RESEARCH ARTICLE

# Power Quality of the 50 MW PV Power Plant

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## Abstract

**This paper presents a power quality analysis of a 50 MW photovoltaic (PV) power plant connected to a 220 kV overhead transmission line in a Southeast European country. The analysis covers a seven-day measurement period. Voltage quality is assessed in accordance with the requirements of the grid codes of three transmission system operators (TSOs) in Southeast Europe. In contrast, current quality was evaluated following the IEEE Std. 2800. The results show that PV power plants, as nonlinear sources of electrical energy, slightly influence power quality parameters, particularly through the generation of harmonics. Continuous monitoring of power quality parameters is important to ensure compliance with relevant technical documents, especially in the case of wide-scale integration of PV and wind power plants into the power system.**

**Keywords**: IEEE Std. 2800, power quality, PV power plant, transmission network.

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## 1 Introduction

Renewable energy sources (RES), mainly wind and photovoltaic (PV) power plants, have become one of the key components within the framework of energy transition activities triggered by global climate change. The integration of RES into the power system leads to the reduction of CO2 emissions in the energy sector, primarily by decreasing the use of fossil fuels in electricity generation [1, 2]. The integration of RES into the power system raises several questions related to the management and operation of such systems. Two main reasons for this can be identified: 1) electricity generation from RES significantly varies over time, depending on the instantaneous values of irradiance, wind speed, etc., and it does not coincide with consumption diagrams, and 2) RES are power electronic-based nonlinear sources of electric power, which harm the power quality in the network. To overcome the first problem, new management strategies of power systems are developed [3, 4]. The second problem is solved through the development of modern power electronic devices with good operating characteristics even at lower power. However, permanent monitoring of the power quality must be done [5, 6], and improvements of power quality must be made when required to keep power quality within defined limits [7, 8]. Some other technical challenges are also related to RES, for example, lightning protection of wind parks [9]. Highly developed countries already have

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extensive experience with RES and their operation and integration, both at the transmission and distribution levels. However, many low-income countries currently face and solve these challenges. That is especially true at the transmission level, since high-power RES are more expensive and complex for implementation.

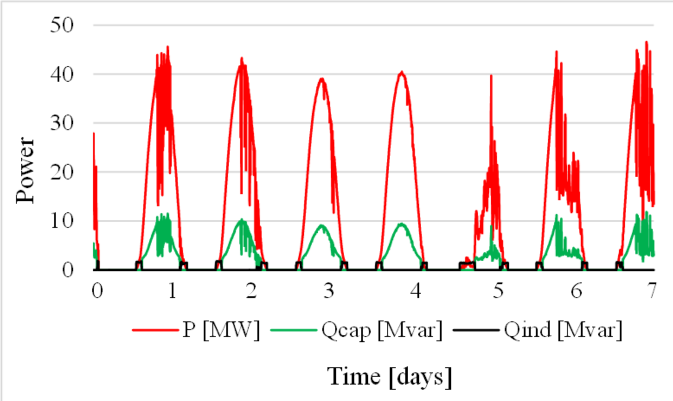
In most of the Southeast European countries, the first high-power RES were connected to the transmission network in the last few years, and there is not enough operational experience with this kind of electric power source, as in the case of distribution networks [10, 11]. Extensive investigations are crucial to enable the wide-scale integration of these systems into the network without compromising its operation. Similar investigations are made in different parts of the world [12–14], but the problem is insufficiently investigated in Southeast Europe. Also, measurements at the PV power plants of similar high power are rare, and in most cases PV power plants installed power is up to 20 MW. Additionally, most publications deal with particular parameters of the power quality together with some other aspects of a PV power plant operation [12–14], while this paper presents analyses of all power quality parameters.

This paper deals with the analysis of the power quality of a 50 MW PV power plant connected to the 220 kV transmission network in the region of Southeast Europe. The main objectives of this research are as follows: 1) To measure and analyze power quality in the point of common coupling (PCC) of the PV power plant, and check whether power quality criteria are satisfied. Near this power plant, additional large PV power plants are being built or are planned for construction, and it is essential to review the technical background for such projects. 2) To analyze and correlate the operation of the PV power plant with variations of some power quality parameters (harmonics, flickers, voltage variation, unbalance, frequency, etc.). In this way, the effect of the PV power plant on the power quality can be detected, and critical power quality parameters can be identified. 3) Both the quality of voltage and current are analyzed to check their compliance with technical documents. 4) Since this is one of the largest PV power plants in the region, the results presented are important for further integration of renewables with high power output into the grid.

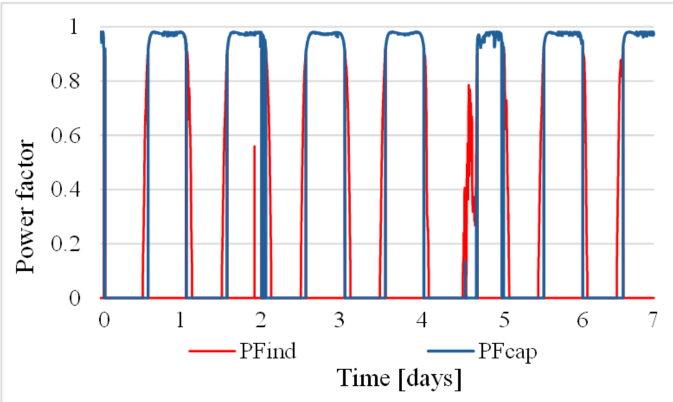
## 2 Main Data About the PV Power Plant and Performed Measurements

The measurement was performed on the 220 kV side of a 220/20 kV/kV power transformer rated at 60 MVA, with a vector group of YNd5. This vector group is common in Southeast Europe. Measurements are performed at the PCC of the PV power plant to the transmission network. The three-phase short-circuit power at the PCC of the PV power plant is about 5000 MVA. The existing 220 kV single circuit overhead transmission line is separated into two new lines, and both are connected to the busbars of the newly constructed substation of the PV power plant. This is the standard way of integrating new power plants into the transmission network in this region. Measured signals are taken from the voltage and current instrument transformers. Standard industrial instrument transformers for measurements installed in the substation 220/20 kV/kV with accuracy class 0.5 are used. The measurement of the power quality parameters was conducted using a three-phase Class A power quality analyzer. PV inverters, model SUNGROW SG250HX, are installed in the PV power plant. This inverter uses a standard integrated passive AC output filter. There is no active harmonic filtering or any other harmonic suppression component installed in the substation.

During the measurement, solar irradiance fluctuated between high and low levels, resulting in variations in the PV power plant's output power. The measured active power (P), reactive inductive power ($Q_{ind}$), and reactive capacitive power ($Q_{cap}$) of the PV power plant during the seven-day registration period are presented in Figure 1 (a). The maximum apparent power of the plant during the analyzed period reached 48.08 MVA, while the maximum active power was 46.56 MW averaged over 1-minute intervals. If averaging is done over 10-second intervals, the maximum apparent power was 50.87 MVA, and the maximum active power was 49.1 MW. Peak values of output occurred in short time periods on days with rapidly changing sunny and cloudy conditions. During cloudy intervals, the panels produce lower power and cool down; once suddenly exposed to sunlight, their efficiency temporarily increases, resulting in a short generation of higher power before stabilizing as the panels heat up again. On the 4th day of measurement, there were no cloudy intervals, and the plant operated at a relatively high and stable output. On that day, the maximum active power reached 40.5 MW, the maximum capacitive reactive power was 9.4 Mvar, while the maximum apparent power was 41.6 MVA.




(a)




(b)

**Figure 1.** (a) Active power, reactive inductive power, reactive capacitive power, and (b) power factor of the PV power plant during the measurement.

Figure 1 (b) presents the corresponding power factor: PFind - the inductive power factor when the PV power plant produces reactive power, PFcap - the capacitive power factor when the PV power plant consumes reactive power. It can be observed that at higher power levels, the plant operated with a slightly capacitive power factor just below unity (typically between 0.97 and 0.98), while at lower output levels, the power factor slightly shifted to inductive. The voltage value in the transmission network of Southeast Europe is mostly up to or above the maximum continuous operating voltage (245 kV in the 220 kV network). Consumption of reactive power dominantly appears in periods when the voltage is too high, and inverters slightly reduce the voltage value by consuming some reactive power. A small part (up to 0.5 Mvar) of consumed reactive power is connected to the magnetizing reactive power of power transformers in the PV power plant: 1×60 MVA 220/20 kV/kV power transformer, 12×3.15 MVA 20/0.8 kV/kV power transformers, and 10×1.25 MVA 20/0.8 kV/kV power transformers.

## 3 Parameters of the power quality

### 3.1 Parameters of the voltage quality as per the Grid Codes of three selected TSOs in Southeast Europe

European norm EN 50160 [15] is frequently applied for power quality assessment. However, EN 50160 define power quality criterions for the low voltage networks ($V_n < 1\,\text{kV}$), medium voltage networks ($1\,\text{kV} < V_n < 36\,\text{kV}$) and for the high voltage networks ($36\,\text{kV} < V_n < 150\,\text{kV}$), but for the high voltage networks with $V_n > 150\,\text{kV}$ power quality is usually addressed through national regulations, transmission system grid codes, or specific utility guidelines. Power quality criteria in the transmission network of Bosnia and Herzegovina, Serbia, and Croatia are defined by the Grid Codes published by their independent transmission system operators (TSO):

1. In Bosnia and Herzegovina: "Nezavisni operator sistema u Bosni i Hercegovini" (NOSBih) [16].
2. In Serbia: "Elektromreža Srbije" (EMS) [17].
3. In Croatia: "Hrvatski operator prijenosnog sustava" (HOPS) [18].

The summarized power quality criterion from these three transmission system operators is given in Table 1. The total harmonic distortion ($THD$), can be calculated using equation (1) [15]:

$$THD = \sqrt{\frac{\sum_{i=2}^{40} U_i^2}{U_1}} \cdot 100\% \qquad (1)$$

where $U_i$ is $i^{\text{th}}$ voltage harmonic and $U_1$ is the fundamental voltage harmonic.

### 3.2 Parameters of the current quality as per the IEEE Std. 2800

Grid Codes [16–18] define only the voltage quality parameters. The parameters of the current quality are defined in the IEEE Std. 2800 [22]. According to this standard, the 95% values of the current harmonics in a 220 kV system, based on a seven-day measurement period, shall not exceed the limiting values defined in Table 2. The total rated current distortion (TRD), includes harmonic distortion, interharmonic distortion, and noise, and is defined by equation (2) [22]:

$$TRD = \frac{\sqrt{I_{RMS}^2 - I_1^2}}{I_{rated}} \cdot 100\% \qquad (2)$$

**Table 1.** Summarized voltage quality criteria from the Grid Codes of three TSOs in Southeast Europe.

| Parameter | NOSBIH [16] | EMS [17] | HOPS [18] |
|---|---|---|---|
| Voltage variation | Under normal operating conditions, the supply line to line voltage at the point of common coupling at the 220 kV voltage level should remain within the limits: 198 kV and 245 kV | 198 kV and 245 kV | 198 kV and 246 kV |
| Flicker | 95% of the one-minute weekly voltage values, excluding the flicker caused by voltage dips, the long-term flicker severity $P_{lt}$ must be: $P_{lt} < 0.6$ | $P_{lt} \leq 0.6$ | $P_{lt} \leq 1.0$ |
| Harmonic distortion | 95% of the 10-minute $THD$ values can be $\leq 1.5\%$. Voltage harmonics up to the 40$^{\text{th}}$ order must be less than the limits defined in IEC 61000-3-6 [19] | 95% of the 10-minute $THD$ values can be $\leq 3\%$. Voltage harmonics must satisfy the following limits: 2$^{\text{nd}}$ $\leq 1.4\%$; 4$^{\text{th}}$ $\leq 0.8\%$; 6$^{\text{th}}$, 8$^{\text{th}}$ $\leq 0.4\%$; 3$^{\text{rd}}$, 5$^{\text{th}}$, 7$^{\text{th}}$ $\leq 2\%$; 9$^{\text{th}}$ $\leq 1\%$; 11$^{\text{th}}$, 13$^{\text{th}}$ $\leq 1.5\%$; 15$^{\text{th}}$ $\leq 0.3\%$; 21$^{\text{st}}$ $\leq 0.2\%$. Odd harmonics not multiple of 3, 17$^{\text{th}}$ $\leq h \leq$ 49$^{\text{th}}$ limit is $\leq 1.2 \cdot 17/h$ [%]. Odd harmonics multiples of 3, 21$^{\text{st}}$ $\leq h \leq$ 45$^{\text{th}}$ limit is $\leq 0.2\%$. Even harmonics 10$^{\text{th}}$ $\leq h \leq$ 50$^{\text{th}}$ limit is $\leq 0.19 \cdot 10/h + 0.16$ [%]. | 95% of the 10-minute $THD$ values can be $\leq 1.5\%$. Voltage harmonics up to the 40$^{\text{th}}$ order must be less than the limits defined in IEC 61000-3-6 [19] |
| Phase unbalance | 95% of the 10-minute voltage values, the negative-sequence component shall be: $\leq 2\%$ | $\leq 1.4\%$ | $\leq 1.4\%$ |
| Frequency | As defined by the ENTSO-E [20, 21]: Under normal operating conditions, ten-second average values of the supply frequency in standard steady-state operation are in the range 49.95 Hz and 50.05 Hz, the maximum quasi-steady-state frequency deviation is in the range 49.8 Hz and 50.2 Hz, while the maximum permissible dynamic frequency deviation is in the range 49.2 Hz and 50.8 Hz. | | |

where $I_{RMS}$ is the root-mean-square current for all frequency components up to the 50$^{\text{th}}$, $I_1$ is the fundamental current harmonic, $I_{rated}$ is the PV power plant rated current.

The defined current quality parameters can be modified if the voltage harmonic distortion satisfies limits defined in a grid code, if the power plant operates as an active harmonic filter, or if the power plant has installed passive harmonic filters [22]. Also, IEEE Std. 2800 is an American standard, and it is not relevant in Southeast European countries, but it can be useful to address the current quality of inverter-based RES, since the analyzed grid codes of TSOs do not consider the current quality.

## 4 Analyses of measured results

### 4.1 Voltage quality

#### *4.1.1 Frequency*

Measured values of frequency are presented in Figure 2. Stable frequency with small deviations is registered in the registration period. All measured values of the frequency were in the range from 49.89 Hz to 50.12 Hz, while 99.5% of measured values were in the range from 49.93Hz to 50.07 Hz. These values are slightly outside the defined range of frequency for standard steady-state operation (49.95 Hz to 50.05 Hz) but are within the maximum steady-state frequency deviation (49.8 Hz to 50.2 Hz), as defined in Table 1. The analyzed PV power plant is not a cause of frequency deviations since it has negligible power compared to the interconnected system in ENTSO-E. Trip-outs of similar power plants at maximum power can cause small instantaneous local frequency oscillations and deviations; however, such deviations are averaged since the mean value of frequency in 10-second periods is calculated.

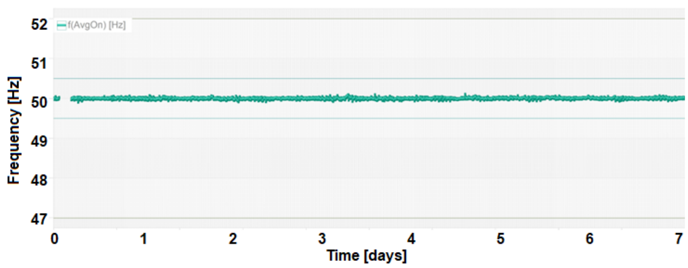



**Figure 2.** Measured values of the supply voltage frequency.

**Table 2.** Maximum current distortion in percent of rated current [22].

| Individual current harmonic order ($h$) | | | | | $TRD$ |
|---|---|---|---|---|---|
| $h$=2 | $h$=4 | $h$=6 | $h$<11 ($h \neq$2,4,6) | $11 \leq h \leq 50$ | 2.0% |
| 1.0% | 2.0% | 3.0% | 1.5% | 1.0% | |

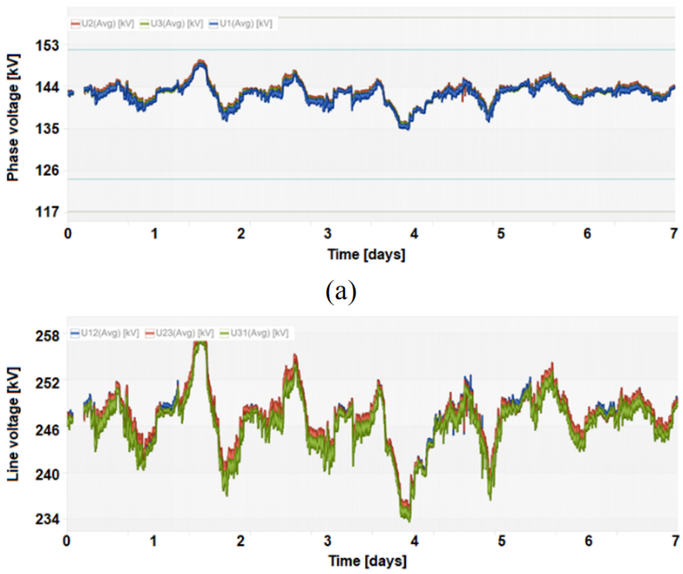
**Table 3.** Detected voltage events during the measurement period.

| Event Type | Start Time [h:min:s] | End Time [h:min:s] | Duration [h:min:s] | Phase | Residual voltage |
|---|---|---|---|---|---|
| Swell (1st day) | 16:59:19.683 | 16:59:19.713 | 00:00:00.0300580 | L1,L2,L3 | 162.0 kV |
| Dip, Interruption (1st day) | 16:59:19.716 | 20:10:11.609 | 03:10:51.8924780 | L1,L2,L3 | 0.3 kV |
| Swell (1st day) | 20:10:11.622 | 20:10:11.635 | 00:00:00.0132819 | L1,L2 | 155.0 kV |
| Dip (3rd day) | 14:17:12.966 | 14:17:13.016 | 00:00:00.0500140 | L3 | 121.3 kV |
| Dip (5th day) | 01:42:36.796 | 01:42:36.850 | 00:00:00.0535060 | L1,L2 | 119.2 kV |
| Dip (5th day) | 04:40:52.910 | 04:40:52.970 | 00:00:00.0599690 | L2 | 90.6 kV |
| Dip (5th day) | 04:40:54.040 | 04:40:54.110 | 00:00:00.0699270 | L2 | 89.9 kV |
| Dip (5th day) | 05:21:02.206 | 05:21:02.276 | 00:00:00.0699231 | L2 | 85.7 kV |
| Dip (5th day) | 05:59:21.668 | 05:59:21.717 | 00:00:00.0499561 | L1,L2 | 119.3 kV |
| Dip (5th day) | 06:15:06.514 | 06:15:06.571 | 00:00:00.0566440 | L1,L2,L3 | 121.5 kV |
| Dip (5th day) | 06:27:52.837 | 06:27:52.907 | 00:00:00.0698980 | L1 | 102.2 kV |
| Dip (5th day) | 09:38:55.234 | 09:38:55.304 | 00:00:00.0699140 | L1 | 106.4 kV |
| Dip (5th day) | 09:55:14.443 | 09:55:14.483 | 00:00:00.0400310 | L1 | 116.2 kV |

#### 4.1.2 *Voltage Variations*

Measured values of the power frequency voltage are presented in Figure 3. The requirements from Table 1 are that the line to ground voltage values must be within the limits of 114.3 kV to 141.4 kV (142 kV), while the measured values were in the range of 134.783 kV to 149.578 kV. Considering the line to line voltage values, the limit is between 198 kV and 245 kV (246 kV), while the measured values were in the range of 233.45 kV to 259.08 kV. This parameter of power quality is therefore not satisfied, and the maximum registered line to line voltage value is 14.08 kV (13.08 kV) higher than the limit. The cause of the problem is not the PV power plant but the inadequate voltage regulation in the Southeast Europe part of the ENTSO-E [23]. The installation of several stationary compensation devices with SVC (Static Var Compensator) and STATCOM (Static Synchronous Compensator) technologies reduces the problem in some countries (for example, in Slovenia and Croatia) [24]; however, the problem is still significant.

Figure 4 presents the dependence of the power frequency voltage value on the generated current (power) of the PV power plant. The PV power plant almost does not impact the grid voltage value, and a small decrease in the grid voltage values during the day is caused by increased power consumption in the system.




(b)

**Figure 3.** Mean measured values of the: (a) RMS line to ground voltages, (b) RMS line to line voltages.

#### 4.1.3 *Long-term flicker severity* (*Plt*)

Flickers are a critical power-quality parameter in many PV power plants. Analyses of the long-term flicker severity ($P_{lt}$) are done for three critical periods, as follows:

1) **Period 1** – is a full period of measurement (7 days), Figure 5(a) and Figure 6(a). In this period, $P_{lt}$ values ranged from 0.21 to 7.19, which is significantly higher than the limiting value of $P_{lt} < 0.6$ ($< 1.0$). However, at the beginning of this period, very high flickers are detected due to the trip out of the grid voltage, as

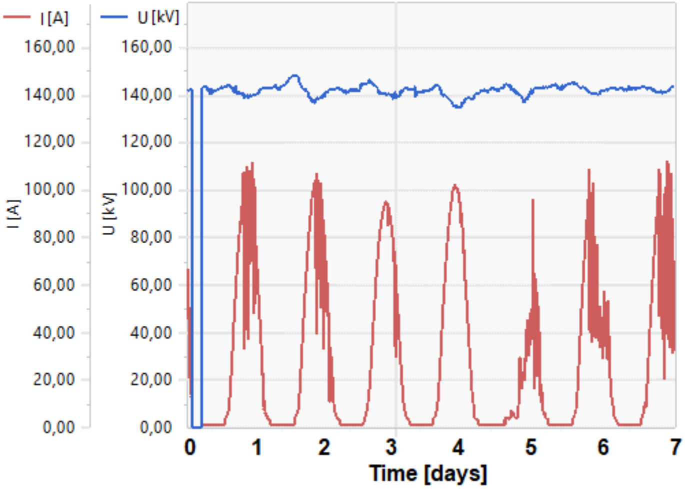
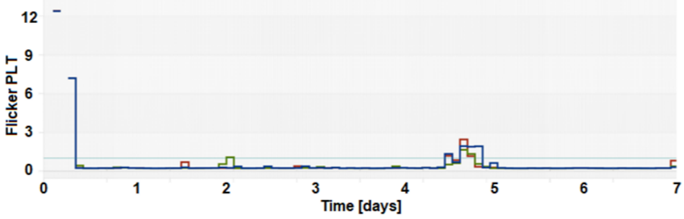
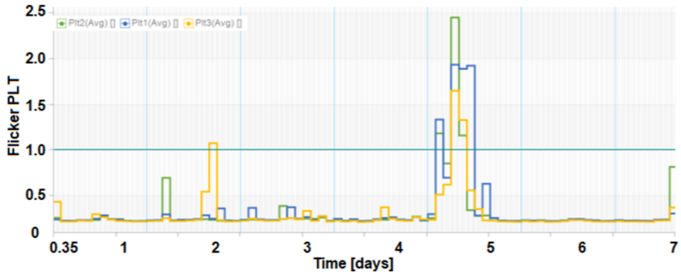



**Figure 4.** Measured values of the grid voltage and current of the PV power plant in one phase.




(a)

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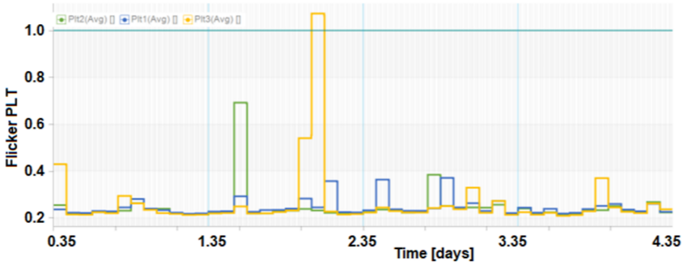



(c)

**Figure 5.** Mean measured values of the long-term flicker severity (Plt): (a) Period 1, (b) Period 2, (c) Period 3.

shown in Table 3.

2) **Period 2** – is reduced Period 1 of measurement, Figure 5(b) and Figure 6(b), excluding a voltage trip out at the beginning of the measuring period, when very high flickers are measured due to the grid disturbance and not due to the operation of the PV power plant, as shown in Table 3. This period of measurement lasts 6d:15h:18 min. In this period, $P_{lt}$ values were in the range of 0.21 to 1.33, which is also higher than the limiting value $P_{lt} < 0.6$ $(< 1.0)$, but is much lower compared to the values from Period 1.

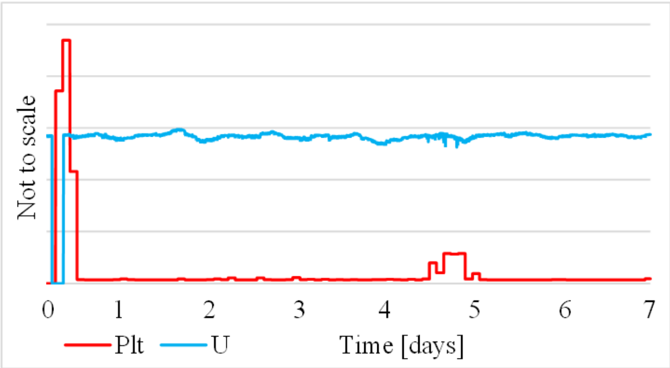
3) **Period 3** – is reduced Period 2, Figure 5(c), excluding a voltage trip out at the beginning of the measuring period (as in Period 2) and excluding the 5th, 6th, and 7th days of measurement. On day five, a nine-voltage dip appears, as shown in Table 3. This happened between 1:42:36 AM and 9:55:14 AM, when the PV power plant does not produce power or produces low power. It can be observed that the cause of high voltage flickers in this period is grid voltage disturbances, and not the operation of the PV power plant. This period of measurement lasts 4 days, and $P_{lt}$ values were in the range of 0.21 to 0.43, which is lower than the limiting value $P_{lt} < 0.6$ $(< 1.0)$.

### 4.1.4 *Voltage Unbalance*

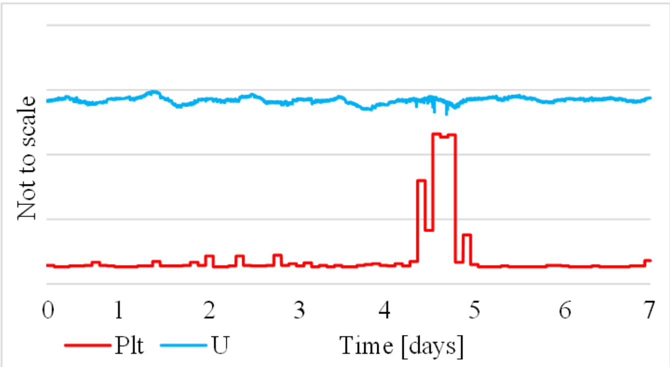
Measured values of the power frequency voltage unbalance are presented in Figure 7 (a). Requirement from Table 1 is that the voltage unbalance in 95% of the week must be $\leq$2% ($\leq$1.4%). The measured values were in the range of 0.01% to 0.32% and contained a significant safety margin. PV power plants are based on three-phase inverters, which are symmetric and do not generate unbalances in the network. On day five significantly larger voltage unbalance is detected, Figure 7 (a). Figure 7 (b) shows the dependence of the voltage unbalance and active power of the PV power plant. It can be observed that increased voltage unbalance on day five is caused by voltage dips (nine of them, as explained in the previous subsection), while the PV power plant does not impact voltage unbalance in a steady state or intermittent operating regime.

### 4.1.5 *Voltage harmonics and THD factor*

Measured values of voltage harmonics are presented in Figure 8. Limiting values from Table 1, as defined by EMS, are applied, and the calculated values of harmonics are given relative to these limiting values. All harmonics satisfy requirements, and the closest to the margin is the 5th harmonic. In phase 1, it reaches 34.0% of the limit, in phase 2, it reaches 28.5% of the limit, while in phase 3, it reaches 34.5% of the limit. Other significant harmonics are 3rd, 7th, 11th, and 13th, etc. This corresponds well with the results measured in distribution networks [10]. Even harmonics are low because inverters have symmetric positive and negative voltage wave periods. The

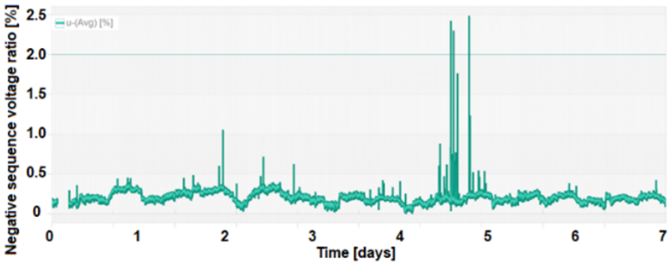



(a)

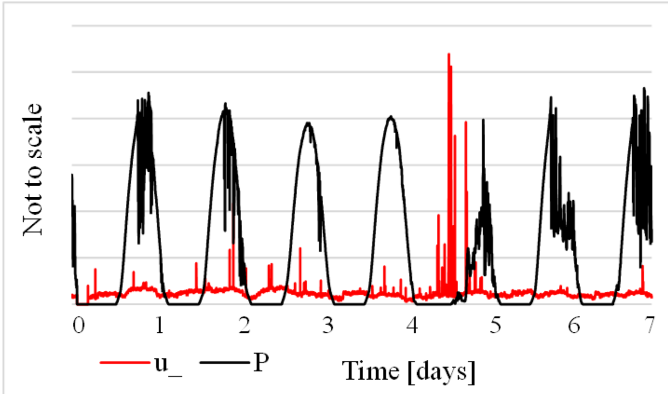



(b)

**Figure 6.** Mean measured values of the flickers and grid voltage in one phase: (a) Period 1, (b) Period 2.




(a)




(b)

**Figure 7.** (a) Mean measured values of the negative sequence ratio u-, (b) dependence on the voltage unbalance and active power of the PV power plant.

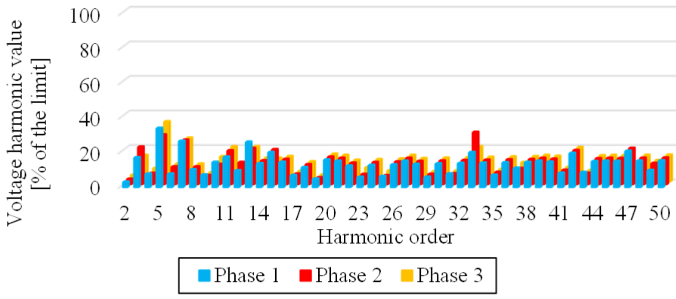



**Figure 8.** Measured values of the voltage harmonics.

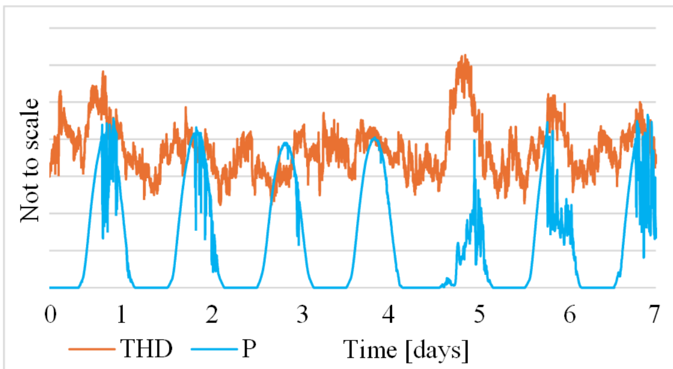



**Figure 9.** Measured values of the voltage THD factor and PV power plant active power in Period 2.

transformer vector group is YNd5, which filters multiples of the 3rd harmonic. The selection of some other vector group of the power transformer cannot improve the filtering of current harmonics.

Measured values of the voltage *THD* factor are 0.92% in phase 1, 0.83% in phase 2, and 0.88% in phase 3, while the limiting value is 1.5% (3%). A significant safety margin is noticeable. The dependence of the voltage *THD* factor and PV power plant active power in Period 2 is presented in Figure 9. It can be observed that values of the *THD* factor are higher when the PV power plant produces active power, because PV inverters are nonlinear equipment and generate harmonics. On day five, when the PV power plant operates with reduced power due to the cloudy weather, a significant increase in the voltage *THD* factor can be observed. A similar situation is on days 1 and 6, proving that harmonics generated by the PV power plant increase the value of the voltage *THD* factor. In [10], it is presented that PV inverters generate low harmonics when operating at high power, while critical harmonic emission appears during the operation with reduced power, or during the days with intermittent cloudy and sunny periods.

Although PV inverters can inject noticeable harmonic currents, the high short-circuit power and consequently low harmonic impedance at the 220 kV level (5000 MVA is three-phase short-circuit power at the PCC) keep the resulting voltage distortion low. In such strong networks, even relatively large harmonic currents produce only minor voltage-harmonic components. However, in weaker grids with lower short-circuit power and consequently higher impedances, the same current harmonics can cause significantly higher voltage distortion.

### 4.2 Current quality

Calculated values of current harmonics relative to limiting values from Table 2 are presented in Figure 10. The 5th and 7th harmonics do not satisfy the requirements defined in IEEE Std. 2800, and they are roughly 2.4 and 1.8 times higher than the limiting values, respectively. Other significant harmonics are the 11th and 13th, but they are significantly below the limiting values (68% and 42% of the limit, respectively). These results correspond well with the results measured in distribution networks [10]. Good correlation between the voltage and current harmonics is detected, Figures 8 and 10, except for the 3rd harmonic, which is low in current waveform (22% of the limit). As in Figure 8, even harmonics are low because inverters have symmetric positive and negative voltage wave periods, while the transformer vector group YNd5 filters multiples of the 3rd harmonic.

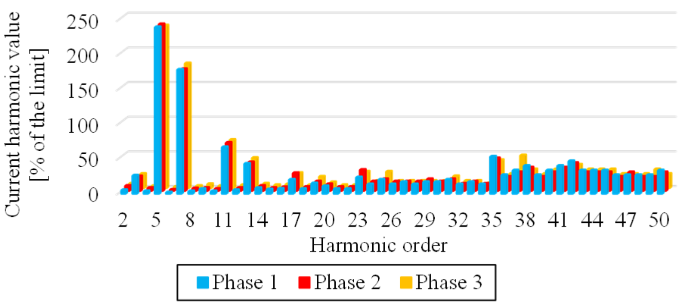



**Figure 10.** Measured values of the current harmonics.

Rated current of the 50 MW PV power plant at the 220 kV voltage level is 131.4 A, and this value is used to calculate the *TRD* factor, equation (2). Measured values of the *TRD* factor during the seven-day registration period are presented in Figure 11. It can be observed that most of the time when the PV power plant generates power, the values of the *TRD* factor are above the limit. Calculated values of the *TRD* factor for 95% of the week are 4.42% in phase 1, 4.40% in phase 2, and 4.38% in phase 3, while the limiting value is $\leq$2.0%. Values of the *TRD* factor are about 2.2 times larger than the limiting values, and this factor does not satisfy the requirements of the standard. It is important to note that in IEEE Std. 2800, the limiting value of the long-term flicker severity *Plt* is 0.25, while in the Grid Codes summarized in Table 1, the limit is 0.6 or 1.0. This shows that IEEE Std. 2800 probably defines conservative values of power quality parameters, particularly for *Plt*, but probably for current harmonics too.

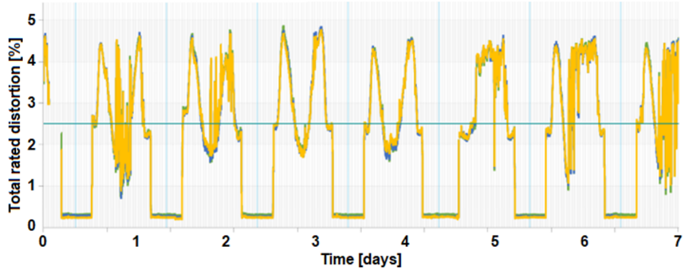



**Figure 11.** Measured values of the current TRD factor.

Dependence between the generated active power of the PV power plant and values of 5th and 7th current harmonics is presented in Figure 12(a), while dependence between the values of 5th and 7th current harmonics and voltage *THD* factor is presented in Figure 12(b)). Harmonics' values are maximum when the PV power plant operates at about 30% of rated power (Figure 12(a)), because inverter PWM and switching control are least efficient at low-to-medium output power. In such cases, the modulation index is small, causing uneven PWM duty cycles and reduced current-control resolution. In this operating region, the inverter's switching devices work farther from their optimal conditions, and harmonic-suppression algorithms are less effective, resulting in increased distortion of the current waveform. As loading rises and the modulation index approaches its nominal range, the switching pattern becomes more linear, and the harmonic emission of PV inverters decreases. Mitigation of high current harmonics can be based on deploying inverters with enhanced low-load PWM or adaptive switching strategies, application of optimized passive harmonic filters at the PCC, application of active harmonic compensation via plant-level control or auxiliary devices (e.g., STATCOM), etc. Current harmonics generated by the PV power plant increase the voltage *THD* factor (Figure 12(b)), however, the *THD* factor is also high during some nights, which can be caused by wind power plants, very large nonlinear loads, or operation of power transformers with increased value of the power frequency voltage.

Figure 13 presents the dependence of the grid voltage

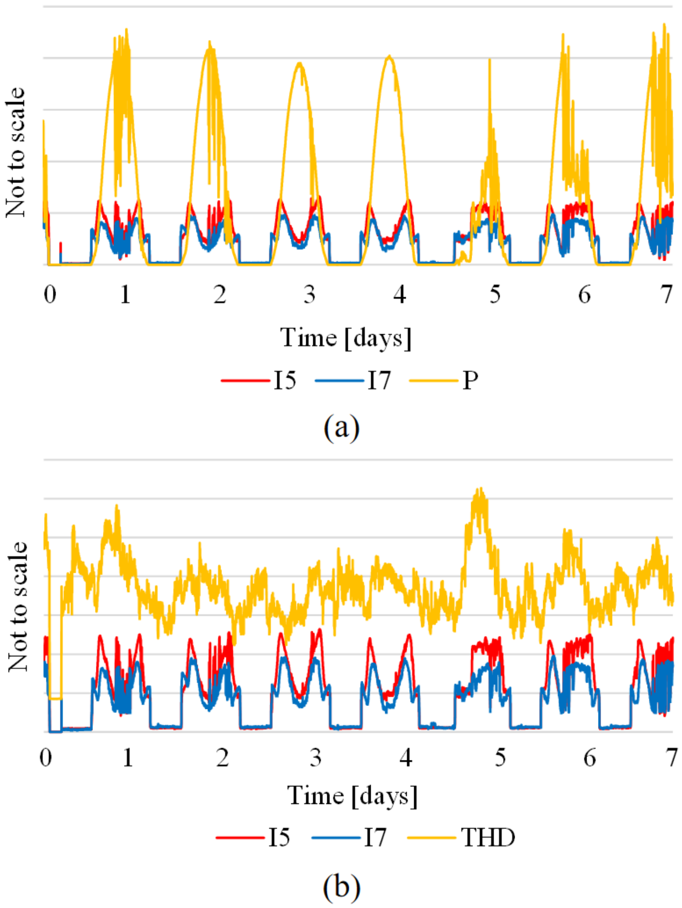



**Figure 12.** Correlation between the 5th and 7th current harmonics and: (a) active power of the PV power plant, (b) voltage THD factor.

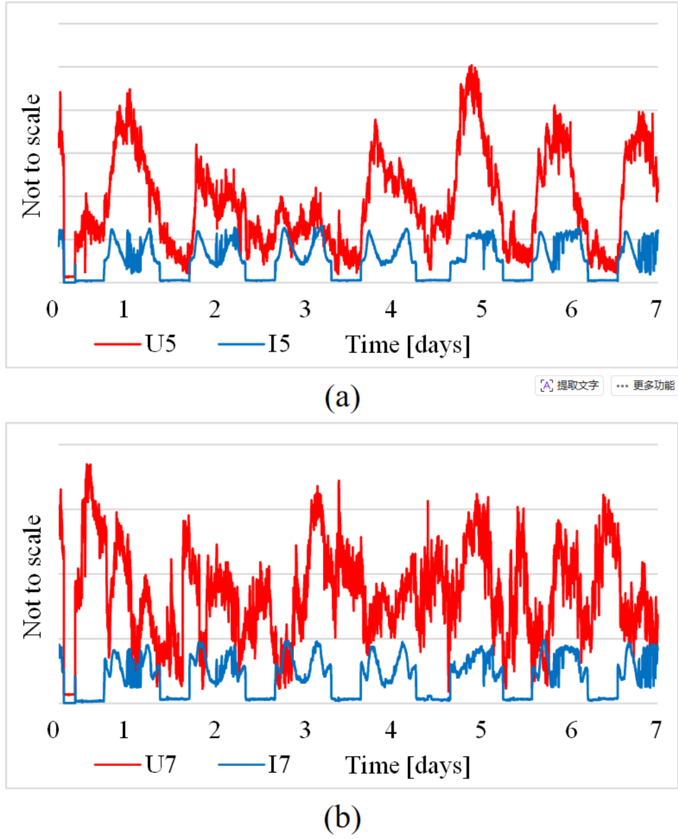



**Figure 13.** Correlation between the: (a) 5th voltage and current harmonics, (b) 7th voltage and current harmonics.

harmonics and PV power plant current harmonics. Good correlation is observed in the case of the 5th harmonic, while weak correlation is observed in the case of the 7th harmonic. This means that the 5th voltage harmonic is strongly influenced by the operation of the PV power plant, while the 7th voltage harmonic has other sources.

Measured waveforms of the voltage and current in one phase of the PV power plant are presented in Figure 14. The most pronounced harmonics in the line to ground voltage are 3rd, 5th, 7th, and 11th harmonics with values of 0.27%, 0.57%, 0.51% and 0.13% of the fundamental harmonic, respectively. The most pronounced harmonics in the line to ground currents are 5th, 7th, 11th, and 13th harmonics with values of 8.90%, 7.19%, 1.35% and 0.73% of the fundamental harmonic, respectively. This agrees well with the results presented in Figures 8 and 10. Measured waveforms correspond to the RMS line to ground voltage value of 142.2 kV and the RMS current value of 48.4 A, and to the apparent power of the PV power plant of 20.6 MW. Current and voltage are almost in phase, which means that the PV power plant operates with a power factor close to unity and produces mainly active power. This agrees with the results presented in Figure 1(b).

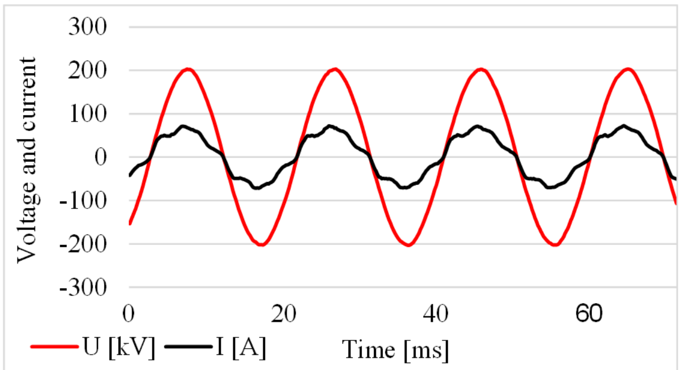



**Figure 14.** Waveforms of measured line to ground voltage and line to ground current of the PV power plant.

## 5 Conclusion

Based on the results presented, the following conclusions can be given:

- Analyzed PV power plant does not impact the frequency of the system, voltage unbalance, and voltage variations. That is because of the low installed power of the PV power plant compared to the power of the interconnected transmission system and compared to the short circuit power at the PCC.

- Analyzed PV power plant can slightly increase:
  - Voltage harmonics and voltage THD factor, since inverters generate current harmonics, and they make voltage harmonics at the system impedances.
  - Flickers, although in this case generated by grid voltage disturbances and not by the PV power plant. This parameter can be critical if the operation of the PV power plant causes voltage fluctuations.
- Analyzed PV power plant generates significant 5th and 7th current harmonics, while other current harmonics are well below the limits. The critical operating point for current harmonics generation is about 30% of the PV power plant's rated power. However, since voltage harmonics and voltage THD factor are well below the limits, detected current harmonics are acceptable. The presented limiting values of current harmonics can be conservative, since the limiting value of long-term flicker severity, Plt, in IEEE Std. 2800 is 0.25, while in the analyzed Grid Codes limit is 0.6 or 1.0 (2.4 or 4 times higher).
- PV power plants are nonlinear sources of electric power and generate significant current harmonics compared to traditional sources of electric power. Current harmonics produce voltage harmonics on system impedances, and this can distort the voltage waveform in the case of wide-scale integration of high-power renewables, especially in the case of weak transmission networks. Continual monitoring of the power quality in the grid must be performed to detect possible problems at an early stage and apply proper solutions.
- Analyzed Grid Codes of transmission system operators do not consider current quality, but only the voltage quality. Voltage quality is not significantly influenced by the PV power plant because its installed power is low compared to the short circuit power of the grid at the PCC and compared to the installed power of the interconnected transmission system. In such cases, from the aspect of power quality, a wide-scale integration of PV power plants in the transmission grid can be done.
- The results presented clearly indicate the need for continuous voltage and current harmonics monitoring in power systems, especially because penetration of PV and wind power plants in the system will grow. Additionally, grid codes of TSOs can be revised to include current quality criteria, since presently, they are not considered. The applicability of the American standard IEEE 2800 in European grids is questionable and must be further investigated. The analyzed case study is interesting since it deals with one of the largest PV power plants in the region, which can be a reference for future high-power RES integrations.

## Data Availability Statement

Data will be made available on request.

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## Conflicts of Interest

The authors declare no conflicts of interest.

## Ethical Approval and Consent to Participate

Not applicable.

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