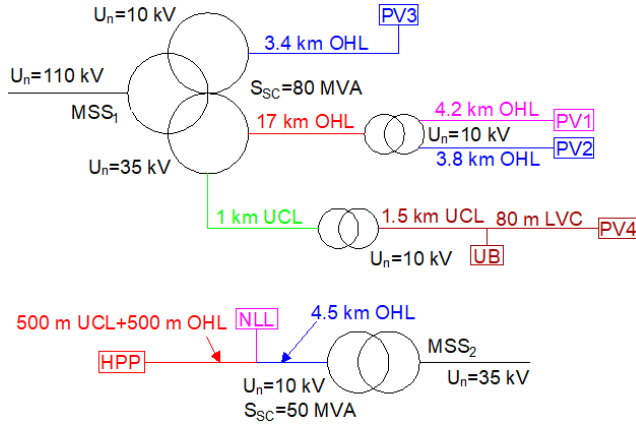


Fig. 1 – Simplified representation of the measurement locations.

The measuring instrument in the case of PV1, PV2, and PV3 power plants is connected at the 0.4 kV side of the 10/0.4 kV/kV pole-mounted transformers [12], while in the case of PV4, it is connected at the output of the inverter. The measuring instrument in the case of HPP is connected at the 10 kV side of the power transformer, and measuring signals are used from the instrument transformers [13].

3. HARMONIC ANALYSES OF THE PHASE VOLTAGE AND CURRENT SIGNALS AS PER IEC 61000-4-7, IEEE 519, AND EN 50160

Calculations of the harmonic content of phase voltages and currents in this section are performed as proposed in standard IEC 61000-4-7, with limiting values adopted from IEEE 519 and EN 50160. Harmonics mean values are calculated by applying FFT on 10 periods (200 ms) of the measured signal whose frequency is 50 Hz. This means that the signal harmonic spectrum is calculated with a resolution of 5 Hz. Calculated signal components are grouped, and mean values of harmonics and inter-harmonics are estimated. The calculation procedure is repeated for every new 200 ms period.

Calculated values of the phase voltages THDU factors as per IEEE 519 and EN 50160 for all five power plants are given in Table 1. Defined limits for THDU factor values are satisfied for all PV power plants, with significant safety margins. In the case of HPP, the following conclusions are obtained:

- The voltage THDU factor is not satisfied in all three phases as per IEEE 519, while it is satisfied in all three phases as per EN 50160. The difference is caused by the different limiting values suggested in these two documents (5% in IEEE 519 and 8% in EN 50160).
- Different values of THDU factors are calculated because in IEEE 519 THDU factor is calculated for harmonics in the range 2÷50, while in EN 50160 THDU factor is calculated for harmonics in the range 2÷40. The higher

value of the THDU factor is calculated as per IEEE 519.

Although PV power plants are nonlinear sources, they satisfy limits set by IEEE 519, while HPP, as an almost linear source, does not satisfy the same standard (Table 1). The reason is large nonlinear loads (regulated electric drives in a quarry), which cause significant distortion of the current and voltage waveshape. This will be analyzed in more detail in the next section using SFFT.

Measured values of the current 95% TDD and 99% TDD as per IEEE 519 are given in Table 2. Values of current harmonics are expressed in percent of the maximum demand current I_L in normal operating conditions (fundamental frequency component). Defined limits for the current 95% TDD and 99% TDD factors are satisfied with a significant safety margin for all PV power plants. In the case of HPP, the current 95% TDD factor value is not satisfied, while the current 99% TDD factor value is satisfied, but with a minor safety margin, since in phase L2, it reaches 96.7% of the limiting value. These results agree with the results presented in Table 1, where poor power quality is also reported in the case of HPP.

Table 1

Measured values of the voltage THDU factor as per IEEE 519 and EN 50160 for all five power plants

Power plant	Limit	THDU		
		Measured values		
		L1	L2	L3
PV1	5% (IEEE 519)	2.55%	2.70%	2.64%
PV2		2.04%	2.03%	2.13%
PV3		3.69%	3.75%	3.78%
PV4		2.91%	3.03%	2.95%
HPP	8% (EN 50160)	6.51%	6.53%	6.27%
HPP		6.07%	6.13%	5.84%

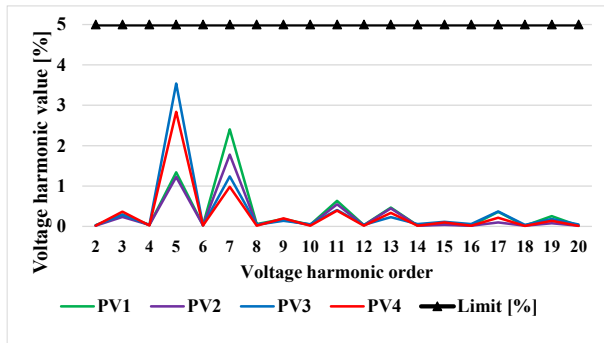
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Measured values of voltage harmonics are given in Fig. 2. Mean values for all three phases are calculated and presented. Calculations are done as per IEEE 519, except in the case of HPP, where calculations are done as per IEEE 519 and as per EN 50160. Standard IEEE 519 defines the same limiting values for all voltage harmonics, and that value is applied in Fig. 2(a), and Fig. 2(b). EN 50160 defines different limiting values for different voltage harmonics, and because of that, all values in Fig. 2(c) are recalculated and compared to their 100% limiting values. In the case of PV power plants, prescribed limits are satisfied and significant safety margins can be noticed, Fig. 2(a). In the PCC of PV3 and PV4, the 5th voltage harmonic is the most pronounced, while in the PCC of PV1 and PV2, the most pronounced is the 7th voltage harmonic. In the PCC of HPP, Fig. 2(b), the most pronounced is the 5th voltage harmonic, and its value is more than two times higher than the limiting value defined in IEEE 519. However, the 5th voltage harmonic is slightly below the limiting value defined in EN 50160, Fig. 2(c), but with a minor safety margin since its value in phase L2 reaches 98.5% of the limiting value, which is equal to 6%. The results presented in Fig. 2 agree well with the results presented in Tables 1 and 2. Values of voltage harmonics calculated as per EN 50160 and IEEE 519 are different because, as per IEEE 519, all values are expressed in the percentage of the rated RMS phase voltage value, while as per EN 50160, all values are expressed in the percentage of the fundamental harmonic RMS phase voltage value.

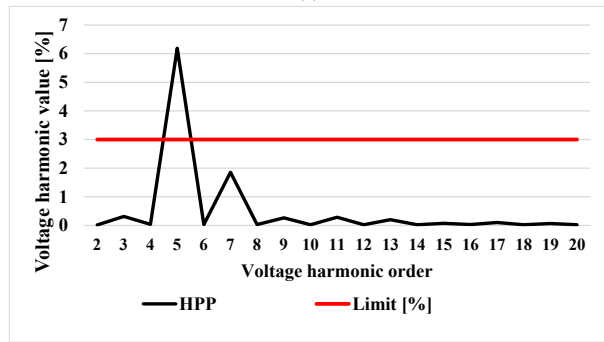
Table 2

Measured values of the current 95% TDD and 99% TDD factors as per the standard IEEE 519 for all five power plants

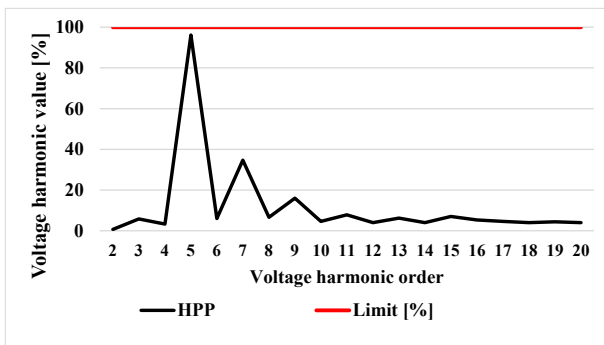
Power plant	TDD 95%			TDD 99%		
	Measured values (limit is 5%)			Measured values (limit is 7.5%)		
	L1	L2	L3	L1	L2	L3
PV1	3.15%	3.09%	3.14%	3.49%	3.48%	3.51%
PV2	1.67%	1.70%	1.82%	3.61%	3.75%	3.87%
PV3	1.16%	1.22%	1.14%	1.24%	1.35%	1.25%
PV4	1.68%	1.61%	1.75%	2.19%	2.14%	2.21%
HPP	5.96%	6.54%	6.06%	6.53%	7.25%	6.59%
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(a)



(b)



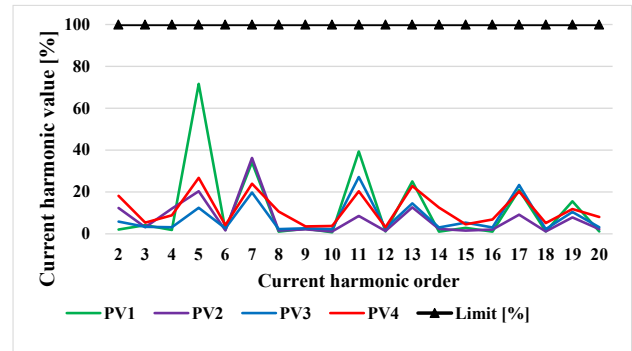
(c)

Fig. 2 – Voltage harmonics values: (a) PV1, PV2, PV3, PV4 (IEEE 519), (b) HPP (IEEE 519), (c) HPP (EN 50160).

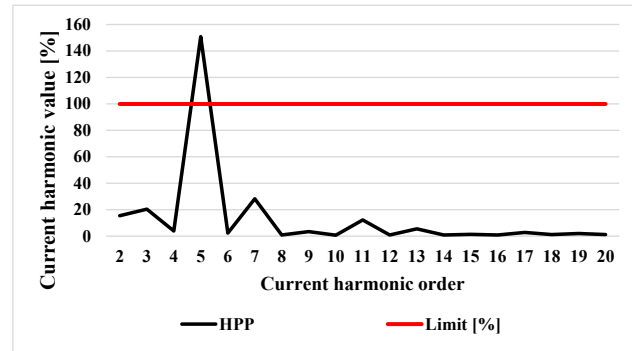
Calculation of the current harmonics is done as per IEEE 519. The measured 95% of individual current harmonic values are given in Fig. 3. In the case of PV1 and PV4, the 5th current harmonic is the most pronounced, in the case of PV2, the 7th current harmonic is the most pronounced, while in the case of PV3, the 11th current harmonic is the most pronounced, Fig. 3(a). Harmonics 5th, 7th, 11th, and 13th are pronounced both in the current and the voltage waveshapes, Fig. 3(a) and Fig. 2(a) respectively. In the case of HPP, the most pronounced is the 5th current harmonic, Fig. 3(b). This harmonic in phase L2 reaches almost 160% of the limiting value, and consequently, the 5th current harmonic does not

satisfy IEEE 519. This agrees well with the results from Fig. 2(b), where the 5th voltage harmonic in the PCC of HPP also does not satisfy the limit set in standard IEEE 519.

The measured 99% of individual current harmonic values are given in Fig. 4. In the case of PV1 and PV2, the 5th current harmonic is the most pronounced, in the case of PV3, the 11th current harmonic is the most pronounced, while in the case of PV4, the 7th current harmonic is the most pronounced, Fig. 4(a). Harmonics 5th, 7th, 11th, and 13th are pronounced both in the current and the voltage waveshapes, Fig. 4(a) and Fig. 2(a) respectively. Closest to the margin is the 5th current harmonic at PV1, but with a safety margin equal to 27% in Fig. 3(a) and 46% in Fig. 4(a). In the case of HPP, the 5th current harmonic does not satisfy the limit set by the standard IEEE 519, Fig. 4(b). This agrees with the results from Fig. 2(b) and Fig. 3(b).



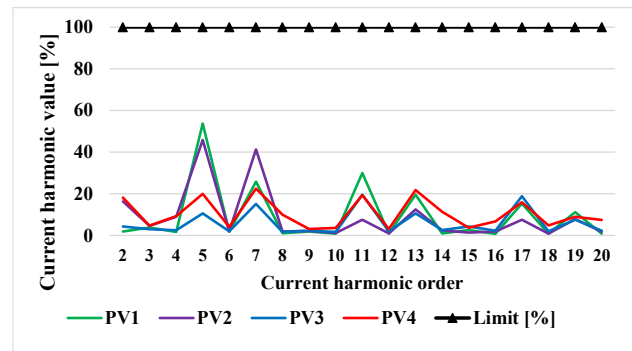
(a)



(b)

Fig. 3 – Measured 95% of individual current harmonic values as per standard IEEE 519: (a) PV1, PV2, PV3, PV4, (b) HPP.

Based on the results presented in Table 1, Table 2, Fig. 2, Fig. 3, and Fig. 4, it is evident that: 1) current and voltage harmonics are correlated because current harmonics make voltage harmonics by voltage drop on system impedances, 2) large nonlinear loads have a high negative impact on the power quality, more pronounced than PV power plants.



(a)

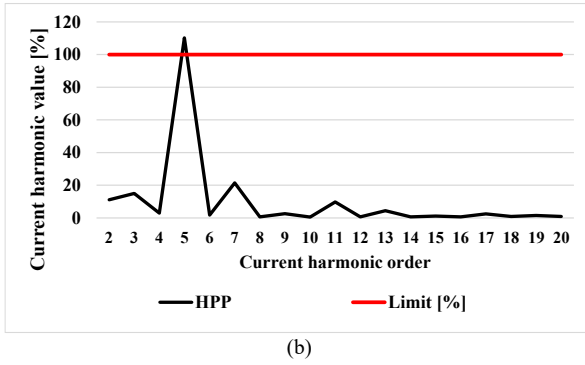


Fig. 4 – Measured 99% of individual current harmonic values as per standard IEEE 519: (a) PV1, PV2, PV3, PV4, (b) HPP.

4. ANALYSES OF THE TIME-VARYING HARMONICS IN THE VOLTAGE AND CURRENT SIGNALS BY SFFT

The approach for harmonics calculation defined in standard IEC 61000-4-7 gives mean values of the signal harmonics and inter-harmonics for periods of 200 ms (10 cycles). This approach is not the best solution in the case when analyzed signals contain time-varying harmonics [11, 16]. In this section current and voltage harmonics are calculated by SFFT, which makes it possible to continually calculate time-varying harmonics in the signal. SFFT analysis is applied as illustrated in Fig. 5. The analyzed signal $u(t)$ has a period of oscillations T . Standard FFT analysis is applied for some period T_1 - T_{11} (20 ms), and the harmonic content of the signal is calculated. Then the samples are updated with one new sample, and the results are recalculated for the new period T_2 - T_{22} , by using the same FFT analysis. The time step of calculation (ΔT) corresponds to the sampling frequency of the measuring device, which is equal to 7 kHz. A similar principle for SFFT analysis of the signals is applied in [16] for the detection of voltage dips and swells in the distribution networks. By using SFFT, analysis results are achieved after 20 ms, while up to that moment, all values are set to zero.

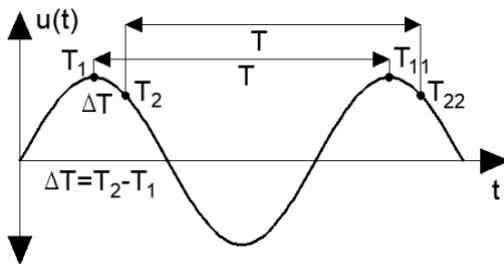
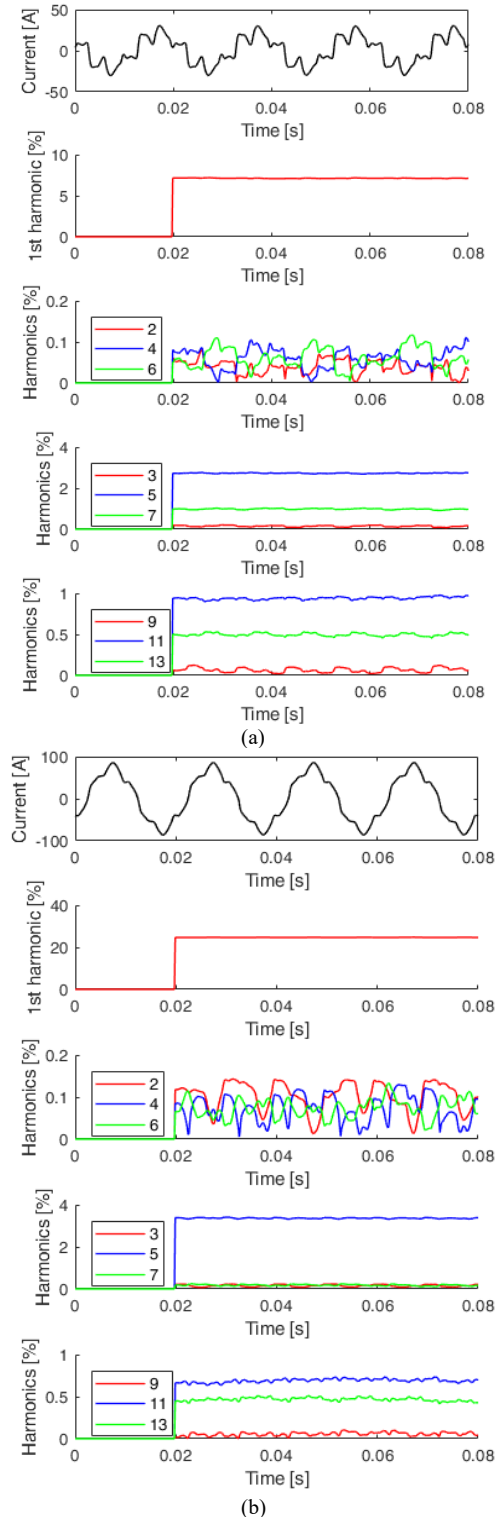


Fig. 5 – Illustration of the applied SFFT analysis.

Figure 6 presents results calculated by applying SFFT to the current measured in phase L1 of PV inverters. Calculations in Fig. 6 are conducted for different values of inverter output current and power. The values of current and voltage harmonics are given relative to the demand current I_L and rated voltage values, respectively. The waveshape of the PV inverter output current significantly improves with the increase of the current RMS value. This agrees with the results presented in [9]. Even harmonics are very low because PV inverters have symmetric positive and negative half-periods of the output current. This agrees with the results from Fig. 2(a), Fig. 3(a), and Fig. 4(a). Odd harmonics

are much more pronounced, especially if the PV inverter works with low power. However, low currents have a limited impact on the power quality in distribution networks. The most pronounced harmonic in Fig. 6 is the 5th harmonic, except in Fig. 6 (c) where that is the 7th harmonic. This agrees well with the results from Fig. 1(a), Fig. 3(a), and Fig. 4(a), where the 5th and 7th harmonics are dominant in most cases. Triple harmonics are eliminated by the delta winding of the step-up power transformers (10/0.4 kV/kV). In the case of larger output current, PV inverters have good performance and generate almost sinusoidal currents, Fig. 6(c). That reduces the 5th, 7th, 11th, and 13th harmonics to about 1% or less.



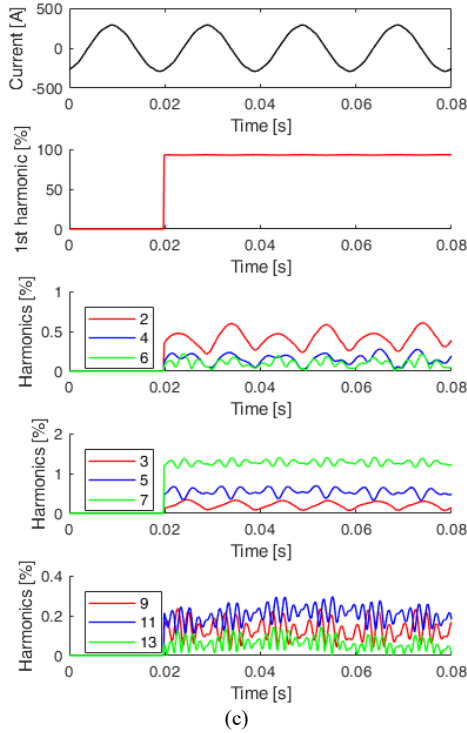


Fig. 6 – SFFT analysis of PV power plant output currents for different values of output power.

In Fig. 7 it is illustrated that the strongly distorted output current of HPP distorts the grid voltage waveshape due to the voltage drop at the impedances of connecting lines, power transformers, etc. An instant increase of the current RMS value in the moment of nearly 0.08 ms, Fig. 7(b), causes significant distortion of the voltage waveshapes, Fig. 7(a), in the 10 kV medium voltage network. A sudden increase of the 1st current harmonic in Fig. 7(b) in the moment of nearly 0.08 ms causes a slight drop of the 1st voltage harmonic, Fig. 7(a), while the appearance of the even and odd current harmonics due to an increase of the nonlinear load current causes appearance of the corresponding voltage harmonics and distortion of the voltage waveshape. The values of the 5th voltage and 5th current harmonics strongly vary in this period. Close correlation of the current and voltage harmonics can be seen in the case of the 2nd, 3rd, and 5th harmonics. Presented distortions of the waveshapes cause that current and voltage harmonics of the HPP mostly do not satisfy limits, or they are close to the limits, defined in IEEE 519 and in EN 50160, as presented in Fig. 2(b), Fig. 2(c), Fig. 3(b), Fig. 4(b), Table 1, and Table 2.

The results from Fig. 7, calculated using SFFT, provide important guidance for harmonic mitigation in distribution networks containing dynamic nonlinear loads. The rapid and significant transient processes strongly increase levels of harmonics within a time frame much shorter than 200 ms, clearly presenting the limitation of standard calculation practices based on cycle averaging, as suggested in IEC 61000-4-7. These rapid fluctuations imply that an active power filter or compensation equipment must have an instant response to limit harmonic levels during oscillations effectively. Instant response requires real-time calculation of harmonic values, and the suggested solution is SFFT.

An additional example of the HPP output current with strongly distorted waveshapes is given in Fig. 8. This waveshape is registered during the operation of the large

regulated electric drives in the quarry. The results presented are very important since they explain the poor power quality at the PCC of the HPP, reported in the previous section. Both odd and even current harmonics are significant in Fig. 8. Even harmonics are caused by nonlinear loads that have nonsymmetrical current waveshapes in positive and negative half-periods such as pumps, compressors, mills, etc. The 5th current harmonic is the most pronounced in Fig. 8. This agrees with results from Fig. 2(b), Fig. 2(c), Fig. 3(b), and Fig. 4(b) where the 5th harmonic is also dominant. This proves that the impact of nonlinear loads on the power quality in the analyzed cases is much more pronounced than the impact of the PV power plants.

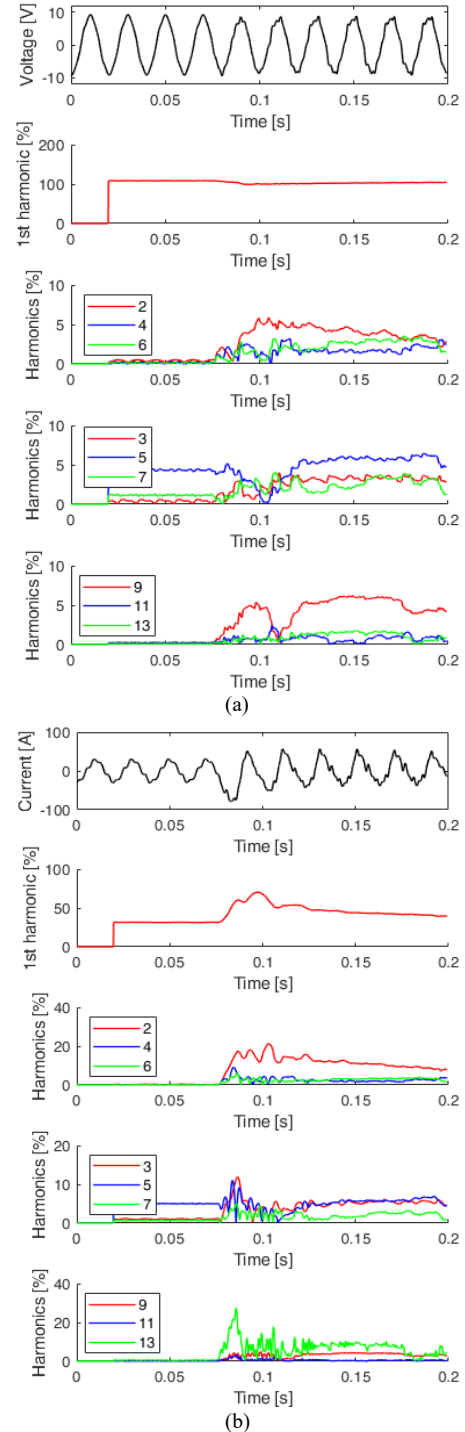


Fig. 7 – SFFT analysis applied on the measured signal in the PCC of the HPP: (a) phase voltage, (b) phase current.

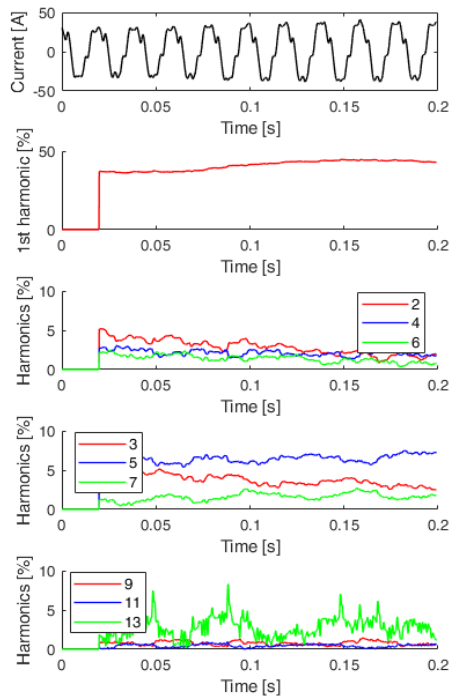


Fig. 8 – SFFT analysis of distorted current waveshapes measured at the PCC of HPP.

5. CONCLUSIONS

In this paper, the current and voltage harmonics at the PCC of one HPP and four PV power plants are analyzed. Harmonics are calculated by SFFT and by IEC 61000-4-7, with limiting values adopted from IEEE 519 and EN 50160. The key finding is that large nonlinear loads have a more pronounced impact on power quality than PV power plants. This can have strong implications for distribution network planning and operation. It is shown that PV power plants can produce nearly sinusoidal currents when operating at high power, whereas HPP can generate strongly distorted current waveshapes when supplying large nonlinear loads. The observed rapid and significant time-varying harmonics generated by the regulated electric drives in the quarry suggest that traditional passive filters may be inadequate in modern distribution networks. Design and optimization strategies in similar networks must prioritize active harmonic compensation devices with fast response times, installed directly at the PCC of nonlinear loads. The effectiveness of SFFT in capturing transient harmonic values validates its application as a superior monitoring technique for grid operators dealing with dynamic load profiles, since 200 ms aggregation of IEC 61000-4-7 often masks peak distortion events. The method specified in IEC 61000-4-7 remains essential for long-term (for example, seven days) power quality assessment. The divergence of results between IEEE 519 and EN 50160 for the HPP (passing EN 50160 but failing IEEE 519) demonstrates that the IEEE 519 requirements are stricter and possibly more appropriate for networks with large nonlinear loads. Finally, good harmonic performance of modern PV inverters supports the wide-scale integration of PV power plants into distribution networks without compromising power quality.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

M.B.: conceptualization and methodology, M.B. and M.I.: measurements, all authors: investigation, writing the original manuscript, writing review, editing, and visualization.

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