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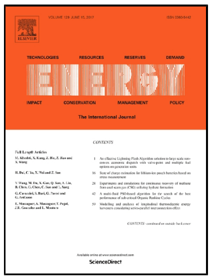

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Highlights

- The production of electric energy by photovoltaic systems.
- Voltage quality and harmonic distortion of current and voltage (EN 50160).
- The power quality of PV systems connected to an urban distribution network.
- PV systems use inverter, which enable synchronous operation with the dist. network.

Power Quality Experimental Analysis of Grid-Connected Photovoltaic Systems in Urban Distribution Networks

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Abstract
This paper presents the analysis of the impact of dispersed source production on the electric distribution network. The focus is on the production of electric energy by photovoltaic systems in public distribution networks. Photovoltaic systems may in certain cases influence voltage quality in public distribution networks, which is determined by the EN 50160 standard. Photovoltaic systems affect the voltage profile and harmonic distortion of current and voltage. Ensuring the appropriate voltage profile is especially important in radial networks because of eventual huge voltage drops. Many photovoltaic systems on a radial network with relatively high short-circuit impedance and relatively low short-circuit power can be problematic with regard to the permitted level of harmonic distortion, particularly at lower power. The analysis of power quality is based on real measurements of total harmonic distortion (THD) on four existing photovoltaic systems and two transformer stations in the urban electric distribution networks.

Keywords: photovoltaic system, SIST EN 50160, inverters, electric distribution network, power quality

1. Introduction

The system of subsidies and state grants for power generation units using renewable energy sources (RES), and cogeneration of heat and power (CHP), has led to an inclusion of a large number of dispersed sources into public electricity networks [1]. However, one of the biggest drawbacks to RES, particularly wind- or solar-generated electricity is that it is an intermittent and a variable source of power [2]. Further research on developments in sustainable energy, mainly related to the enhanced use of RES, is summarized by [3 – 5]. Authors in [6] provide an understanding of the recent distributed photovoltaic systems policy progress and insights for policy makers in other economies that are experimenting distributed photovoltaic systems power policies. Photovoltaic systems as power generation units using RES represent the largest share of dispersed sources. Photovoltaic systems are most often connected to the distribution grid (low-voltage network) or the user-end grid. Maribor is the second largest city in Slovenia with over 20,000 buildings, on which more than 100 photovoltaic systems are installed. Fig. 1 shows the location of Slovenia and the location of the city of Maribor (MB 45°33' N, 15°38' E, 278 m).

Figure 1: Location of the city Maribor (MB), Slovenia.

The first step in the analysis of the impact of photovoltaic systems with inverter circuits on a distribution network is the literature review. Despite a thorough search in databases of publications in the fields of photovoltaic systems and distribution network operation, only a few tens among hundreds of reviewed studies were at least partly related to the research field of this paper.
Methodologies described in [7] to [15] deal with harmonic analysis of currents and voltage and the factor of total harmonic distortion (THD), which is defined in standard EN 50160 [16]. Authors in [17] to [19] describe different approaches in three-phase and single-phase inverter circuits. Authors in [20] to [22] describe different systems of tracking maximum power points of photovoltaic systems, which also influence THD.
The novel procedure for determining roof surfaces suitable for their installation is presented in [23] where the photovoltaic potential of roof surfaces is assessed, based on Light Detection And Ranging (LiDAR) data and pyranometer measurements. Also the near-term economic benefits from grid-connected residential photovoltaic systems are presented in [24] and [25].
This research presents a power quality analysis of photovoltaic systems connected to an urban distribution network. The operation of photovoltaic systems can in certain cases influence the power quality in a distribution network. The scope of this impact on the power quality at a connection point was assessed with measurements, performed on photovoltaic systems and on transformer stations. Different cases of photovoltaic system connection to urban distribution network were analysed. Measurements on photovoltaic systems and on transformer stations were then used to show the impact of photovoltaic systems on the power quality according to standard EN 50160 [16].
The presented study first provides an overview of standards in the field of power quality and a description of considered photovoltaic systems. Photovoltaic systems use inverter circuits for their operation, which enable synchronous operation with the distribution network. The so-called network managed inverters, which are a part of the photovoltaic system, have an integrated maximum power point tracking system, a DC/DC converter to ensure appropriate direct current voltage at the inverter input, and a DC/AC inverter. Inverters can be single-phase or three-phase. Three-phase inverters are increasingly being used nowadays, along with the so-called micro inverters, which are also gaining in popularity. The results present the impact of photovoltaic systems with inverters on the power quality in the electric distribution network.
Standards and analysis of power quality are presented in the 2nd section. After that, a description of photovoltaic systems in the case of connection to an urban distribution network is presented in the 3rd section. Analysis of power quality in an urban electric distribution network was performed on four photovoltaic systems in the 4th section. The last section concludes this paper.

2. Standards and analysis of power quality

Technological development is in principle always related to power consumption and therefore also with its quality. Power quality can be considered from a commercial or a technical viewpoint. The commercial viewpoint describes the relation between the supplier and the user. Different internal standards or quality-of-service rules describe this relation, and they vary from country to country. The technical viewpoint focuses especially on power supply continuity and voltage quality. Power supply continuity is assessed with the number and duration of interruptions in supply voltage. In other words, indexes such as SAIFI (System Average Interruption Frequency Index) and SAIDI (System Average Interruption Duration Index) are used. Voltage quality is described in standard EN 50160 [16]. This standard defines thirteen parameters related to voltage waveform. These are: power frequency, voltage magnitude, voltage magnitude variations, rapid voltage changes, supply voltage dips, short interruptions of supply voltage, long interruptions of supply voltage, temporary power frequency overvoltages, transient overvoltages, supply voltage unbalance, harmonic voltage, interharmonic voltage, and main signalling voltage.

The amplitudes of high harmonic components in voltage and current cause additional losses in the network, therefore they are limited according to standards EN 50160 and IEC 61727 [26]. This study focuses mostly on the analysis of harmonic voltage, which under normal operating conditions has to be in any week 95% of all 10-minute mean effective values of individual harmonic voltages equal to or lower than the values in standard EN 50160. In terms of voltage, it is also required that the total harmonic distortion (THD) factor, considering the basic harmonic and harmonics up to order 40, is smaller than or equal to 8%. The maximum allowed values of the total harmonic distortion factor are according to standard IEC 61727 2% for voltage and 5% for current at the maximum converter power. Both factors of total harmonic distortion are determined considering the basic harmonic component and 40 harmonic components of higher order. The power factor should be at least 0.9 during operation at 50% of the nominal inverter capacity.

It needs to be emphasized that the most important standards in the fields of quality measurements and analysis are EN 50160: Voltage Characteristics in Public Distribution Systems and IEC 61000-4-30: Testing and measurements techniques - Power quality measurement methods [27].

Photovoltaic systems or inverters must meet the criteria defined in power quality standards. Photovoltaic systems must not cause flickers, as defined by standard IEC 61000-3-3 [28] for systems with current under16A, and IEC TS 61000-3-5 [29] for systems with current above 16A.

When the values of output voltage $U_{\mathrm{k\,AC}}$ (1), output current $I_{\mathrm{k\,AC}}$ (2) and active output power $P_{\mathrm{k\,AC}}$ (3) are obtained, the power factor *PF*, for each phase separately and the total power factor *PF* can be calculated with (4) and (5):

$$U_{k\,AC} = \sqrt{\frac{1}{N}\sum_{j=1}^{N} u_{k\,AC}^{2}(j)} \quad \text{and} \quad U_{AC}^{2} = U_{a\,AC}^{2} + U_{b\,AC}^{2} + U_{c\,AC}^{2} \tag{1}$$

$$I_{k\,AC} = \sqrt{\frac{1}{N}\sum_{j=1}^{N} i_{k\,AC}^{2}(j)} \quad \text{and} \quad I_{AC}^{2} = I_{a\,AC}^{2} + I_{b\,AC}^{2} + I_{c\,AC}^{2} \tag{2}$$

$$P_{k\,AC} = \frac{1}{N}\sum_{j=1}^{N} u_{k\,AC}(j)\, i_{k\,AC}(j) \qquad \text{and} \qquad P_{AC} = P_{a\,AC} + P_{\mathrm{b}\,AC} + P_{c\,AC} \tag{3}$$

where $k \in$ {phase a, phase b, and phase c}, N is the number of simples while j denotes the sample.

$$PF_k = \frac{P_{k\,AC}}{U_{k\,AC}\, I_{k\,AC}} \qquad k \in \{\text{a, b in c}\} \tag{4}$$

$$PF = \frac{P_{AC}}{U_{AC}\, I_{AC}} \tag{5}$$

The photovoltaic system efficiency is the ratio of the output power of system P_{AC} (W) to the irradiance G (W/m^2) and surface area (m^2). Using the measured data, the efficiency of photovoltaic system η_{PV} can be calculated according to (6):

$$\eta_{\mathrm{PV}} = \frac{P_{AC}}{G \cdot \mathrm{Area}} \tag{6}$$

The root mean square (RMS) values of individual harmonic components are determined with Fourier analysis. They are used to determine THD for inverters' output voltages and currents. The output voltage THD_U and the output current THD_I are determined with (7) and (8):

$$THD_{Uk\,AC} = \sqrt{\frac{\sum_{h=2}^{40} U_{k\,hAC}^2}{U_{k\,1AC}^2}} \qquad k \in \{\text{a, b in c}\} \tag{7}$$

$$THD_{Ik\,AC} = \sqrt{\frac{\sum_{h=2}^{40} I_{k\,hAC}^2}{I_{k\,1AC}^2}} \qquad k \in \{\text{a, b in c}\} \tag{8}$$

where h is individual higher harmonic component.

3. Considered photovoltaic systems in urban distribution network system

A description of considered photovoltaic systems in case of connection to an urban electric distribution network is provided below. Analysis of power quality in an urban electric distribution network was performed on four photovoltaic systems, connected at two transformer stations (TS1 and TS2), as shown in Fig. 2 and 3. In order to protect personal data of photovoltaic systems owners, photovoltaic systems are marked with serial numbers from PV1 to PV4. PV1 marks a photovoltaic system with installed capacity 228 kW, PV2 a photovoltaic system with installed capacity 45 kW, PV3 a photovoltaic system with installed capacity 45 kW, and PV4 a photovoltaic system with installed capacity 49 kW. All considered photovoltaic systems, from PV1 to PV4, have installed polycrystalline silicon (p-Si) modules. Photovoltaic systems were connected to the distribution network in 2010. For a better overview, the data of photovoltaic systems are presented in Table 1.

Figure 2: Discussed area with installed photovoltaic systems.

Figure 3: Discussed low voltage network with installed photovoltaic systems.

Table 1: Discussed photovoltaic systems in an urban distribution network system.

Measurements were performed on the abovementioned photovoltaic systems and transformer stations in a period of one week (7 days), as defined in standard EN 50160. Power quality measurements of photovoltaic systems PV1, PV2, PV3 and PV4 were performed in March 2015 to demonstrate the impact of photovoltaic systems on power quality when photovoltaic systems operate with lower capacity (up to 50 % of nominal peak capacity).

4. Results

Results obtained with tests and power quality analysis performed on four photovoltaic systems and transformer stations (TS1 and TS2) are presented in Fig. 4 to 8. Fig. 4, 5, 7, and 8 show results as functions of output power P_{AC}. Fig. 4 and 5 shows RMS values of output AC voltage U_{AC} and current I_{AC} of PV1 – PV4, TS1 and TS2. Fig. 6 shows active output power P_{AC} of PV1 – PV4, TS1 and TS2, given as functions of time t.

Figure 4: RMS value of output voltage U_{AC}, measured during tests, given as a function of output power P_{AC}.

Figure 5: RMS value of output current I_{AC}, measured during tests, given as a function of output power P_{AC}.

Figure 6: Output power P_{AC}, measured during tests, given as a function of time (day).

Fig. 7 and 8 show voltage and current THD marked as THD_U and THD_I. Fig. 7 and 8 show THDs determined for fundamental frequency 50 Hz and 40 higher order harmonic components.

Figure 7: Voltage THD for fundamental frequency 50Hz and 40 higher order harmonic components, given as a function of output power P_{AC}.

Figure 8: Current THD for fundamental frequency 50Hz and 40 higher order harmonic components, given as a function of output power P_{AC}.

Fig. 9 shows power factor PF given as a function of output power P_{AC}.

Figure 9: Power factor PF measured during tests, given as a function of output power P_{AC}.

As shown in [30], the energy potential of an urban environment can be assessed based on airborne LiDAR (Light Detection And Ranging) scans. LiDAR is an active remote sensing technology, where laser from an aircraft scans the surface from which a 3D model can be generated. To correctly assess the energy potential of the considered roof surfaces (PV1, PV2, PV3 and PV4), a comparison of measured values of power generated by photovoltaic systems, and values simulated with the method described in [30], was first performed. Figure 10 shows the estimated photovoltaic potential based on LiDAR data for the considered location. The simulation was carried out by considering nonlinear efficiency characteristic of p-Si modules. Table 2 shows that the difference between the measured and calculated values of generated power of PV systems is less than 10 %. The error can be partially assigned to the fact that calculated values do not take into account the possibility of modules being covered in snow in the winter, while also the 3D slopes and aspect data can be prone to errors due to lower LiDAR data resolution. Results are nevertheless satisfactory and can be used for further analysis of possible installation and optimisation of power generation with PV systems in an urban environment. The abovementioned results can serve to rationally plan the development of a distribution network with minimum distortion of power quality.

Table 2: Generated power of PV systems in the period from 11th March 2015, 12:30 to 18th March 2015 14:00.

Figure 10: Estimated photovoltaic potential of the PV1, PV2, PV3, and PV4 systems.

5 Conclusions

The aim of this work is to present the analysis of the impact of photovoltaic systems connection to public distribution networks according to standard EN 50160, which describes the voltage characteristics in public distribution systems. Analysis of power quality was performed on four photovoltaic systems and two transformer stations where these photovoltaic systems are connected.

The analysis of the given example shows that the inclusion of dispersed sources into an urban electric distribution network with relatively low short-circuit power could compromise voltage quality according to standard EN 50160, in the sense of meeting harmonic distortion requirements, particularly in the case of operation with low output power. That is, low short-circuit impedance is related to larger voltage drops, caused on network elements and indirectly on short-circuit impedance by subharmonic and high harmonic current components. The latter are generated by inverter systems of photovoltaic systems, especially at lower output power, as shown by the analysis in this paper. This is especially true if there is a possibility of mutual impacts of several independently operating photovoltaic systems connected to the same DTS buss.

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Figure 1:

Figure 1: Location of the city Maribor (MB), Slovenia.

Figure 2:

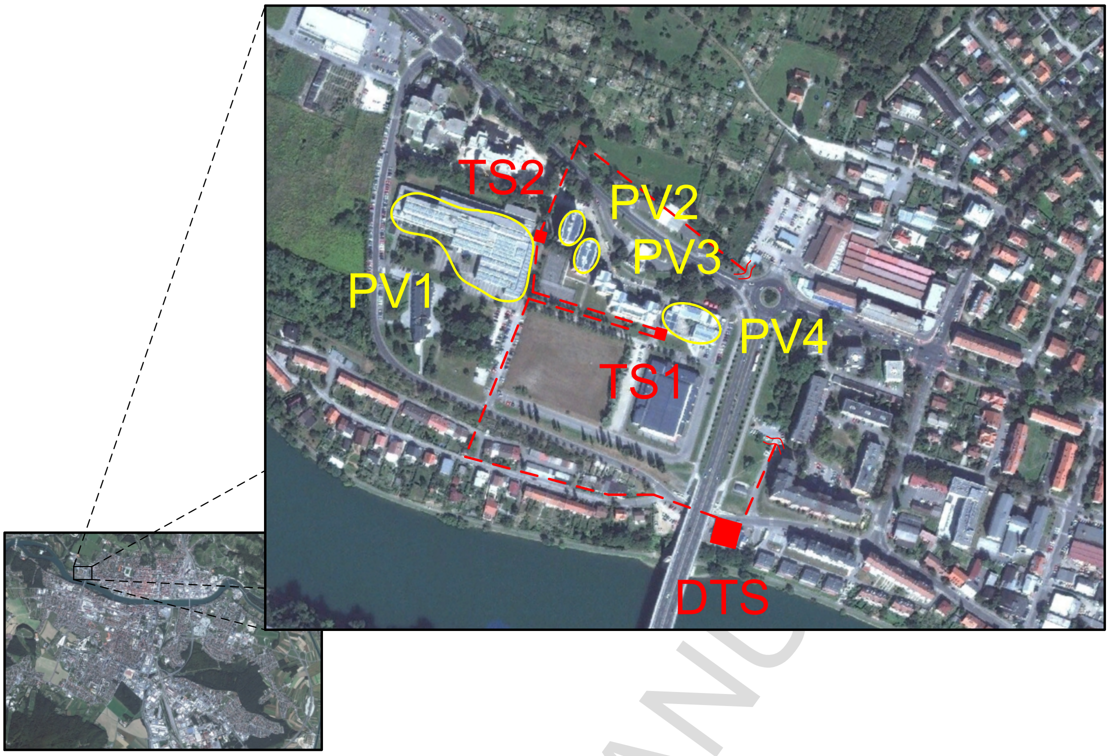

Figure 2: Discussed area with installed photovoltaic systems.

Figure 3:

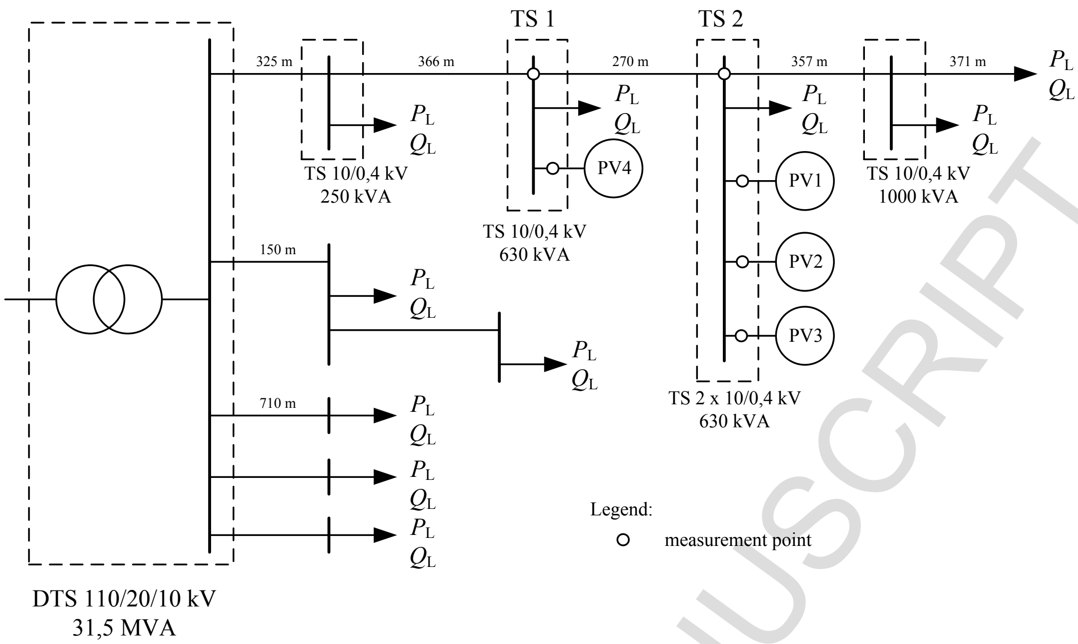

Figure 3: Discussed low voltage network with installed photovoltaic systems.

Figure 4:

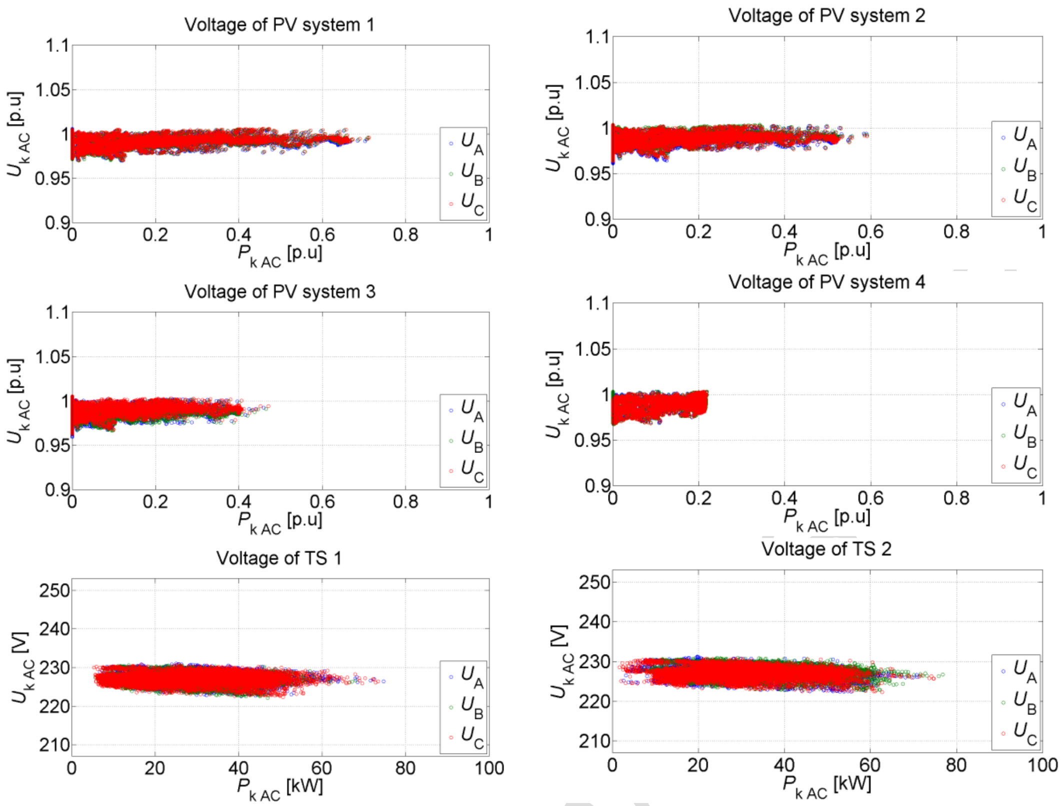

Figure 4: RMS value of output voltage U_{AC}, measured during tests, given as a function of output power P_{AC}.

Figure 5:

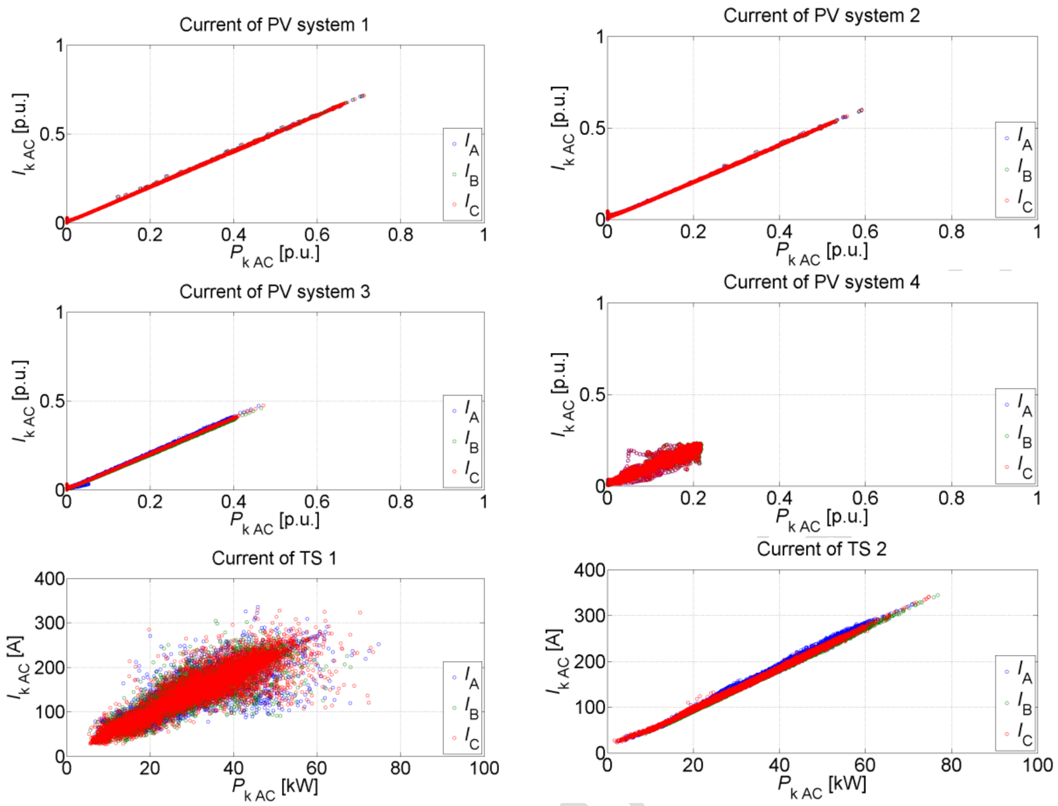

Figure 5: RMS value of output current I_{AC}, measured during tests, given as a function of output power P_{AC}.

Figure 6:

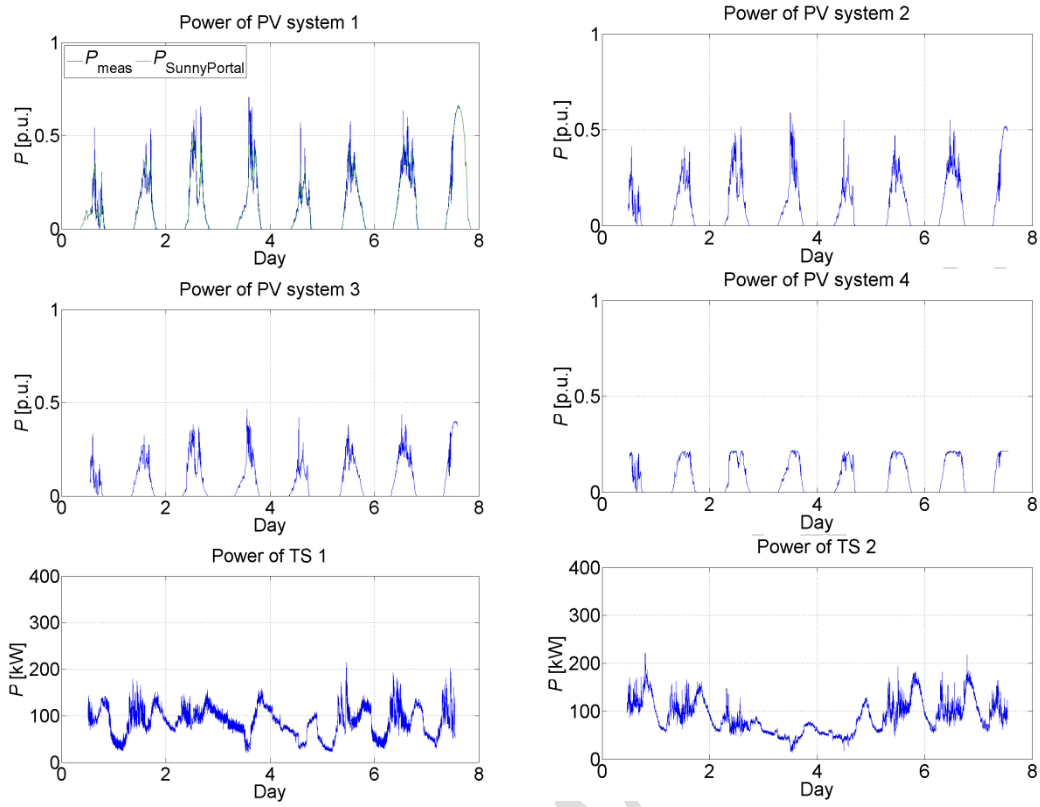

Figure 6: Output power P_{AC}, measured during tests, given as a function of time (day).

Figure 7:

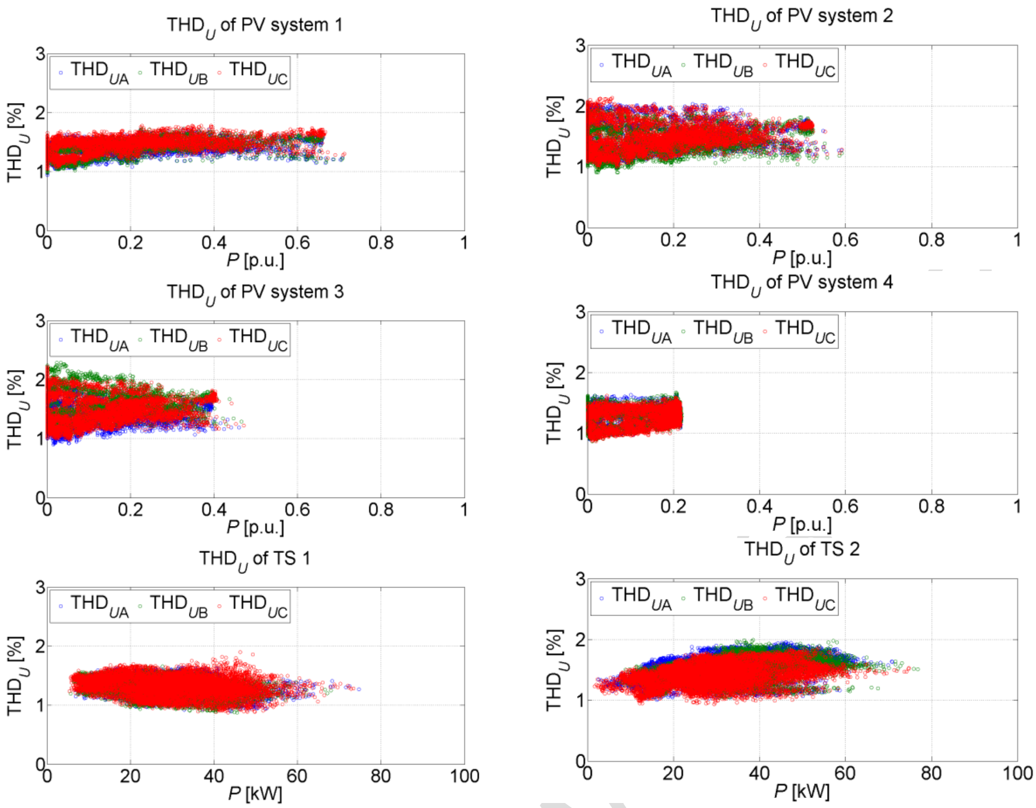

Figure 7: Voltage THD for fundamental frequency 50Hz and 40 higher order harmonic components, given as a function of output power P_{AC}.

Figure 8:

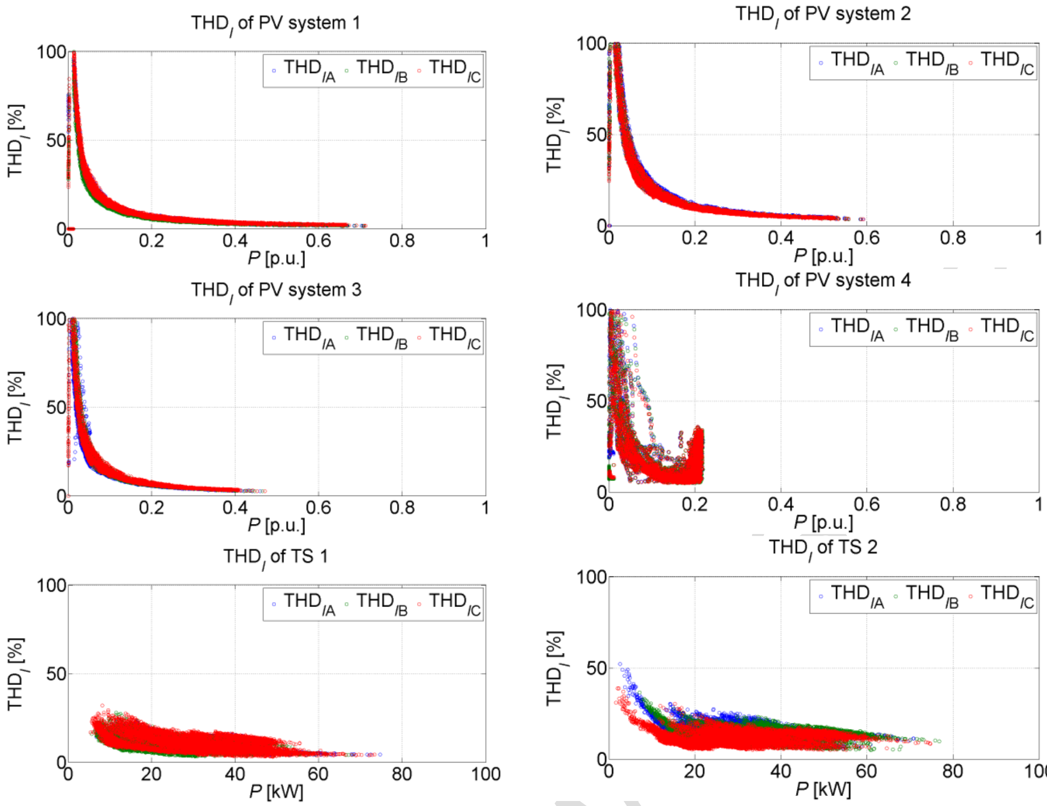

Figure 8: Current THD for fundamental frequency 50Hz and 40 higher order harmonic components, given as a function of output power P_{AC}.

Figure 9:

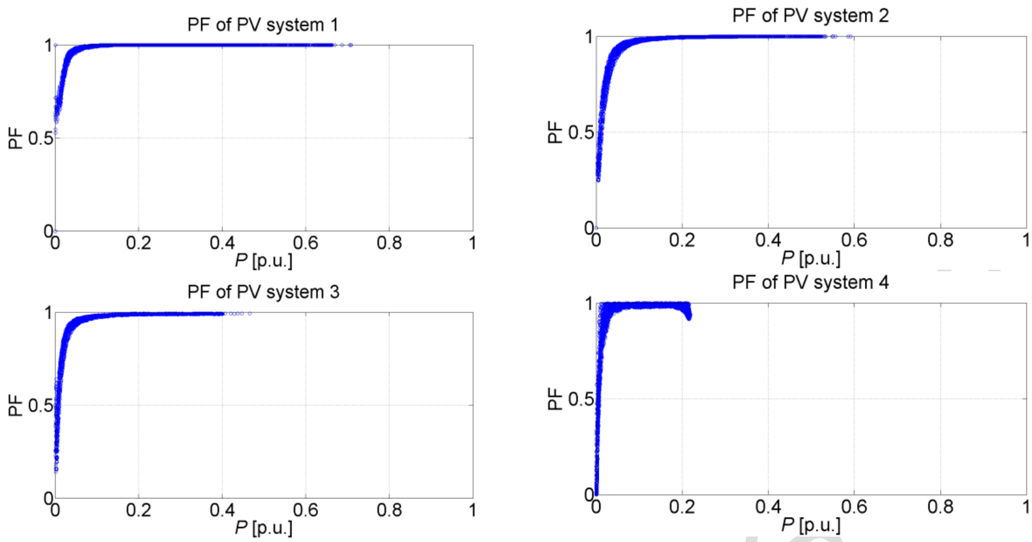

Figure 9: Power factor *PF* measured during tests, given as a function of output power P_{AC}.

Figure 10:

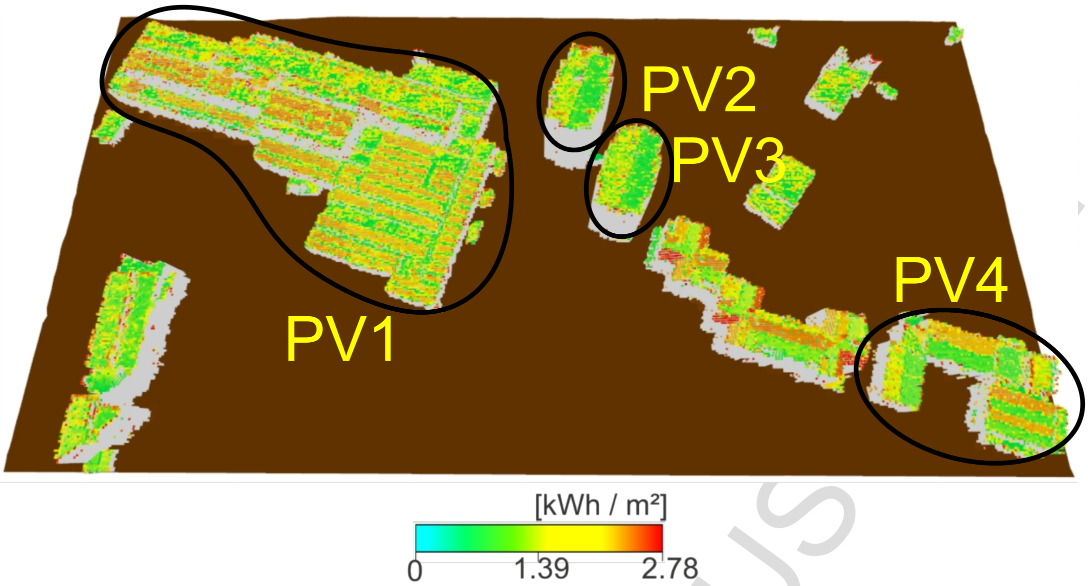

Figure 10: Estimated photovoltaic potential of the PV1, PV2, PV3, and PV4 systems.

Table 1:

Table 1: Discussed photovoltaic systems in an urban distribution network system.

Photovoltaic system	***Peak power* [kWp]**	***Year***	***Photovoltaic modules***	***Inverter***
PV1	228	2010	924 x BMU-215-2/233 (p-Si)	5 x Sunny Tripower 15000TL-10 9 x Sunny Tripower 17000TL-10
PV2	45	2010	168 x BMU-215-2/233 (p-Si)	3 x Sunny Tripower 15000TL-10
PV3	45	2010	168 x BMU-215-2/233 (p-Si)	3 x Sunny Tripower 15000TL-10
PV4	49	2010	210 x BMU-215-2/233 (p-Si)	1 x Sunny Tripower 15000TL-10 2 x Sunny Tripower 17000TL-10

Table 2:

Table 2: Generated power of PV systems in the period from 11th March 2015, 12:30 to 18th March 2015 14:00.

Photovoltaic system	**W_m (kWh) - measured**	**W_L (kWh) - Lidar**	**$(W_L - W_m/W_L)$*100 (%)**
PV1	3661.29	3884.37	6.1
PV2	565.15	598.051	5.8
PV3	588.27	625.615	6.2
PV4	526.22	574.745	9.1