Distributed Generation and Its Impact on Power Quality in Low-Voltage Distribution Networks

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Additional information is available at the end of the chapter

Abstract

This chapter is dedicated to review and investigate present approaches to power quality assessment in low-voltage (LV) networks with distributed generation (DG). Two complementary approaches are considered: firstly, origin of the emission limits requirement for the DG is searched in general electromagnetic compatibility (EMC) conditions used for the equipment and adopted to DG; secondly, rules and regulation of integration with a power system network is used in order to estimate the possible influence of DG on power quality in point of common coupling (PCC). An example of the regulation is control of reactive power consumption in function of active power generation known as $\cos\varphi$ (P) characteristic. **This chapter constitutes the attitude that complementary approach brings improvement to the decision about the possible impact of DG in a power system network.** It was shown that a combined approach allows to define a proposition of the limits of particular power quality parameters associated with the investigated node of LV network characterized by apparent short circuit power in the PCC (S_{kPCC}). This combination brings desirable effect of criterion, making for integration of DG with LV networks. Mentioned attitude was investigated using a real case study of a photovoltaic (PV) system consisting of three independent one-phase subsystems. Estimated influence of the investigated PV on power quality parameters in the PCC was verified using real measurement. The measurement procedure allows to verify the real influence of the investigate DG on power quality in the PCC, however, the task in not easy due to problems of separation of the searched influence from the measurement background. One of the proposed approach is to affiliate changes of investigated power quality parameters with activities of the investigated DG, e.g., energy production. As it was presented in the case of influence of the investigated PV static voltage changes or total harmonic distortion in current in the PCC, a correlation index can be also implemented in order to classify the force of the common influence.

Keywords: Power quality, distributed generation, distribution network, connection criteria

1. Introduction

Distributed generation (DG, dispersed generation, distributed resources or DR, embedded generation or EG) is currently one of the most actively-developed energy sector, mainly for the reason of environmental energy technologies and the idea of smart power grids. While this is not a new concept, there is still a lack of unified definition that explicitly allows the classification of DG [1, 11,13,14,16, 22, 42]. The main issue is the acceptance criterion, which can be both the capacity of the installed power, the point of connection to the transmission or distribution system or subject to the disposal of the central power regulations, and finally the type of technology. One of the most frequently quoted definition is based on the report of the Working Group 37.23 CIGRE (Council on Large Electric Systems) [14], at present the committee SC C6, which suggests to treat as distributed generation all generation units independent from central regulation and to introduce a capacity of power limit of 50–100 MW. For comparison, the limit in the power of distributed generation in the United Kingdom is set at 100 MW, in the United States 50 MW, New Zealand 5 MW, and 1.5 MW in Sweden. Recent work on distributed generation CIGRE run by the Study Committee SC6 Distribution Systems & Dispersed Generation proposed to minimize the definition of DG to a connection to the distribution network without central regulation. Additionally, some subdivisions of DG related to power capacity can be also found in the literature including: microgeneation (1 W÷5 kW), small generation (5 kW÷5 MW), medium generation (5 MW÷50 MW), and large generation (50 MW÷150 MW).

Since the last quarter century a significant growth of DG, also recognized as dispersed generation or distributed energy resources (DER), was indicated in electrical power systems (EPS). The mentioned process is strongly supported by global convention of pollution reduction and promotion of environment-friendly technologies. The natural consequence is an increasing contribution of renewable energy sources (RES) and combined heat and power (CHP) systems. Additionally, special mechanisms concerning deregulations in energy markets and purchase tariffs were developed in many countries. In parallel to the mentioned convention, a progress in generation technologies is observed that indicates economic benefit in distributed generation investments.

Such convention has given rise to new challenging concepts for future power system architectures, giving a significant position to smart power grids (SPG). Here, ideas are revealed for using DG in islanding scenarios, fault-ride-through (FRT) concepts, voltage stability, and virtual power plants (VPP). DG is also inseparably linked with interoperability concepts, communication protocols, and control and regulation procedures. These mentioned concepts becomes significant when the scale of DG contribution is expanded and when location of the DG is related to parts of power systems characterized by a weak level of reliability. Such scenario can be especially used for ideas for many prosumers connected to LV distribution networks.

Besides the global growth of DG in power systems and new smart grids concepts, several issues have been consequently discussed and investigated for years. These issues do not stay in opposition to the common concepts but try to reveal answers for crucial techical problems

about the integration of DG with EPS. One of the issues raised is the impact of DG on power quality (PQ). A wide discussion can be found in [2, 7, 10, 11, 14, 15, 17, 19, 20, 21, 22, 24].

In the general discussion of PQ and DG in distribution networks, we can distinguish two approaches:

a. "pro-prosumer", which can be represented by the discussable convention "feed and forget";

b. "pro-operator", which is associated with responsibility for control, regulation, stability, and maintenance of grid codes standards.

The aim of this work is to compare the mentioned approaches and reveal significant relations between regulations applied in LV DG systems and its effect on power quality. One of the crucial examples is the standard characteristics $\cos\varphi$ (P) of power factor in relation to the levels of generated active power. Another example is the effect of rapid switching operation executed in DG or the contribution of DG in waveform distortion.

In order to reveal the aim of the work, a case study of power quality investigation in real photovoltaic (PV) system, connected to LV power systems is presented.

Contents of the work is based on:

a. introduction of power quality as a part of electromagnetic compatibility (EMC)

b. actual discussion about EMC standards related to LV DG, including classical EMC IEC 61000 standard family [31]÷[34] consisting of emission limits for LV equipment, technical report IEC/TR 61000-3-15 [35] considering assessment of low frequency electromagnetic immunity and emission requirements for dispersed generation systems in LV network,

c. actual discussion about connection criteria related to LV DG represented by VDE-AR-N 4105 [43], IEEE Std. 929 [40] and 1547 [42], CIGRE criterion rapport [13, 14], which represents technical requirements for the connection and parallel operation with LV distribution networks,

d. description of regulations of LV DG based on predefined curve exhibits relation between active power (P) and reactive power (Q), which is also known as $\cos\varphi$(P) characteristic,

e. association of power quality indices with connection criteria of DG used by distribution system operators (DSO),

f. definitions of statistics and correlation tools proposed as supporting tools in the assessment of the influence of DG on power quality,

g. real case study of power quality measurement and assessment in LV PVs with special consideration to reveal the effect of DG on power quality,

h. summary concerning the contrast between present power quality requirements used for DG systems and the possible real contributions of DG in power quality issues,

i. summary concerning statistics and correlation tools as supporting indices applied in the assessment of the influence of DG on power quality,

j.   discussion about the possible effect of the scale of DG contribution in LV networks in relation to the present connection criteria.

2. Power quality issues in the integration process of distributed generation with electrical networks

At present, there is a broad discussion on the development of regulatory provisions in relation to the connection criteria and terms of cooperation of LV DGs with distribution electrical networks. An example of the efforts is the intensive work on the draft standards including the methodology for evaluating the possibility of connecting small generations to LV system. Existing projects of VDE-AR-N-4105 [43] or IEC/TR 61000-3-15 [35], as well as IEEE Standards 929 [40] and 1547 [42] are worth mentioning.

The influence of the source on the power grid depends on several elements:

a.   conditions at the connection point defined by the short-circuit power at the PCC (S_{kPCC}),

b.   nominal parameters and regulation characteristics of the DG source,

c.   compatibility features of the DG.

The influence of the connection of the source on LV power system may be assessed on the basis of the known power quality indicators. The list of considered parameters followed by their definitions [4, 5, 8, 9, 12, 18, 23, 26, 28, 38]:

1.   Power frequency, frequency variations (f)

2.   Voltage magnitude variation, slow voltage changes, level of voltage (Δu_a)

3.   Rapid voltage changes (Δu_{max})

4.   Voltage fluctuation, flicker severity (P_{st}, P_{lt})

5.   Voltage unbalanced (asymmetry) (k_{u2})

6.   Voltage harmonics, interhamonics, subharmonics, DC injection

7.   Current harmonics, interhamonics, subharmonics, DC injection

8.   Events

8a. Voltge dips

8b. Short interruptions

8c. Long interruptions

8d. Temporary overvoltages (swells)

8e. Transient overvoltages, oscillatory, impulsive

8f. Commutation notches (d_{kom})

9.   Mains signaling, audio-frequency centralized ripple-control

2.1. "Pro-prosumer" approach" — Feed and forget, unconditional connection

The "pro-prosumer" approach is related to unconditional connection criteria used in the electromagnetic compatibility emission limit references. Generally, the idea is to connect small- and microgeneration to LV distribution networks on the condition that the classical defini- tion of IEC EMC emission limits is passed during standard laboratory tests and the generation equipment have obtained specific certifications. That means that selected emission limits, as well as methods of measurement for particular power quality parameters, should be defined also for LV DG technologies. In practice, the mentioned approach expresses the direction that LV DG equipment should be treated the same as LV load. Then, classical relation between emission limits, system disturbances level, compatibility level, and equipment immunity levels known from the IEC EMC approach [30] is adapted to the LV DG equipment (Figure 1).

Figure 1. General relations between emission limits, system disturbances level, compatibility level, and equipment im- munity level [30].

Following this approach, new draft standards or technical reports are created in order to define a standardized laboratory setup and test procedures for LV DG. Examples are EN: 50438 [29], IEC / TR 61000-3-15 [35], and VDE-AR-4105 [43]. In order to emphasize the mentioned idea, a laboratory setup for emission and immunity tests for DC-supplied inverters proposed in IEC/ TR 61000-3-15 [35] is illustrated in Figure 2.

After defining the laboratory setup, the next issue is to define the emission limits for the LV DG. Reviewing the proposition of standards [29, 35, 42, 43] allows us to conclude that a group of standards dedicated to emission limits for the equipment is adapted to LV DG. Thus, permissible emission limits of particular power quality disturbances of LV DG are proposed to be the same as for the LV load. An example can be emission limits for harmonic current emissions IEC 61000-3-2 [31] and 3-12 [32], limitation of voltage changes, voltage fluctuations,
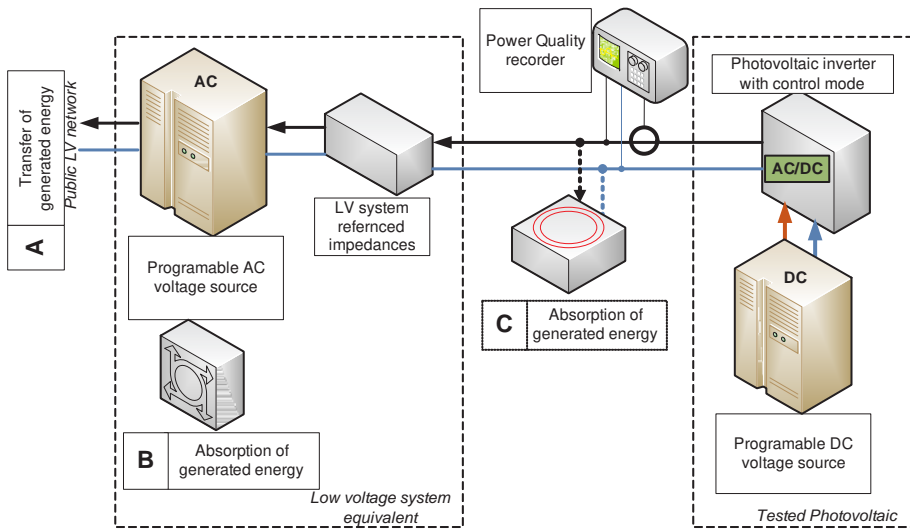
Figure 2. Laboratory setup for emission and immunity tests for DC-supplied inverters IEC/TR 61000-3-15 [35].

and flicker IEC 61000-3-3 [33] and 3-11 [34]. An example of the certification procedure for the DG directly associated with standards dedicated to load in the range of emission limits for voltage changes, voltage fluctuations, and flicker is presented in Figure 3.

Referring to the mentioned EMC approach illustrated in Figure 1, a LV public distribution network constitutes the environment for the load and LV DG. Thus, an LV network is characterized by higher levels of disturbances.

2.2. "Pro-operator approach" – Network support and connection criteria

Distribution system operators (DSOs) are responsible for the reliability of the power system. In case of crucial issues for distributed generation, the role of the DSO is to control the generation unit. During disturbances in the power system, as well as during normal operating conditions, selected issues of regulation are necessary to consider. Particularly, in the steady state condition where the regulation is dedicated to active and reactive power that has a prominent effect on voltage regulation. In transient state, under or overvoltage, as well as under and over frequency regulation is necessary in order to preserve network security management.

2.2.1. Static voltage stability

Due to popular inverter-based methods of integration with power systems, LV DG are able to contribute to static voltage stability using two modes of active (P) and reactive (Q) power control:

a.   work with a fixed power factor cosφ,

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┌─────────────────────────────────┐
│ Algorithm of connection to network referring │
│           to voltage changes            │
└─────────────────────────────────┘
                  │
                  ▼
             ◇ <=16A ◇ ──NO──▶ │ IEC 6100-3-11 │
                  │ YES
                  ▼
        ┌─────────────────────┐
        │    Test with Z_ref      │
        │  Z_ref=(0.4+j0.25)   │
        │    Ref. 61000-3-3    │
        └─────────────────────┘
                  │
                  ▼
            ◇ Positive ◇ ──NO──▶ │ IEC 6100-3-11 │
                  │ YES
                  ▼
        ┌─────────────────────┐
        │   Confirmity with     │
        │    IEC 61000-3-3     │
        └─────────────────────┘
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Test with Z_{ref}

$Z_{ref}=(0.4+j0.25)$

Responsibility of the producer

Responsibility of the user/ Distribution System Operator (DSO)

Direct (unconditional) connection
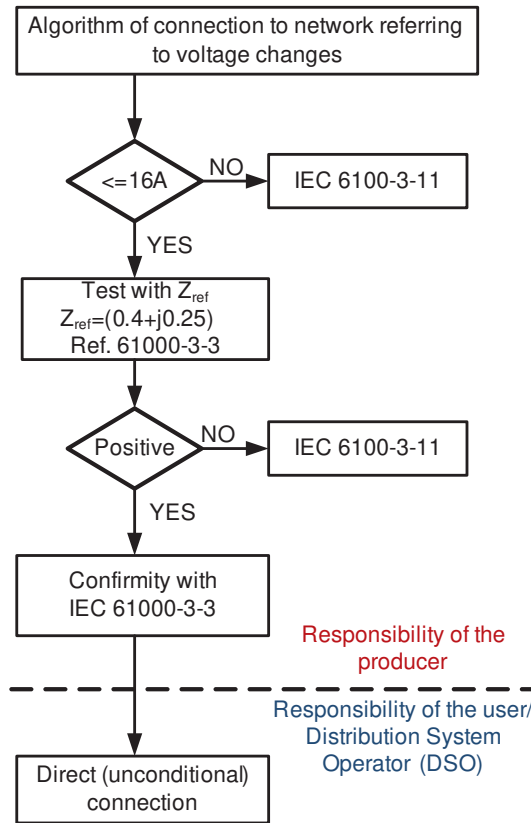
Figure 3. Example of an algorithm for assessment of possible voltage fluctuation and flicker severity applied for the device and LV DG in PCC [33].

b. work with variable power factors depending on the level of generated active power that in practice is realized by the application of defined by the operator characteristics $\cos\varphi(P)$.

In the regime of constant power factor, it is determined that depending on the **maximum apparent power of the generation unit (S_{Emax}),** power factor cannot be less than 0.9 or 0.95. An example can be the approach to force the photovoltaic systems to work with power factor $\cos\varphi$ equals 1. Constant power factor is also used in the case of asynchronous generators directly connected to low voltage using capacitor banks as reactive power control. Synchronous and double-fed asynchronous generators might be involved in the regulation of reactive power in LV distribution networks. Inverterbased power generation units are predisposed for implementation of the **characteristics of power factor depending on the active power production $\cos\varphi$ (P)** [10, 43]. It has to be emphasized that the shape of the characteristic and its crucial coordinates can be defined by DSOs on the basis of power system conditions in the

area of PCC with respect to the maximum apparent power of the generation unit. However, in practice, a standard characteristic $\cos\varphi$ (P) is implemented. The standard $\cos\varphi$ (P) characteristic depends on the maximum apparent of the generation unit (S_{Emax}). Examples of the characteristic are presented in Figure 4 for units with S_{Emax} < 13,8 kVA and Figure 5 for units with S_{EMAX} > 13,8 kVA. Describing the regulation, it can be seen that in up to 20% of the **maximum active power generation of the generation unit P_{EMAX}**, both generation and consumption of reactive power is allowed. In many cases of this range, the generation of active power is realized simultaneously with the generation of reactive power. This mode of work can be treated as work with **induction power factor $\cos\varphi_{ind}$**. In the range of 20% to 50% of P_{EMAX}, only active power generation is recommended. Operating above 50% of P_{EMAX} generation of active power is accompanied by a reactive power consumption that can be treated as a mode with **capacitive power factor $\cos\varphi_{cap}$**. The level of reactive power consumption depends on the size of the generation unit. For units with S_{Emax} < 13,8 kVA the desirable coordinate is **$\cos\varphi_{ap}$ = 0.95** and for units of S_{Emax} > 13,8 kVA it is **$\cos\varphi_{cap}$ = 0.9**. The aim of implementation of reactive power consumption has a significant meaning in the reduction of voltage increase due to high levels of active power generation.
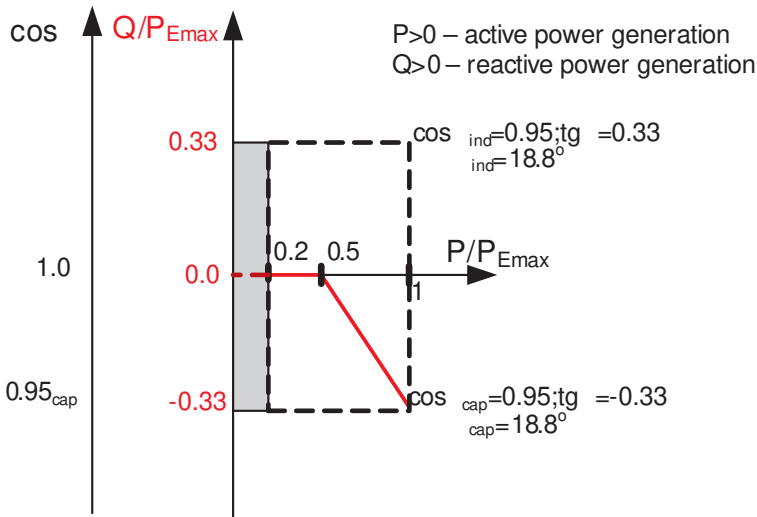
Figure 4. Standard characteristic $\cos\varphi$ (P) for the generation unit within the range of maximum apparent power S_{Emax} from 3,68 kVA to 13,8 kVA.

2.2.2. Active power feed-in at under and over frequency

When studying network security management, few other limitations of power generation units can be introduced. One of the limitations is the reduction of active power generation in selected ranges of over frequency condition known as **frequency regulation characteristic P(f)** [10, 43].
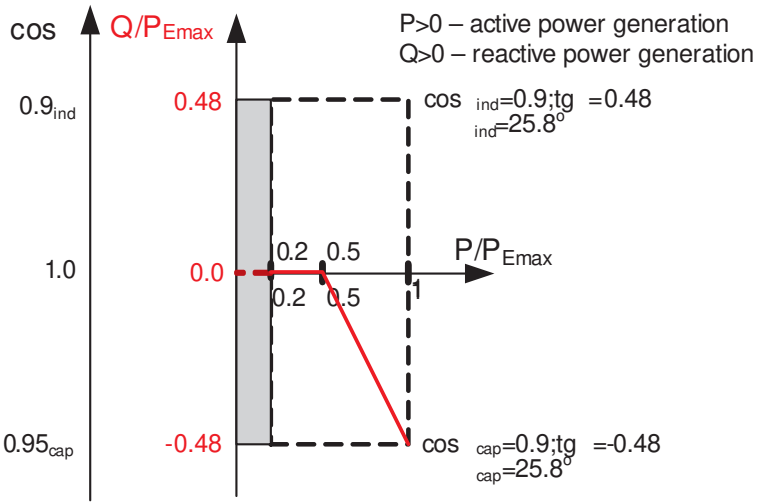
Figure 5. Standard characteristic $\cos\varphi$ (P) for the generation unit within the range of maximum apparent power S_{Emax} of more than 13,8 kVA.

Figure 6 exhibits the idea of the regulation. It is visible that for power system frequency in the range of 50.2Hz to 51.5Hz it is recommended to reduce active power generation from the instantaneous level P_M generated at the time of over frequency detection with gradient 40% of P_M per Herz. At system frequencies higher than 51.5 Hz, the power generation unit shall be disconnected immediately.
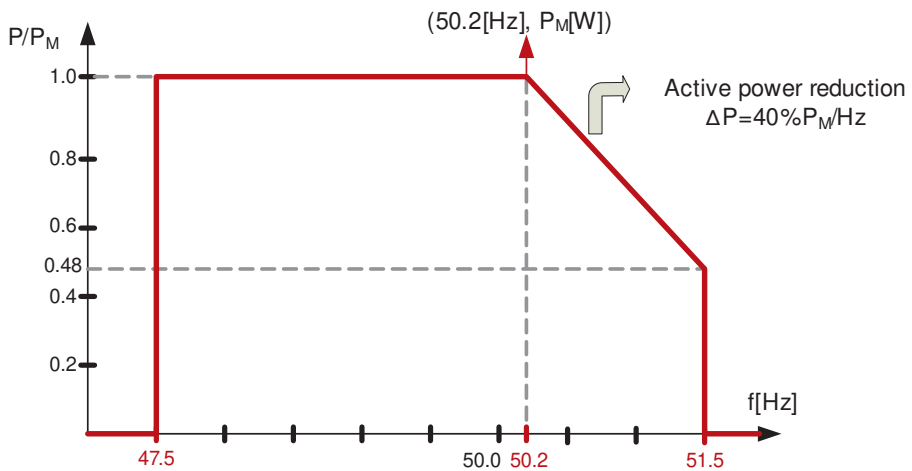
Figure 6. Standard characteristic P(f) for the generation unit.

2.2.3. Disconnection by network protection

The present approach to the disconnection of the DG due to power system protection is dictated by a few selected cases: risk of islanding, risk of overload on the power system network, risk of steady-state and dynamic network stability, rise in mains frequency, and resynchronization of sub-systems. These mentioned aims are realized through under and over voltage protection, as well as under and over frequency protection. In [27], a review of different standards of distributed generation development in several countries was presented. For comparison, the selected settings of the mentioned protection, as well as disconnection time for view in European countries was grouped in Table 1.

Country	U<	U>	f<	f>
Germany	$0.7 \div 1.0 \cdot U_N$; t≤0.2s	$1.0 \div 1.15 \cdot U_N$; t≤0.2s	47Hz; t≤0.2s	52Hz; t≤0.2s
Italy	$0.8 \cdot U_N$; t≤0.2s	$1.2 \cdot U_N$; t≤0.1s	49÷49.7Hz; immediately	50.3÷51Hz; immediately
Spain	$0.85 \cdot U_N$; t≤1.2s	$1.1 \cdot U_N$; t≤0.5s	48Hz; t≤3s	51Hz; t≤0.2s
Belgium	$0.5 \div 0.85 \cdot U_N$; t≤1.5s	$1.06 \cdot U_N$; immediately	49.5Hz; immediately	50.5Hz; immediately

Table 1. Comparison of power system protection settings and disconnection time in selected countries.

2.2.4. Change of the voltage level, slow voltage changes

Changes in voltage at the point of common coupling of the generation unit depends on the **short-circuit power of the upstream network at this node (S_{kPCC})**. Using short circuit calculations, the mentioned S_{kPCC} can be recalculated to short circuit impedance in point of common coupling $Z_{kPCC} = R_{kPCC} + jX_{kPCC}$, where:

$$S_{kPCC} = \frac{U_N^2}{Z_{kPCC}}; \quad Z_{kPCC} = \sqrt{R_{kPCC}^2 + X_{kPCC}^2}; \quad \psi_{kPCC} = \arctan\left(\frac{X_{kPCC}}{R_{kPCC}}\right) \tag{1}$$

Considering the influence of the generation unit with the given maximum apparent power S_{Emax} on voltage change (change of voltage level) in the PCC characterized by given Z_{kPCC}, the regulation of active and reactive power of the DG can be also considered. Referring to characteristics shown in Figure 4 and Figure 5, **static change of voltage level Δu_a** can be determined by generation or consumption of reactive power. When the generation unit delivers feed-in active and reactive power the change of voltage level can be expressed as:

$$\Delta u_a = \frac{S_{Emax}\left(R_{kPCC}cos\left(\varphi_{ind}\right) + X_{kPCC}sin\left(\varphi_{ind}\right)\right)}{U_N^2}100\% \tag{2}$$

For generation-only active power, the change of voltage level comes only from active power:

$$\Delta u_a = \frac{S_{Emax}(R_{kPCC})}{U_N^2}100\%$$

(3)

When the active power cross 50% of P_{EMAX}, then the regulation introduces consumption of reactive power. It means correction in influence of DG on voltage level in PCC as:

$$\Delta u_a = \frac{S_{Emax}\left(R_{kPCC}cos\left(\varphi_{cap}\right) - X_{kPCC}sin\left(\varphi_{cap}\right)\right)}{U_N^2}100\%$$

(4)

Revision of references [13, 27, 33, 34] allows to constitute the permissible limit for voltage level change in the PCC caused by the connection of DG should be not higher than 3%:

$$\Delta u_a \leq 3\%$$

(5)

It should be added that the influence of many DG sources installed in the LV network on the voltage level in particular nodes of the network can be approximated using the superposition technique. For comparison to requirements dedicated to LV public network a permissible voltage level is 10%.

2.2.5. Rapid voltage changes

Rapid voltage changes Δu_{max} at the connection point of generation unit can be caused by switching operations. It is possible to estimate the impact of the operating condition of the generation unit on sudden voltage change at the connection point PCC using the formula:

$$\Delta u_{max} = k\frac{S_{E max}}{S_{kPCC}}100\% = k \cdot \frac{1}{R_k}100\%$$

(6)

$$k = \frac{I_{aE}}{I_{rE}}; \quad R_k = \frac{S_{kPCC}}{S_{E max}}$$

(7)

where: S_{kPCC} - short-circuit power at PCC of the generation unit, S_{Emax} – maximum apparent power of the generation units, I_{aE} – start inrush current of generation unit, I_{rE} - rated continuous output current of generation unit, k – start coefficient, R_k – short circuit power coefficient.

If the coefficient k is not determined on the basis of accurate data generation unit, it can be assumed using the reference values:

a. k = 1.2 – generation units being connected through an inverter, for example, photovoltaic systems

b. k = 1.2 – for synchronous generators

c. k = 4 – asynchronous generators connected to the network after reaching 95 ÷ 105% of the synchronous speed

d. k = 8 – asynchronous generators

Short circuit power coefficient R_k is used in the test of the emission limits in the EMC standard [32, 34]. In the mentioned documents, it is assumed that every tests are performed in the condition that R_k is not less than 33.3. Taking into consideration the value 33.3 of R_k and assuming start coefficient k = 1, it is possible to estimate the influence of the switching condition of the generation unit on rapid voltage changes on the level of 3%. The start of different generation sources using asynchronous generation where k = 8 in the same node, R_k = 33.3 will cause a rapid voltage change 8 time deeper, e.g., on the level of 24%.

The revision of references [13, 27, 33, 34] allows to constitute that the DG unit in normal operation conditions should not generate rapid voltage changes exceeding 3% of the nominal voltage U_N:

$$\Delta u_{max} \leq 3\% \tag{8}$$

The value cannot occur more than once every 10 minutes.

2.2.6. Voltage fluctuation

The technical parameters used in the evaluation of **voltage fluctuation are long-term (P_{lt}) and short-term (P_{st}) flicker severity indices**. Investigation of voltage fluctuation emission is carried out, referring to the same standards as investigation of rapid voltage changes [33, 34]. Thus, connection criteria of considered sources at given PCCs may also corresponds to the R_{kPCC} parameter as in case of rapid voltage changes. Revision of references [13, 27, 33, 44] allows to constitute permissible level of (P_{lt}) and short-term (P_{st}) as:

$$P_{lt} \leq 0.65; \quad P_{st} < 1 \tag{9}$$

It is worth mentioning that additionally, in [43] there is a recommendation that together all power generation units in LV networks shall not exceed P_{lt} = 0.5 at the most unfavorable PCC. This condition seems to be hard to revise in practice. Requirements for the measurement of P_{lt} and P_{st} follow a standard [37].

2.2.7. Voltage asymmetry

The unbalanced distribution of single-phase distribution generation units can become a source of negative sequence currents and voltage asymmetry. The asymmetry is depicted by changing

the effective values of voltages or phase angles with respect to the symmetric arrangement of three-phase vectors. Voltage asymmetry can be expressed by the **voltage asymmetry index k_{u2}** calculated as the ratio of negative sequence component U_2 to positive sequence U_1:

$$k_{u2} = \frac{U_2}{U_1} \cdot 100\% \tag{10}$$

Additionally, in [43] there is a recommendation that the asymmetry caused by connecting single-phase DG can be practicaly evaluated by the ratio of the power of the connected single-phase generation S_{1Emax} to the short-circuit power at the PCC S_{kPCC}:

$$k_{u2} = \frac{U_2}{U_1} \approx \frac{S_{1E\max}}{S_{kPCC}} \tag{11}$$

In [43], another practical requirement is proposed that connecting principle should be a symmetrical three-phase source or if at a given point, several one-phase generation units are considered, then the maximum permissible difference between individual phases should not be more than 4,6 kVA.

2.2.8. Current harmonics, interharmonics, and DC injection

The first approach corresponds to limits of harmonics in the current recommended for load in the EMC standards [31] and [32]. Examples of the limits for the rated current range to 16 A are presented in Table 2. If the limits are not preserved for the considered DG, then similar to rapid voltage changes and voltage fluctuation approach, a recalculation of the requirements is allowed using short-circuit power in investigated PCC S_{kPCC}. In [43], acceptable limits for a particular **current harmonic are expressed in A/MVA of S_{kPCC} denoted as i_{vzul}**. Absolute limits in Ampers I_{vzul} can be recalculated using S_{kPCC} by following fomula:

$$i_{vzul} = \frac{I_{vzul}}{S_{kPCC}} \rightarrow I_{vzul} = i_{vzul} \cdot S_{kPCC} \tag{12}$$

Table 3 consists of permissible current harmonics related to S_{kPCC}. It should be noted that higher levels of S_{kPCC} correspond to higher levels of coefficient R_k, which is used in the EMC standards. For the EMC, the typical R_k is 33.3. For a "stonger network", higher levels of S_{kPCC} are intro-duced and the relation to the considered S_{Emax} increases that finally reveals as higher levels of R_k. For higher levels of R_k, higher levels of current harmonics emission can be allowed.

The requirements for harmonic measurement method should follow the standard [36].

Additionally, revising [29, 40] constitutes that **inverter-based systems should not inject DC current I_{DC}** > 0.5% of the rated inverter output current I_{rE}.

$$\frac{I_{DC}}{I_{rE}} < 0.5\% \tag{13}$$

where: I_{rE} – rated continuous output current of generation unit.

The difference of current DC injection can be caused by different kinds of applied PV technologies and inverters [6, 25]. Generally, higher levels of DC injection are related to transformerless inverters. Application of inverters with a transformer gives the possibility of a better separation of AC from DC.

The methods of measurement and parameterization is discussed in standards [36, 39, 41, 42].

Harmonic order n	Permissible current harmonics [A]
Odd harmonics	
3	2,30
5	1,14
7	0,77
9	0,40
11	0,33
13	0,21
$15 \leq n \leq 39$	$0,15 \cdot \frac{15}{n}$
Even harmonics	
2	1,08
4	0,43
6	0,30
$8 \leq n \leq 40$	$0,23 \cdot \frac{8}{n}$

Table 2. Limits for harmonic current emission for distributed generation units within the range of current up to 16 A that corresponds to limits for class A equipment [31] (for R_k=33.3).

Order of harmonic (v – harmonics, μ - interharmonics),	Permissible harmonic current emission related to S_{kPCC} i_{vzul} [A/MVA]
Odd harmonics	
3	3
5	1,5
7	1

Order of harmonic (ν – harmonics, μ - interharmonics),	Permissible harmonic current emission related to S_{kPCC} i_{vzul} [A/MVA]
9	0,7
11	0,5
13	0,4
17	0,3
19	0,25
23	0,2
25	0,15
25< v <40	0,15-25/v
Even harmonics	
v,μ<40	1,5/ v
42<v,μ<178	4,5/ v

Table 3. Limits for harmonic current emission related to short-circuit power in PCC S_{kPCC} [43].

2.2.9. Voltage harmonics, interharmonics, and DC component

There are no requirements for permissible voltage wave distortion of the DG. The assumption is that generation realizes good quality of voltage sinusoidal form. It is a similar approach used in the equipment that influence of the device on voltage shape distortion is controlled by limitation of current harmonics. It can be concluded that voltage represents environment and current the unit, load or generation equipments.

2.2.10. Commutation notches

Commutation notches in DG systems are disturbances typical for inverter-based integration. **The disturbances can be expressed by index d_{com}** representing the relative depth of the collapse of voltage made by line-commutated converters:

$$d_{com} = \frac{\Delta U_{com}}{U_N}$$
(14)

where: ΔU_{com} depth breakdown in [V], U_N phase to phase voltage nominal voltage

The [43] provides acceptable limits for d_{com} not more than 5%.

2.2.11. Mains signaling, audio-frequency centralized ripple-control

Transmission of control signals used by the system operator is usually in the range of frequencies 100–1500 Hz. The general principle is that the connection of distributed generation

does not interfere with the transmission signals. In particular, connection of the LV DG to the network should not cause attenuation of mains singling greater than 5% in relation to the transmission without connected generation units. The given requirement does not include the issue of transmission of signals used in data transmission systems with the present popular power line communication technology (PLC) where transmission frequency range is 9–148 (400) kHz and 2–80 MHz depending on the technology.

2.3. Summary

The impact of DG on power quality can be considered for every parameter. The discussed "pro-prosumer" approach attaches a significance to EMC certification of DG products so that positive results of emission limits tests obtained using laboratory condition allow to prevent power quality deterioration by DG as it is in case of the equipment. At present the emission limits used for the DG is proposed to be the same as for the equipment. The mentioned approach inclines to unconditional decision about the interconnection of DG to LV public electrical networks as it is practical for the equipment that have EMC confirmation. On the other hand, DG can play an undisputed role in the regulation of electrical networks. Thus, the "pro-operator" approach aims on the impact of DG on static voltage stability, risk of islanding, risk of overload on the power system network, or impact on mains frequency or resynchronization of the subsystems. It can be noted that the mentioned issues are crucial for the operator. That is why the EMC certifications of the DG can be treated by the system operator as a necessary point of the documentation, but not the obligation for unconditional connection. Both mentioned approaches "pro-prosumer" and "pro-operator" do not have to be treated as opposites but should play complementary roles.

Comparisons of the permissible levels of power quality disturbances in LV distribution networks noted in standards [28] and [30], and LV DG proposed in [29] and [30], [31], [32], [33], [34] are shown in Table 4. It can be concluded that requirements for LV DG emission limits are usually much restricted than for the distribution network.

Power quality parameter	Label	Limits for generator	Limits in public LV network
Power frequency, frequency variations	f	Additional reference to characteristic $f(P)$ [section 2.2]	50 Hz ± 2 % (e.g., 49 Hz; 51 Hz) during 95% of a week; 50 Hz ± 15 % (e.g., 42,5 Hz; 57,5 Hz) during 100% of the time.
Voltage magnitude variation, slow voltage changes, level of voltage	Δu_a	3,0% Additional reference to characteristic $\cos\varphi\,(P)$ [section 2.2.4]	10%
Rapid voltage changes (Δu_{max})	Δu_{max}	3,0%	5%,

Power quality parameter	Label	Limits for generator	Limits in public LV network
		Additional reference to S_{kPCC} section 2.2.5	several times of the day - 10%
Voltage fluctuation, flicker severity (P_{st}, P_{lt})	P_{st}	1,0	-
	P_{lt}	0,65	1,0
Voltage unbalanced (asymmetry)	k_{u2}	2,0%	2,0%
Current harmonics, inter harmonics,DC injection	$THDI$ $I_n/I1$ Idc/IrE	Refer to emission limits for load or recalculated to condition of S_{kPCC} section 2.2.8	-
Voltage harmonics, inter harmonics, DC component	$THDU$ U_n/U_1	-	Refer to the table of emission limits for particular components
Commutation notches	d_{com}	5%	5%
Mains signaling, audio-frequency centralized ripple-control	Suppression of the voltage	< 5%	< 5%

Table 4. Comparison of power quality limits for distributed generation and public distribution networks.

3. Field measurement case study results

As supplement for the discussion provided in the previous sections, this chapter is dedicated to real measurements and assessments of power quality impact of photovoltaic (PV) systems with maximum apparent power S_{Amax} = 15 kVA. The system is based on three independent PV generation subsystem of S_{Emax} = 5 kVA integrated with the LV network by independent one-phase PV inverters. The nominal power of the subsystems are the same, however, few differences should be emphasized. The described PV subsystems use different types of PV technologies: phase L1 - monocrystalline; phase L2 - thin layer copper indium gallium selenide; and phase L3 - polycrystalline. Due to the thin-layer technology applied in phase L2, a PV inverter with transformer is applied. Phases L1 and L3 have transformerless inverters. Additionally, the subsystem associated with phase L3 is localized in different geographical directions: phases L1 and L2 are in the 135° South-East direction, phase L3 is in the 255° South-West. Thus, irradiation of phase L3 has natural delay. PCC is the same for every subsystem and directly connected with main LV switchgear of the building with the transformer 630 kVA MV/LV. The LV switchgear is supplemented by reactive power compensation realized by capacitor banks 120 kvar with step of regulation 20 kvar and set regulation of 1:1:2:2. Short circuit power on the level of MV switchgear is 340 MVA. The diagram of interconnection of the investigated PV system with the LV network and its short circuit equivalent is presented in Figure 7.
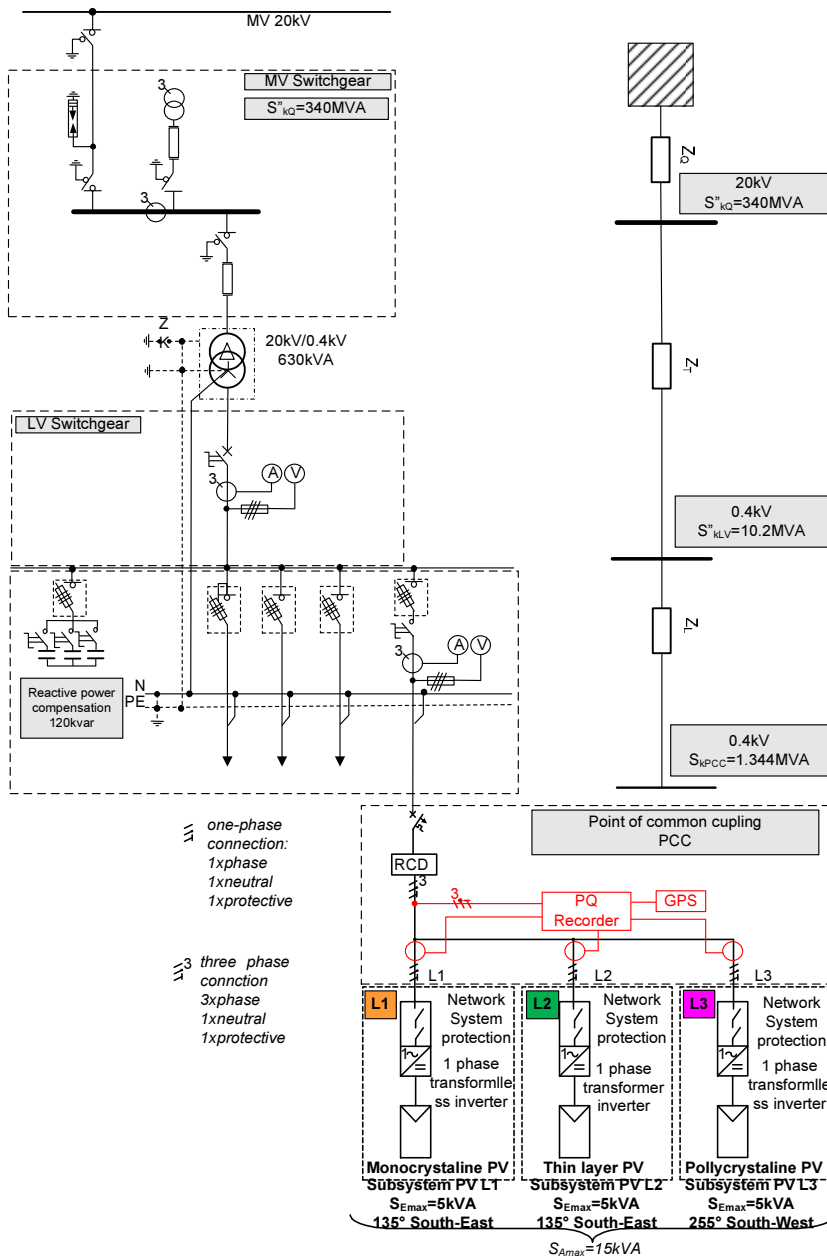
Figure 7. The diagram of interconnection of the investigated PV system with the LV network and its short circuit equivalent.

3.1. Calculation of short circuit condition in PCC

This section contains an example of a simplified calculation of short circuit condition in PCC. The aim is to obtain short circuit apparent power in PCC S_{kPCC}, as well as the equivalent of the short circuit system impedance in PCC Z_{kPCC} that can be used for the prediction of possible influences of the investigated PV system on changes of selected power quality parameters in the PCC.

Medium voltage system:

$$U_{NQ} = 20 \text{ kV, } S''_{kQ} = 340 \text{ MVA}$$

Transformer in LV switchgear:

$$20/0.4 \text{ kV, } S_{NT} = 630 \text{ kVA, short-circuit voltage } \Delta U_{k\%} = 6\%,$$

load losses in cuprum $\Delta P_{Cu} = 6.3$ kW ($\Delta P_{CU\%} = \Delta P_{Cu} / S_{NT} = 1\%$)

Photovoltaic conductor from LV switchgear to PCC:

Cuprum (Cu) 5 x 16 mm^2, section (s) = 16 mm^2, length (l) = 100 m = 0.1 km, electrical conductivity (γ_{Cu}) = 55 m/Ωmm^2, unit resistance (r') = 1.9 Ω/km, unit reactance per 1 km (x') = 0.1 Ω/km, unit capacitance (C') = 61 nF/km.

a.   **Short circuit current at medium voltage switchgear 20 kV**

$$I''_{kQ} = \frac{S''_{kQ}}{\sqrt{3}U_{NQ}} = \frac{340 \cdot 10^6}{\sqrt{3} \cdot 20 \cdot 10^3} = 9.8 kA$$

b.   **Equivalent of the system impedance visible in LV level $U_N = 0.4$ kV**

$$Z_Q \approx X_Q = \frac{c \cdot (U_N)^2}{S''_{kQ}} = \frac{1.1 \cdot (0.4 \cdot 10^3)^2}{340 \cdot 10^6} = 0.000518\Omega = 0.5 m\Omega$$

$$R_Q \approx 0 m\Omega$$

c.   **Equivalent of transformer impedance visible in LV level $U_N = 0.4$ kV**

$$Z_T = \Delta u_{k\%} \cdot \frac{(U_N)^2}{S_{NT}} = \frac{6}{100} \cdot \frac{(0.4 \cdot 10^3)^2}{630 \cdot 10^3} = 0.0152\Omega = 15.2 m\Omega$$

$$R_T = \Delta P_{Cu\%} \cdot \frac{(U_N)^2}{S_{NT}} = \frac{1}{100} \cdot \frac{(0.4 \cdot 10^3)^2}{630 \cdot 10^3} = 0.0025\Omega = 2.5 m\Omega$$

$$X_T = \sqrt{Z_T^2 - R_T^2} = 0.01499\Omega = 15.0 m\Omega$$

d.   Short circuit condition in LV switchgear $U_N = 0.4$ kV

$$R_{kLV} = R_Q + R_T = 0 + 2.5m\Omega = 2.5m\Omega$$

$$X_{kLV} = X_Q + X_T = 0.5m\Omega + 15m\Omega = 15.5m\Omega$$

$$Z_{kLV} = \sqrt{R_{kLV}^2 + X_{kLV}^2} = 15.7\,m\Omega$$

$$\frac{R_{kLV}}{X_{kLV}} = \frac{2.5}{15.5} = 0.16$$

$$S_{kLV}^{"} = \frac{U_N^2}{Z_{kLV}} = \frac{\left(0.4 \cdot 10^3\right)^2}{15.7 \cdot 10^{-3}} = 10.2\,MVA$$

$$I_{kLV}^{"} = \frac{S_{kLV}^{"}}{\sqrt{3}U_N} = \frac{10.2 \cdot 10^6}{\sqrt{3} \cdot 0.4 \cdot 10^3} = 14.7\,kA$$

e.   Equivalent of the conductor impedance from LV switchgear to PCC $U_N = 0.4$ kV

$$R_L = \frac{l}{\gamma \cdot s} = \frac{100}{55 \cdot 16} = 0.113\Omega = 113.6m\Omega$$

$$X_L = x_L^{'} \cdot l = 0.1 \cdot 100m\Omega = 10m\Omega$$

f.   Short circuit condition in point of common coupling PCC $U_N = 0.4$ kV for symmetrical three-phase fault scenario

$$R_{kPCC} = R_Q + R_T + R_L = 0 + 2.5m\Omega + 113.6m\Omega = 116.1m\Omega$$

$$X_{kPCC} = X_Q + X_T + X_L = 0.5m\Omega + 15m\Omega + 10m\Omega = 25.5m\Omega$$

$$\underline{Z}_{kPCC} = R_{kPCC} + jX_{kPCC} = \left(116.1 + j25.5\right)m\Omega$$

$$\frac{R_{kPCC}}{X_{kPCC}} = \frac{115.5}{25.5} = 4.55; \quad Z_{kPCC} = \sqrt{R_{kPCC}^2 + X_{kPCC}^2} = 119.0m\Omega, \quad \psi_{kPCC} = \arctan\left(\frac{X_{kPCC}}{R_{kPCC}}\right) = 12.4^0$$

$$S_{kPCC} = \frac{U_N^2}{Z_{kPCC}} = \frac{\left(0.4 \cdot 10^3\right)^2}{119 \cdot 10^{-3}} = 1.344\,MVA$$

$$S_{kPCC} = \sqrt{3} \cdot U_N \cdot I_{kPCC} \rightarrow I_{kPCC} = \frac{S_{kPCC}}{\sqrt{3}U_N} = \frac{1.344 \cdot 10^6}{\sqrt{3} \cdot 0.4 \cdot 10^3} = 1.941kA = 1941A$$

3.2. Estimation of influence of the investigated PV system on power quality parameters in PCC

Having short circuit condition in the PCC, it is possible to estimate the influence of the considered PV system on particular power quality parameters in the PCC. At the same time, it is worth stressing that the general level of the power quality in the investigated PCC depends on the network and should be treated as the background. It means that estimation should be dedicated to independent influences coming from the investigated PV system. In order to precisely present the estimation, the calculation is performed for the whole PV system is considered as a three-phase unit not particularly a one-phase subsystem. Thus, S_{Amax} = 15 kVA is used instead of S_{Emax} = 5 kVA.

a. **Estimation of change of voltage level, slow voltage changes in PCC**

The influence of the investigated PV system on voltage level in PCC depends on the regulation of $\cos\varphi$ (P). If the system is considered working with constant $\cos\varphi$=1 the influence on static voltage change can be approximated as:

$$\Delta u_a = \frac{S_{Amax}(R_{kPCC})}{U_N^2}100\% = \frac{15 \cdot 10^3 \left(116.1 \cdot 10^{-3}\right)}{\left(0.4 \cdot 10^3\right)^2}100 = 1.01\%$$

If the characteristic $\cos\varphi$ (P) is implemented and reactive power consumption is realized, then the static voltage changes can be reduced to:

$$\Delta u_a = \frac{S_{Amax}\left(R_{kPCC}cos\left(\varphi_{cap}\right) - X_{kPCC}sin\left(\varphi_{cap}\right)\right)}{U_N^2}100\% =$$

$$= \frac{15 \cdot 10^3 \left(116.1 \cdot 10^{-3} \cdot 0.9 - 25.5 \cdot 10^{-3} \cdot 0.44\right)}{\left(0.4 \cdot 10^3\right)^2}100\% = 0.88\%$$

It is worth noticing that the permissible level is noted at 3%.

b. **Estimation of rapid voltage changes in PCC**

For PV systems, the start coefficient is k = 1.1. The influence of the PV system on rapid voltage changes caused by the switching operation can be estimated using the formula:

$$\Delta u_{max} = k\frac{S_{Amax}}{S_{kPCC}}100\% = 1.1 \cdot \frac{15 \cdot 10^3}{1.344 \cdot 10^6}100\% = 1.22\%$$

In comparison to the obtained value, the permissible level of fast voltage changes is 3%.

c. Estimation of voltage fluctuation in PCC

For given short circuit conditions in PCC, the short circuit power coefficient R_k equals:

$$R_k = \frac{S_{kPCC}}{S_{E\max}} = \frac{1.344 \cdot 10^6}{15 \cdot 10^3} = 89.7$$

It is not possible to estimate directly the level of P_{lt} or P_{st} coefficients contributed by the investigated PV system. However, corresponding to EMC standards [33] and [34] where the limits of $P_{lt} = 0.65$ and $P_{st} = 1$ are given for the condition $R_k = 33.3$, it can be concluded that for obtained $R_k = 89.7$, the influence of the PV system on voltage fluctuation should be not higher than the required standards.

d. Estimation of voltage asymmetry in PCC

Because the PV system consists of three subsystems with the same nominal power $S_{E\max} = 5$ kVA, no influence on voltage asymmetry can be assumed. However, it should be precisely noted that subsystems are based on different solar technologies and one of the subsystem in phase L3 has a different geographical direction (L3: 255° South-West) than other subsystems (L1 and L2: 135° South-East). From these reasons, some possible influence on voltage asymmetry is predicted but cannot be directly estimated.

e. Estimation of current harmonic, interharmonics, and DC injection

For the considered PCC, short circuit power coefficient $R_k = 89.7$. Thus, it can be assumed that the current harmonics should not be higher than the limits given in the EMC standards [31] and [32] established for the condition $R_k = 33.3$. However, due to higher levels of the coefficient $R_k = 89.7$, the permissible harmonic current can be higher and recalculated basing on estimated $S_{kPCC} = 1.344$ MVA following the proposed formula in [43]:

$$i_{vzul} = \frac{I_{vzul}}{S_{kPCC}} \rightarrow I_{vzul} = i_{vzul} \cdot S_{kPCC}$$

Following by this suggestion Table 5 express comparison of the permissible current harmonics taking into consideration directly from standard [31] as well permissible values recalculated on the basis of the short circuit apparent power in PCC as it is proposed in [43].

There is no possibility to asses DC injection. However, it should be emphasized that due to different PV technologies in phase L2 a PV inverter with transformer is applied. Phases L1 and L3 have transformerless inverters. Following the EN standard [29] and IEEE standard [40] it can be specified that PV systems shall not inject DC current greater than 0.5% of the full-rated output current. Thus, it is required that DC injection should not cross value:

$$I_{dc} = 0.005 \cdot I_{rE} = 0.005 \cdot \frac{S_{E\max}}{U_N} = 0.005 \cdot \frac{5000}{230} = 108.7\, mA$$

Order of harmonic	Permissible harmonic current emission R_k=33.3 [31]	Permissible harmonic current emission related to S_{kPCC} [43]	Permissible harmonic current emission recalculated for considered PCC S_{kPCC}=1.344MVA, R_k=89.7
n	I[A]	i_{vzul} [A/MVA]	I_{vzul}[A]
Odd harmonics			
3	2.3	3	4.03
5	1.14	1.5	2.02
7	0.77	1	1.34
9	0.40	0.7	0.94
11	0.33	0.5	0.67
13	0.21	0.4	0.54
17	0.132	0.3	0.40
19	0.118	0.25	0.34
23	0.098	0.2	0.27
25	0.077	0.15	0.20
Even harmonics			
2	1.080	0.75	1.01
4	0.430	0.38	0.50
6	0.300	0.25	0.34
8	0.230	0.19	0.25
10	0.184	0.15	0.20
12	0.153	0.13	0.17
14	0.131	0.11	0.14
16	0.115	0.09	0.13
18	0.102	0.08	0.11

Order of harmonic	Permissible harmonic current emission R_k=33.3 [31]	Permissible harmonic current emission related to S_{kPCC} [43]	Permissible harmonic current emission recalculated for considered PCC S_{kPCC}=1.344MVA, R_k=89.7
n	I[A]	i_{vzul} [A/MVA]	I_{vzul}[A]
20	0.092	0.08	0.10
22	0.084	0.07	0.09
24	0.077	0.07	0.08

Table 5. Limits for harmonic current emission for distributed generation units within the range of current up to 16 A in correspondence to limits for class A equipment [31] (for R_k = 33.3) and limits for harmonic current emission for the considered PV system recalculated for the given S_{kPCC} = 1.344 MVA [43] - fragment up to 25 harmonics.

3.3. Verification of the influence of the investigated PV system on power quality parameters in PCC using real measurement

In order to compare the estimated contribution of the investigated PV system on changes of particular power quality disturbances in the PCC, some real measurement was performed. A class A power quality recorder was installed in the PCC in order to analyze the influence of the PV system on power quality disturbances using field measurement data. In real measurement, the crucial problem is separating the influence of the PV from whole measurement. It constitutes a hard task to separate the background, which characterizes network and desired influence of the object. In order to obtain this aim, some correlation analysis is performed taking into account the production of energy with changes of the observed quality parameter. Due to one point measurement in some cases, a sharp separation between background and impact of the PV is not possible, and summary disturbances are evaluated in point of network requirements.

The general assessment of power quality parameters in the PCC was performed on the basis of one week of data following by the EN standard [28]. Thus, in this chapter, statistics is calculated on the basis of one week of data. However, in order to present the impact of the observed PV system on power quality parameters, **one-day data is selected with high generation level**. Secondly, in order to express the relationship between active power generation and changes of the investigated power quality parameter the construction of the figures has common manner. The bottom part of the figures contains the daily shape of active power production of particular phases associated with right additional Y-axis (**L1, monocrystalline, 135° South-East - black**; **L2, thin-layer copper indium gallium selenide, 135° South-East - brown**, **L3, polycrystalline 255° South-West - gray**) also with an additional line representing characteristic coordinates (0.2_{PEmax} = 1 kW red dashed and 0.5_{PEmax} = 2.5 kW red continuous). In the higher part of the figures, investigated parameters of particular phases are presented associated with left Y-axis (L1 – orange, L2 – green, L3 – magenta). The aim of the figures

construction is to represent the behavior of power quality parameters with relations to active power generation.

Classification of the relative impact of the PV subsystems on the investigated power quality parameters can be achieved using classical correlation index r_{xy}. In searching relations, x is the active power generated by the PV subsystem, y is the particular power quality parameter. Then using mean values of x and y, the correlation index r_{xy} can be expressed by:

$$r_{xy} = \frac{\sum_{i=1}^{N}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{N}(x_i - \overline{x})^2 \sum_{i=1}^{N}(y_i - \overline{y})^2}}; \quad -1 \le r_{xy} \le 1 \tag{15}$$

Using the correlation index, a classification of the correlation can be introduced. Table 6 consists of ranges of correlation index and classification of the correlation.

Positive correlation	Negative correlaiton	Classification
$r_{xy}= 0$	$r_{xy}= 0$	Lack of correlation
$0 < r_{xy} \le 0.1$	$-0.1 \le r_{xy} < 0$	Faint correlation
$0.1 < r_{xy} \le 0.4$	$-0.4 \le r_{xy} < -0.1$	Weak correlation
$0.4 < r_{xy} \le 0.7$	$-0.7 \le r_{xy} < -0.4$	Visible correlation
$0.7 < r_{xy} \le 0.9$	$-0.9 \le r_{xy} < -0.7$	High correlation
$r_{xy} > 0.9$	$r_{xy} < -0.9$	Force correlation

Table 6. Classification of the correlation using correlation index r_{xy}.

3.3.1. Assessment of power factor regulation

Referring to Figure 4, every 5 kW one-phase subsystem realizes a reactive power regulation in relation to active power generation. Standard characteristic $\cos\varphi$ (P) contains two characteristic points: $0.2_{PEmax} = 1$ kW and $0.5P_{Emax} = 2.5$ kW. After $0.5P_{Emax}$ PV inverters are forced to consume reactive power. Figure 8 emphasizes that $\cos\varphi$ (P) regulation is performed by the PV inverters. However, the level of reactive power consumption is less than the noted standard characteristic $\cos\varphi$ (P). Figure 9 shows that the reduction of reactive power is performed before characteristic point $0.5P_{Emax}$, but the speed of the reduction is slower than th standard characteristic. Maximum reactive power consumption is $P_{Emax} = 5$kW should be on the level of $Q_{Emax}= -1.65$ kvar (the ratio Q_{Emax} / P_{Emax} -0.33).
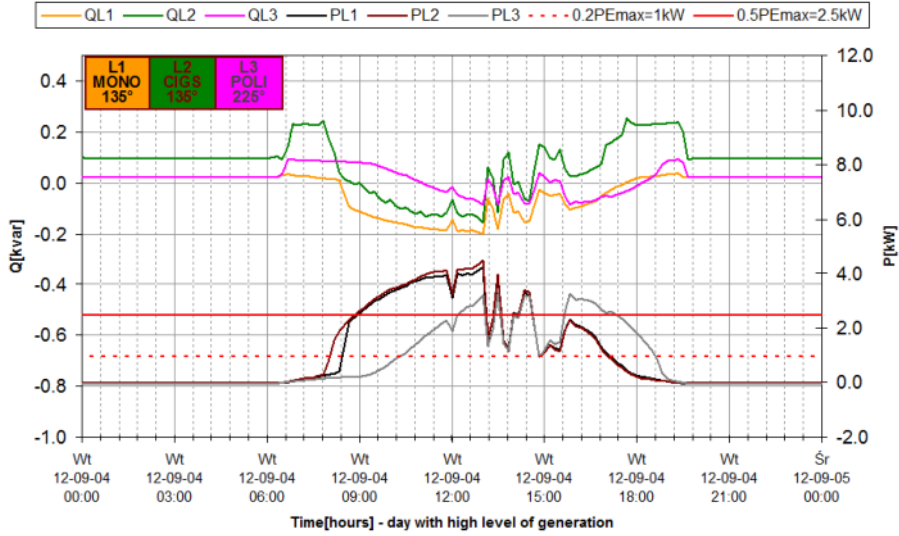
Figure 8. Reactive power regulation in relation to active power generation with characteristic coordintaes $0.2P_{Emax}$=1 kW and $0.5P_{Emax}$= 2.5 kW.
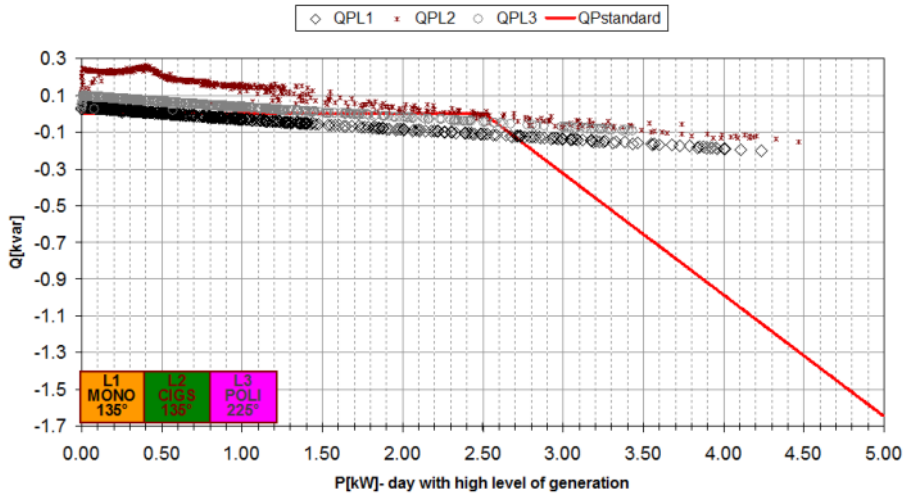

Figure 9. Comparison of reactive power regulation for particular PV subsystems in relation to the standard $\cos\varphi$ (P) characteristic.

3.3.2. Assessment of frequency change

Generally, **faint impact** of the PV subsystems on mains frequency is concluded. In Figure 10, some relations are visible especially when production of active power changes rapidly, however, direct relation is hard to identify. Moreover, the fluctuation of frequency is contaminated by changes of network parameters. The general statistics using 10 s averaging data shows that during one week of measurement, the PCC has fulfilled the low-voltage network requirements for frequency changes.
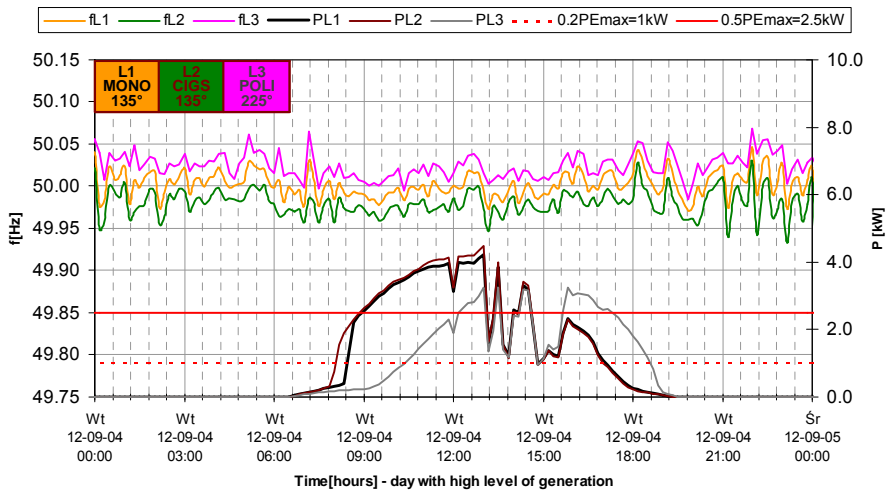
One week frequency changes parameters		f
		[Hz]
f	min	49.902
	P99.5	50.088
	max	50.111

Figure 10. Mains frequency changes in the PCC with reference to the PV subsystem's active power generation and selected one-week data statistics.

3.3.3. Assessment of change of voltage level, slow voltage changes

Figure 11 shows the **visible impact** of PV subsystems on voltage levels in the PCC. This impact stays in relation to the $\cos\varphi$ (P) characteristic. Increasing active power generation causes an increase in voltage levels. However, after crossing $0.5P_{Emax}$, the positive aspect of consumption of reactive power generation on reduction of voltage increase is visible. Additional proof for the relationship between the voltage level and active power generation is the independent behavior of voltage levels in phase L3, where different geographical positions introduce natural delay in the irradiation and energy production that affects the delay of voltage changes.

Calculation of the statistics using one week of data with a 10-minute average time concludes that the maximum voltage changes in the PCC is not higher than 1.7%. This value consists of changes caused by the network and the considered PV subsystems. However, referring to the standards, the limit of 3% of the voltage change is preserved. Additionally, referring to section 3.2 where the estimated influence of the static voltage change caused by connecting the PV system was calculated on the level of 0.88÷1.01%, it can then be concluded that the estimation is near percentile 95% of real measured data.
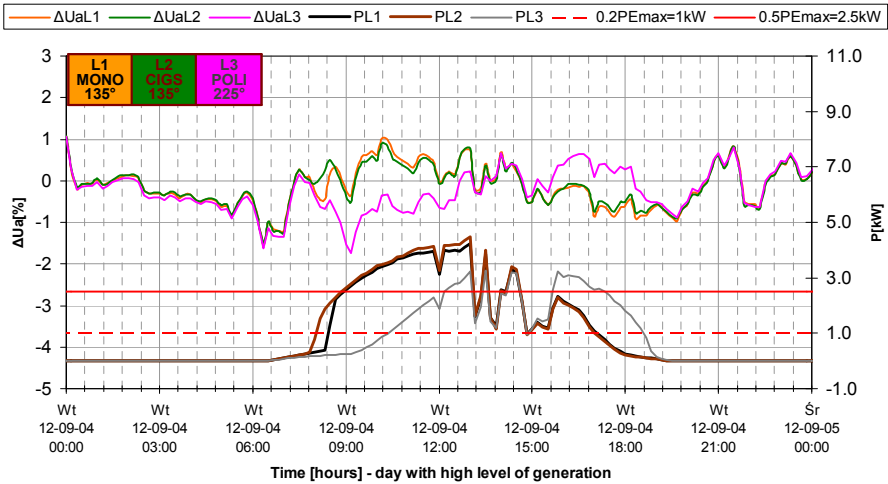
One week static voltage changes parameters		L1 / MONO 135⁰	L2 / CIGS 135⁰	L3 / POLI 225⁰
		[%]	[%]	[%]
$|\Delta u_a|$	min.	0	0	0
	mean	0,5	0,5	0,6
	percentile 95	1,1	1,2	1,2
	max	1,5	1,6	1,7

Figure 11. Static voltage changes in the PCC with reference to the PV subsystem's active power generation and selected one-week data statistics.

In order to emphasise the relationship between PV generation and voltage in the PCC, the correlation index r_{xy} can be calculated. Correlation analysis is presented in Figure 12 and reveals that the impact of active power generation on voltage level classifies the relation as visible.

3.3.4. Assessment of rapid voltage changes

In order to investigate the influence of the operating condition of the PV system on transient voltage behavior, a sudden switching off test was performed. Figure 13 represents rapid

voltage changes during the test. Parameterization of the voltage behavior allows to find the maximum rapid voltage changes equals 2.4%. Corresponding to the estimates in section 3.2 with rapid voltage changes on the level of 1.22%, it can be concluded that the real influence is about two times higher.
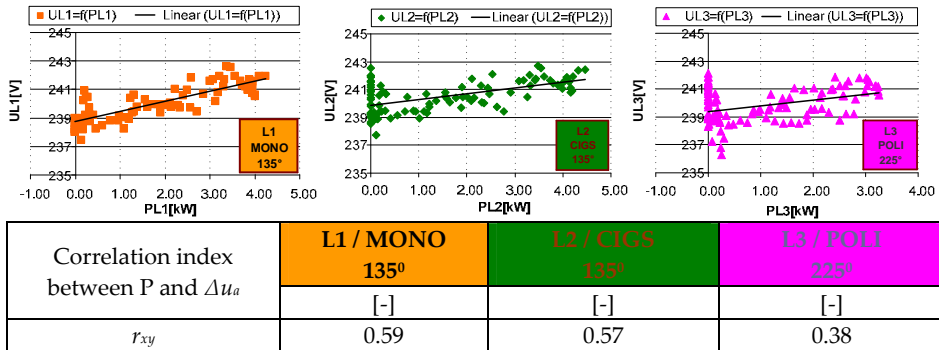

Correlation index between P and Δu_a	L1 / MONO 135^0	L2 / CIGS 135^0	L3 / POLI 225^0
	[-]	[-]	[-]
r_{xy}	0.59	0.57	0.38

Figure 12. Correlation analysis of the impact of active power generation on static voltage levels.

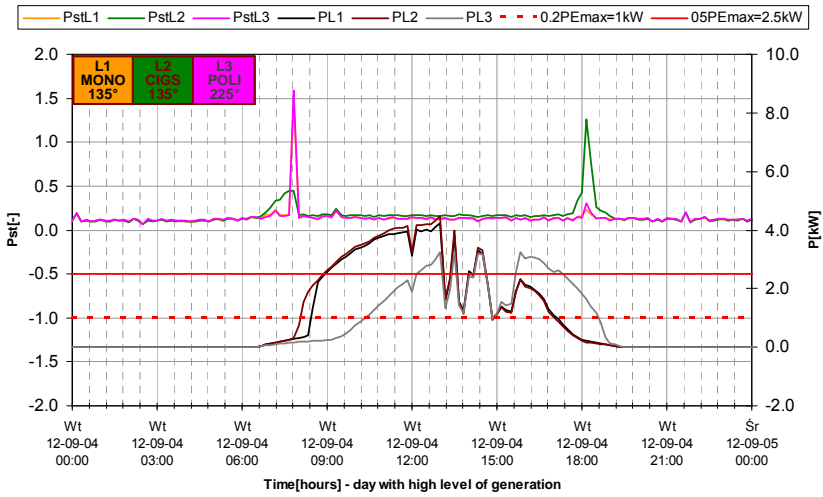| 200 ms rapid voltage changes parameters	L1/ MONO 135^0	L2 / CIGS 135^0	L3 / POLI 225^0
	[%]	[%]	[%]
Δu_{max}	2,1	2,4	1,4
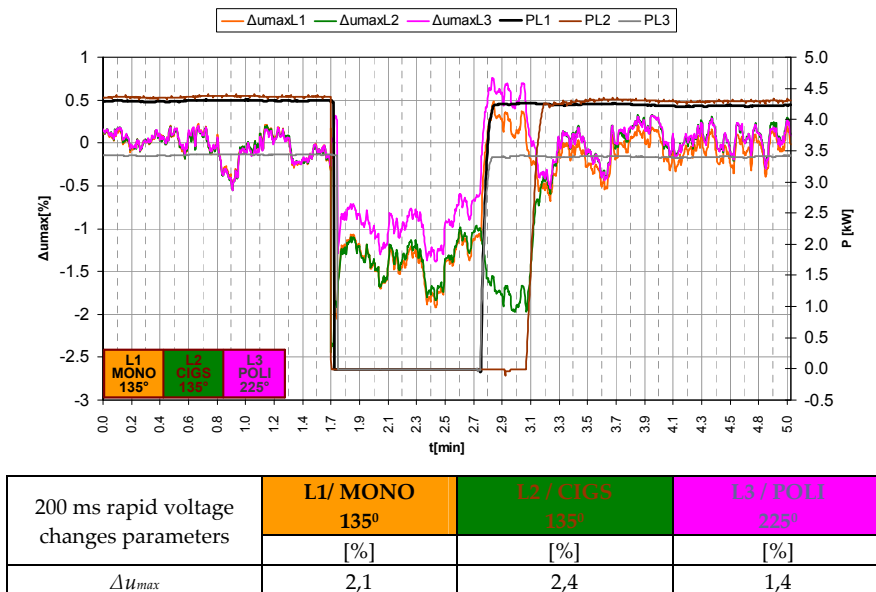
Figure 13. Rapid voltage changes caused by switching off the generation and selected parameters of the change on the basis of continuous 200 ms recording.

| One week voltage fluctuation parameters		L1 / MONO 135⁰	L2 / CIGS 135⁰	L3 / POLI 225⁰
		[%]	[%]	[%]
P_{st}	min.	0,07	0,07	0,07
	mean	0,13	0,17	0,13
	percentile 95	0,17	0,35	0,16
	max	1,46	1,77	1,58

Figure 14. Voltage fluctuations in the PCC with reference to the PV subsystem's active power generation and selected one-week data statistics.

3.3.5. Assessment of voltage fluctuations

In section 3.2, it was estimated that due to the higher levels of short circuit coefficient R_k=89.7 than the standard R_k=33.3, voltage fluctuation should be not higher than P_{lt} = 0.65 and P_{st} = 1. Verification of this assumption using real measurement of P_{st} is presented in Figure 14. Generally, it can be concluded that 95% of one week short term flicker severity index is not higher than 0.35, which follows what is expected. However, some local extremes are founded with cross-permissible value equals 1. Unfortunately, it cannot be acertained if the local increase of voltage fluctuation comes from the PV systems or is an effect of network influence. A wider investigation should be performed in order to eliminate influence of dominating loads or capacitor banks, or focus on specific point of regulation characteristic of $\cos\varphi$ (P) $0.2P_{Emax}$ when PV systems are forced to produce only active power.

3.3.6. Assessment of voltage asymmetry

Rough assessment assuming the same nominal power of the three PV subsystems brings to the conclusion that the PV system has no influence on voltage asymmetry. However, detailed investigation should be taken into consideration and fact that one of the subsystem in phase
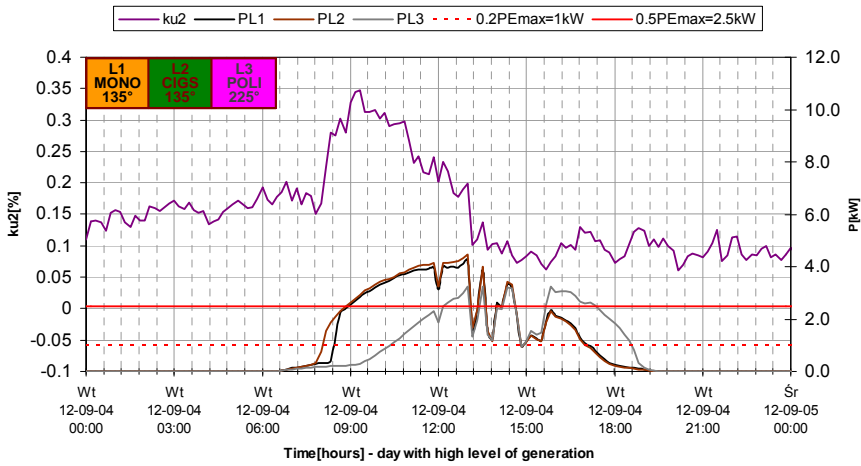
One week voltage asymmetry parameters		k_{u2}
		[%]
k_{u2}	min.	0,02
	mean	0,12
	percentile 95	0,21
	max	0,35

Figure 15. Voltage asymmetry in the PCC with reference to the PV subsystem's active power generation and selected one-week data statistics.

L3 has a different geographical direction (L3: 255° South-West) than other subsystems (L1 and L2: 135° South-East). From these reason, Figure 15 shows that an influence on voltage asymmetry is visible due to the delay in irradiation in subsystem L3. Maximum asymmetry coefficient k_{u2} found among one-week data measurement is 0.35.

3.3.7. Assessment of current harmonics, DC injection

Field measurement uncovers relationships between active power generation and the types of PV technologies on current harmonics. Observing Figure 16 and Figure 17, it can be concluded that the total harmonic distortion index in the current is **high negative correlated** with generated active power. It means that for higher levels of generation, current harmonics is reduced. Additionally, in phase L2 where thin-layer copper indium gallium selenide PV technology with inverter and transformer is applied, the THDI is higher than in other technologies with transformerless inverters. Maximum measurement of harmonics from 1 to 25 during one week of measurement was collected in Table 7. Corresponding to section 3.2, the table shows that using limits from the EMC standard as base of the assessment, 7th and 15th harmonics have not passed the assessment. However, assessment using recalculated limits related to short circuit power condition gives a positive assessment for all presented harmonics.

Harmonic order	One week measurement max.			Limits R_k=33.3 [31]	Assessment R_k=33.3	Limits R_k=89.7 [43]	Assessment R_k=89.7
	L1 / MONO 135^0	L2 / CIGS 135^0	L3 / POLI 225^0				
n	[mA]	[mA]	[mA]	[mA]	[mA]		
2	15,47	115,04	17,70	1080	√	1010	√
3	120,54	443,08	134,53	2300	√	4030	√
4	13,79	65,17	12,21	430	√	500	√
5	94,61	836,59	116,04	1140	√	2020	√
6	13,71	52,22	13,07	300	√	340	√
7	103,06	**786,21**	140,34	770	-	1340	√
8	9,65	34,73	11,27	230	√	250	√
9	43,32	235,22	46,63	400	√	940	√
10	6,87	33,67	7,00	184	√	200	√
11	32,45	177,10	46,15	330	√	670	√
12	6,23	27,86	6,51	153	√	170	√
13	17,05	150,90	16,00	210	√	540	√
14	4,32	26,33	5,50	131	√	140	√
15	17,05	**150,90**	16,00	150	-	x	x
16	5,73	25,81	5,08	115	√	130	√
17	24,18	128,54	33,44	132	√	400	√
18	5,01	25,67	5,18	102	√	110	√
19	12,08	110,96	17,38	118	√	340	√
20	5,33	27,28	6,03	92	√	100	√
21	14,73	88,03	21,28	107	√	x	x
22	5,42	30,69	5,00	84	√	90	√
23	19,84	83,83	26,06	98	√	270	√
24	5,22	33,33	5,42	77	√	80	√
25	21,64	82,41	26,91	90	√	200	√

√ - positive assessment; - negative assessment, x – not specified in the standard

Table 7. Assessment of harmonic current emissions in correspondence to limits for class A equipment [31] (for R_k=33.3) and limits for harmonic current emission for the considered PV system recalculated for the given S_{kPCC}=1.344MVA (for R_k=89.7) [43] - fragment up to 25 harmonics.
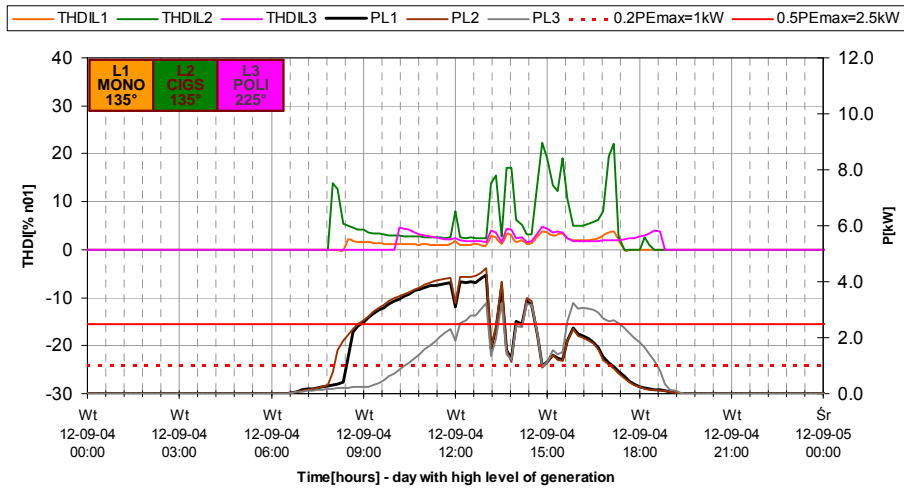
One week THDI parameters		L1 / MONO 135⁰	L2 / CIGS 135⁰	L3 / POLI 225⁰
		[%]	[%]	[%]
THDI	min.	0,00	0,00	0,00
	mean	0,64	3,12	0,79
	percentile 95	3,23	19,50	4,18
	max	4,03	30,36	5,41

Figure 16. Total current harmonic distortion index in the PCC with reference to the PV subsystem's active power generation and selected one-week data statistics.
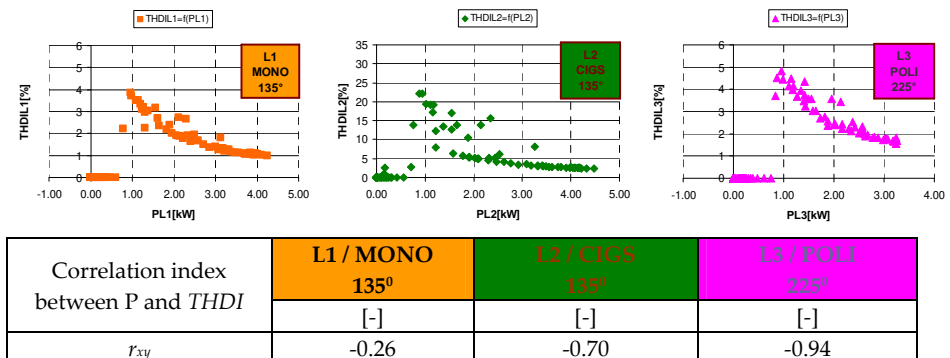

Correlation index between P and *THDI*	L1 / MONO 135⁰	L2 / CIGS 135⁰	L3 / POLI 225⁰
	[-]	[-]	[-]
r_{xy}	-0.26	-0.70	-0.94

Figure 17. Correlation analysis of the impact of active power generation on current harmonics THDI.

In order to investigate DC current injection, a maximum 200 ms data recorded during one week of measurement was utilized. Corresponding to section 3.2, the limit for DC current injection is 0.5% of the rated output current, which in case of investigated PV subsystems, gives a limit of about 108.7 mA. Figure 18 presents the measured changes of DC current injection. It can be concluded that 95% of the one-week measurement data fulfill the requirements. Additionally, phase L2 where thin-layer copper indium gallium selenide PV technology with inverter and transformer is applied is characterized by higher levels of DC current injection. The presented results provide a general assessment due to medium class precision of the DC current measurement.
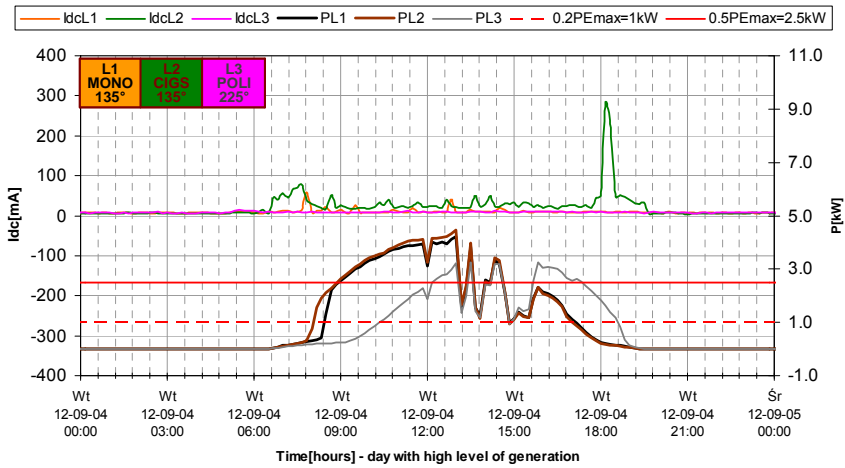

One week dc current injection parameters		L1 / MONO 135⁰	L2 / CIGS 135⁰	L3 / POLI 225⁰
		[mA]	[mA]	[mA]
I_{dc}	min.	5.610	3.700	5.745
	mean	9.231	20.214	8.476
	percentile 95	14.222	55.717	11.791
	max	209.650	279.980	27.876

Figure 18. DC current injection in the PCC with reference to the PV subsystem's active power generation and selected one-week data statistics.

3.3.8. Assessment of voltage harmonics

Generally, **faint impact** of the PV subsystems on voltage harmonic distortion is recognized. In Figure 19, some relations are visible when generation units start working with reactive power consumption mode (e.g., near $0.5P_{Emax}$). However, this effect is not prominent. The general statistics using 10-minute averaging data shows that during one week of measurement, the PCC has fulfilled the low-voltage network requirements for total harmonic distortion index.
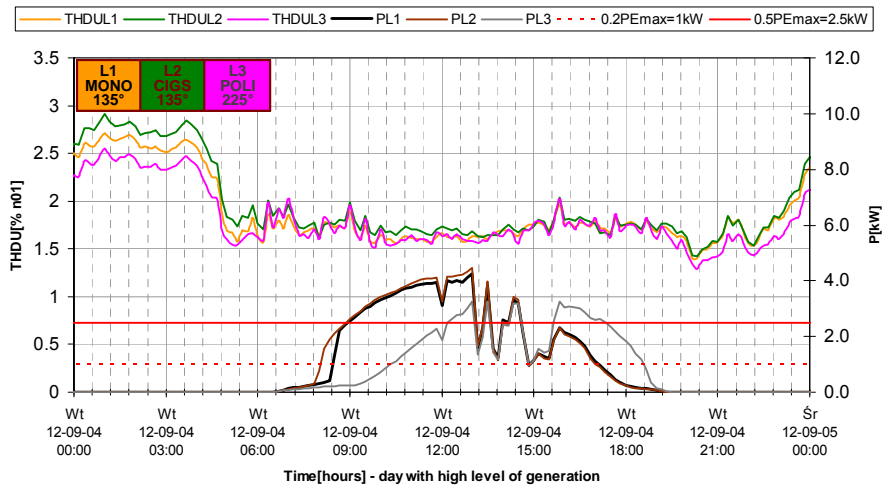
One week voltage harmonic distortion parameters		L1 / MONO 135^0	L2 / CIGS 135^0	L3 / POLI 225^0
		[%]	[%]	[%]
THDU	min.	1,32	1,40	1,27
	mean	1,88	1,92	1,77
	percentile 95	2,64	2,78	2,43
	max	2,92	3,05	2,69

Figure 19. Total voltage harmonics distortion index in the PCC with reference to the PV subsystem's active power generation and selected one-week data statistics.

4. Summary

The review of the current approaches that impact DG power quality in LV networks reveals a few issues. Generally, one of the direction is to consider DG as LV public equipment and adopt the EMC approach, i.e., the same rules of interconnections, test methods, and emission limits as defined for the equipment before they obtain permission for unconditional connection in every point of the LV network. This approach can be named "pro-prosumer" approach. Second direction is to demand certifications of EMC as an undisputed part of equipment documentation, and additionally implement some rules and regulation in the point of integration of power system networks. This regulation considers reactive power regulation as a function of active power generation, active power reduction as a function of mains system frequency, as well as protective rules in case of under and over voltage or under and over frequency conditions. **This chapter believes that both of the mentioned approaches should be used as complementary methods, which finally brings improvement on the possible impacts of the DG on power system networks**. As it was shown, the combined approach allows to define a proposition of the limits of particular power quality parameters associated with the investi-

gated node of LV network, but also allows to estimate the possible influences of DG on changes of particular power quality parameters in the PCC. This combination brings desirable effects in making the criteria for integration of DG with LV network.

The mentioned attitude was investigated using a real case study of a PV subsystem consisting of three independent one-phase subsystems. The estimated possible influence of the investigated PV on power quality parameters was delivered and calculated. As supplement, real measurement was also performed. Comparisons of measured power quality parameters with their calculated equivalent show similarities in the 95% range of the data. In reality, usually maximum results of measurement can be found in the 5% range of data, which exceed the calculated estimation. It should be emphasized that not every power quality can be estimated by calculations precisely. Measurement procedure allows to verify real influence of the investigated DG on power quality in the PCC, however, the task in not easy due to problems of separation of the searched influence from the measurement background.

One of the proposed approach is to affiliate changes of the investigated power quality parameters with the activities of the investigated DG, e.g., energy production. As it was presented, influence of the investigated PV static voltage changes or total harmonic distortion in current in the PCC correlation index can be also implemented in order to classify the force of the influence.

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