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Power Quality in Low-Voltage Distribution Network with Distributed Generation

Abstract. *The aim of this work is to combine electromagnetic compatibility standardization and control strategy of low-voltage distributed generations in order to define possible impact of the generation unit on power quality at the point of common coupling with low-voltage distribution network. Selected relations between power quality indices and parameters as well as regulation characteristic of the distributed generation is discussed. Verification of predicted impact of the distributed generation on power quality is performed using a field-measurement case study of power quality behaviour in real photovoltaic system connected to low-voltage distribution network.*

Streszczenie. *Celem pracy jest wykorzystanie normalizacji stosowanych w zagadnieniach kompatybilności elektromagnetyczne oraz zasad regulacji źródeł rozproszonych niskiego napięcia w celu określenia możliwego wpływu źródła rozproszonego na zaburzenia jakości energii elektrycznej w punkcie przyłączenia. W pracy przedstawiono wybrane relacje pomiędzy parametrami źródła oraz stosowaną charakterystyką regulacyjną źródła a możliwym wpływem na parametry jakościowe w punkcie przyłączenia. Weryfikacja przewidywanego wpływu rozważanego źródła na parametry jakościowe zrealizowana jest na podstawie rzeczywistych pomiarów zaburzeń jakości energii w punkcie przyłączenia systemu fotowoltaicznego. (**Jakość energii elektrycznej w elektroenergetycznych sieciach niskiego napięcia z generacją rozproszoną**).*

Keywords: power quality, distributed generation, photovoltaic, low-voltage distribution network.
Słowa kluczowe: jakość energii eklektycznej, generacja rozproszona, fotowoltaika, sieci niskiego napięcia.

Introduction

Distributed generation (dispersed generation DG, distributed energy resources DER or DR, embedded generation 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 and microgrids. While this is not a new concept, there is still a lack of unified definition explicitly allows to classify DG [1,6,7,10,14]. The main issue is the acceptance criterion, which can be both the capacity of the installed power as well as point of connection to the transmission or distribution system as well as 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, at present the committee SC C6, which suggests to treat as distributed generation all generation units independent from central regulation as well introducing capacity of power limit to the value of 50-100 MW. For comparison, limit the power of distributed generation in the United Kingdom is set at 100 MW, in the United States 50 MW, New Zealand 5 MW, 1.5MW in Sweden. Recent work on distributed generation CIGRE run by Study Committee SC6 Distribution Systems & Dispersed Generation proposed to precise the definition of DG to connection to distribution network without central regulation. Additionally some subdivision of DG related to power capacity can be also find in the literature including: microgeneation (1W÷5kW), small generation (5kW÷5MW), medium generation (5MW÷50MW) and large generation (50MW÷150MW).

Since last quarter of century a significant increase of distributed generation (DG) was indicated in electrical power systems (EPS). Mentioned process is strongly supported by global convention of pollution reduction and promotion of environmental friendly technologies. Natural consequence is 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 was developed in many countries. In parallel to mentioned convention a progress in generation technologies is observed which indicates economic benefit in distributed generation investments. New concepts became significance when the scale of DG contribution is expanded and when location of the DG is related to parts of power systems characterized by week level of reliability. Such scenario can be especially depicted for idea of many prosumers connected to low-voltage distribution network (LV).

Besides undisputed mainstream of global growth of distributed generation 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 mainstream but try to reveal an answer for crucial problems, usually technical, which correspond to process of integration of DG with EPS. One of the rise issue is an impact of DG on power quality (PQ). A wide discussion can be found in [2,3,5,6,7,8,11,12,13,15].

First approach to assess relations between PQ and DG is classical electromagnetic approach (EMC) which indicates to treat low-voltage sources as low-voltage equipment. It requires definition of power quality disturbances emission limits and method of measurements. Reviewing new proposition of standards for DG [20,26,33,34] it can be found that current harmonics emission limits for the DG is suggested to be related with IEC 61000-3-2(12) [22,23] or limits for voltage changes and voltage fluctuations is related to IEC 61000-3-2(12) [24,25] which are typical standards for LV equipment. However this approach requires definition of laboratory setup to make a test of the emission of power quality disturbances dedicated to generation. In case of sources the laboratory setup should be extended due to absorption of energy. A suggestion proposed in [26] is presented in Fig. 1. Mentioned approach is attractive for developed the idea of prosumers contribution in LV distribution network because it leads to direction of unconditional connection of the DG after positive results of tests on emission limits. However few problems are constituted. First of all is the contribution of the DG to protective issues and stability of low-voltage network which introduced special modes of the control strategy for the DG that finally can be superior to power quality. It reveals as the conclusion that EMC standardization can not be considered separately but should be a part of the assessment of impact of the DG on PQ.

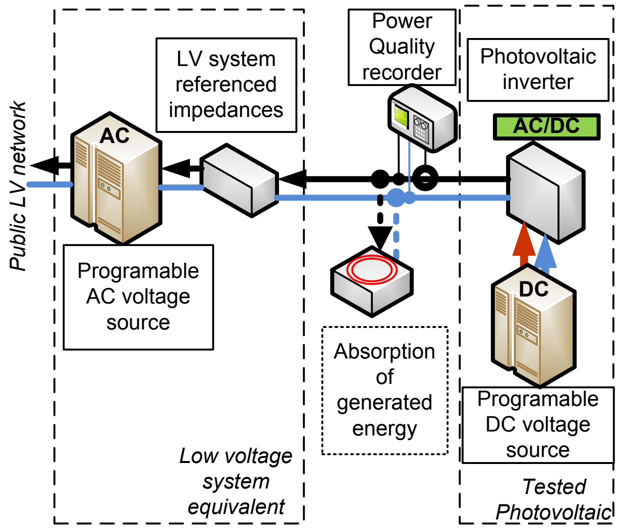

Fig. 1. Laboratory setup for emission and immunity tests for DC supplied inverters proposed in [26]

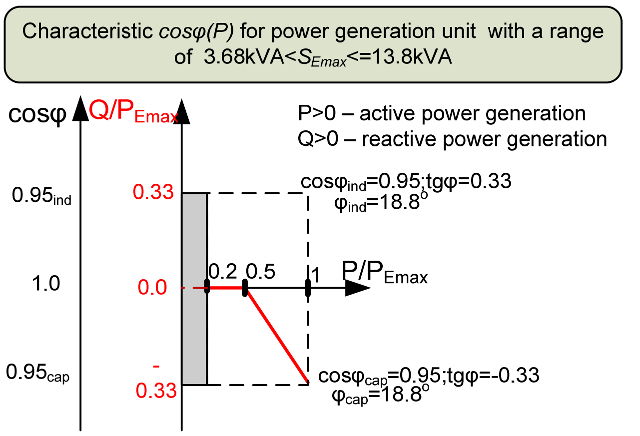

Fig. 2. Standard characteristic cosφ(P) for the generation unit within the range of maximum apparent power S_{Emax} from 3,68kVA to 13,8kVA proposed in [34]

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

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

Second approach proposes to extend EMC emission limits using additional criteria of the connection of the DG to LV distribution network. Influence of the DG on LV grid depends on condition of the network at the point of common coupling (PCC), revealing by short-circuit power $\mathbf{S_{kPCC}}$, as well as nominal power of generation unit S_{Emax} and implemented characteristics of regulation of the DG. This issues are individual for particular condition at the PCC and are not included in standardized EMC tests. Reviewing proposition of standards for interconnection of the DG with distribution network [26,33,34] as well as example of reports and literatures [5÷8] it can be found redefinition of the limits related to particular $\mathbf{S_{kPCC}}$ and considering **characteristic regulation of reactive power in function of active power known as cosφ(P)** characteristic. Especially inverter based power generation units are predisposal for implementation of the characteristics of power factor depending on the active power production **cosφ(P)**. It has to be emphasized that the shape of the characteristic and its crucial coordinates can be generally defined by distribution system operator (DSO) on the basis of power system condition in the area of point of common coupling with respect to maximum apparent power of the generation unit. However in practice a standard characteristic cosφ(P) is implemented. The standard cosφ(P) characteristic for unit with S_{Emax} <13,8kVA is presented in Fig. 2 and is proposed in [34]. Describing the regulation it is visible that up to 20% of maximum active power of the generation unit $\mathbf{P_{Emax}}$ both generation and consumption of reactive power is allowed. In practice in many cases in this range the generation of active power is realized simultaneously with generation of reactive power. This mode of work can be treated as work with induction power factor $\mathbf{cos\varphi_{ind}}$. 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 with reactive power consumption that can be treated as mode with capacitive power factor $\mathbf{cos\varphi_{cap}}$. The level of reactive power consumption depends on the size of the generation unit. For discussed units with S_{Emax} <13,8kVA desirable coordinates is $cos\varphi_{cap}$=0.95. The aim of implementation of reactive power consumption has a significant meaning for reduction of voltage increasing due to higher level of active power generation.

Additional issues are priority of disconnection of the DG due to power system protection. Few selected cases are considered: risk of islanding, risk of overload on the power system network, risk of steady-state and dynamic network stability, rise in mains frequency, resynchronization of sub-systems. Mentioned aims are realized by under and over voltage protection as well as under and over frequency protection. In [18] a review of different standards of distributed generation protection schemes developed in few countries was presented. As an example selected settings of mentioned protection as well as disconnection time for few European countries was compared in Table 1.

The aim of this work is to combine EMC standardization and control strategy of low-voltage DG in order to define possible impact of the DG on power quality at the PCC. Selected relations between power quality indices and parameters as well as regulation characteristic of the DG is discussed. Verification of predicted impact of the DG on power quality is performed using a field-measurement case study of power quality behaviour in real photovoltaic system (PV) connected to LV distribution network.

Selected relations between power quality and DG parameters and regulations

The influence of the connection of the DG on low-voltage power system can be assessed on the basis of the known power quality indices. The list of considered parameters follow by the suitable definitions in standards [19,21] and described in exampled literatures [4,9]:

1. Power frequency, frequency variations (f).
2. Voltage magnitude variation, slow voltage changes, level of voltage ($\mathbf{\Delta u_a}$).
3. Rapid voltage changes ($\mathbf{\Delta u_{max}}$).
4. Voltage fluctuation, flicker severity ($\mathbf{P_{st}}$, $\mathbf{P_{lt}}$).
5. Voltage unbalanced (asymmetry) ($\mathbf{k_{u2}}$).
6. Current harmonics, interhamonics, subharmonics, DC injection.
7. Voltage harmonics, interhamonics, subharmonics, DC offset.
8. Events.

8a. Voltge dips.
8b. Short interruptions.
8c. Long interruptions.
8d. Temporary overvoltages (swells).
8e. Transient overvoltages, oscillatory, impulsive.
8f. Commutation notches ($\mathbf{d_{kom}}$)
9. Mains signaling, audio-frequency centralized ripple-control.

Change in voltage level (static change, Δ_{ua}) 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 calculation for nominal voltage U_N mentioned S_{kPCC} can be recalculated to short circuit impedance in point of common coupling $\underline{Z}_{kPCC} = R_{kPCC} + jX_{kPCC}$, where:

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

Referring to characteristics cosφ(P) shown in Fig. 2 static change of voltage level Δ_{ua} can be determined by generation or consumption of reactive power. When generation unit delivers feed-in active and reactive power the change of voltage level can be expressed as:

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

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

(3)
$$\Delta u_a = \frac{S_{Emax}(R_{kPCC})}{U_N^2}100\%$$

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

(4)
$$\Delta u_a = \frac{S_{Emax}\left(R_{kPCC}cos\left(\varphi_{cap}\right) - X_{kPCC}sin\left(\varphi_{cap}\right)\right)}{U_N^2}100\%$$

Revision of references [6,18,20,34] allows to constitute the permissible limit for voltage level change at the PCC caused by connection of DG should be not higher than 3%. For comparison to requirements dedicated to voltage level changes in low voltage public network is 10% [19].

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 operating condition of the generation unit on rapid voltage change at the connection point PCC using formula:

(5)
$$\Delta u_{max} = k\frac{S_{E\,max}}{S_{kPCC}}100\% = k\cdot\frac{1}{R_k}100\%$$
$$k = \frac{I_{aE}}{I_{rE}};\quad R_k = \frac{S_{kPCC}}{S_{E\,max}}$$

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 reference values:

a. k = 1.2 - generation units connected through an inverter, for example. photovoltaic systems,
b. k = 1.2 - for synchronous generators,
c. k = 4 - asynchronous generators connected to network after bringing to 95 ÷ 105% of the synchronous speed,
d. k = 8 - asynchronous generators.

Short circuit power coefficient R_k used in the test of the emission limits in EMC standard [24,25] is not less than 33.3. Taking into consideration value 33.3 of R_k and assuming start coefficient k=1 it is possible to estimate influence of switching condition of the generation unit on rapid voltage changes on the level of 3%. Revision of the references [6,7,20,34] in relations to [24,25] allows to constitute that DG unit in normal operation condition should not generate rapid voltage changes exceeding 3% of the nominal voltage U_N.

Voltage fluctuation are determine by long-term (Plt) and short-term (Pst) flicker severity indices. Investigation of voltage fluctuation emission is carried out referring to the same standards as investigation of rapid voltage changes [24,25]. Thus connection criteria of considered source at given PCC may also corresponds to R_k parameter. Revision of the references [6,7,20,34] in relations to [24,25] allows to constitute permissible level of P_{lt} not htigher than 0.65 and P_{st} not higher than 1.

Voltage asymmetry can be expressed by voltage asymmetry index k_{u2} calculated as ratio of negative sequence component U_2 to positive sequence U_1:

(6)
$$k_{u2} = \frac{U_2}{U_1}\cdot 100\%$$

Additionally, in [34] there is a recommendation that the asymmetry caused by connecting single-phase DG can be practicably evaluated by the ratio of the power of the connected single-phase generation S_{1Emax} to short-circuit power at the PCC S_{kPCC}:

(7)
$$k_{u2} = \frac{U_2}{U_1} \approx \frac{S_{1E\max}}{S_{kPCC}}$$

Harmonic current requirements corresponds to limits recommended for load in the EMC standards [22,23] where condition assumes short circuit power coefficient not less than R_k=33.3. Example of the current harmonics limits for the equipment with rated current range to 16A is presented in Table 2. If the limits are not preserved for considered DG then similar to rapid voltage changes and voltage fluctuation approach a recalculation of the requirements is allowed using short-circuit power condition at investigated point of common coupling S_{kPCC}. In [34] acceptable limits for particular current harmonic are expressed in A/MVA of S_{kPCC} denoted as i_{vzul}. Table 3 contains relative harmonics limits i_{vzul}. Absolute limits in Amperes I_{vzul} can be recalculated using S_{kPCC} by following formula:

(8)
$$i_{vzul} = \frac{I_{vzul}}{S_{kPCC}} \rightarrow I_{vzul} = i_{vzul}\cdot S_{kPCC}$$

Revising of [7,16,17,31,33] constitutes that inverter based system should not inject **dc current I_{DC}** more than 0.5% of rated inverter output current I_{rE}. Additionally, the differences of current DC injection can be caused by different kind of applied PV technologies and inverters [16,17].

Table 2. Limits for harmonic current emission for distributed generation unit within the range of current up to 16A which corresponds to limits for class A equipment [23] (for R_k=33.3)

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
$15 \le n \le 39$	$0,15 \cdot \frac{15}{n}$
Even harmonics	
2	1,08
4	0,43
6	0,30
$8 \le n \le 40$	$0,23 \cdot \frac{8}{n}$

Table 3. Limits for harmonic current emission related to short-circuit power in PCC S_{kPCC} [35]

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
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 4. Limits for DC current permitted in DC/AC inverters, according to mandatory specific standards of each country [16],[17]

Country	Max DC current permitted with transformer	Max DC current permitted without transformer
USA	0.5% rated power inverter	0.5% rated power inverter
Japan	1.0% rated power inverter	1.0% rated power inverter
Germany	-	1000mA
Spain	-	-
Australia	5mA	5mA
UK	-	5mA

Generally higher level of DC injection is related to transformerless inverters. Application of inverters with transformer gives possibility for better separation of AC from DC. Limits for DC current permitted in DC/AC inverters, according to mandatory specific standards of selected countries was studied in [16,17] and is grouped in Table 4.

There is no requirements for permissible **voltage wave distortion of the DG**. The assumption is that generation realizes good quality of voltage sinusoidal form. It is similar approach as used in the equipment that influence of the device on voltage shape distortion is controlled by limitation of current harmonics. Voltage waveform distortion is controlled in distribution network following by standard [19,21].

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

$$d_{com} = \frac{\Delta U_{com}}{U_N} \tag{9}$$

Studying [30,34] provides an acceptable limits for d_{com} not more than 5%.

Transmission of control signals used by the system operator is usually in the range of frequencies 100-1500Hz. 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 a attenuation of mains singling grater than 5% in relation to the transmission without connected generation units. Given requirement does not include the issue of transmission of signals used in data transmission systems using power line communication technology (PLC) where transmission frequency range is 9÷148(400)kHZ and 2÷80MHz depending on the technology.

Field measurement case study

As supplement for the discussion provided in previous section this chapter is dedicated to real measurement and assessment of power quality impact of photovoltaic (PV) system with maximum apparent power S_{Amax} equals 15kVA. The system is based on three independent one-phase PV generation subsystem of S_{Emax} equals 5kVA integrated with the low-voltage network by independent one-phase PV inverters. The nominal power of the subsystems are the same however few differences should be emphasized. Described PV subsystems use different types of PV technologies : phase L1 - monocrystalline, phase L2 - thin layer copper indium gallium selenide, phase L3 - polycrystalline. Due to thin layer technology applied in phase L2 a PV inverter with transformer is applied. Phases L1 and L3 use transformerless inverters. Additionally, subsystem associated with phase L3 is localized in different geographical direction: phases L1 and L2 have 135° South-East direction , phase L3: 255° South-West. Thus irradiation of the phase L3 has natural delay depending on the season. The diagram of interconnection of investigated PV system with the low-voltage network and short circuit equivalent is presented in Fig. 3. Additionally Table 5 consists of parameters of the short circuit equivalent and condition of the low-voltage network at the PCC. Short circuit coefficient R_k equals 89.7, approximately three times higher than minimum required in the IEC standards (33.3). The low-voltage switchgear is supplemented by reactive power compensation realized by capacitor banks 120kvar with step of regulation 20kvar and set of regulation 1:1:2:2.

Referring to expressed by equations (1)÷(9) relations between selected power quality parameters and condition of power system at the PCC (S_{kPCC}=1.344MVA) it is possible to estimate possible changes of selected power quality indices caused by connection of described photovoltaic system (S_{Amax}=15kVA, S_{Emax}=5kVA). Table 6 presents results of selected calculations. Additionally, due to higher level of the coefficient R_k=89.7 the permissible harmonic current can be recalculated basing on S_{kPCC} following by proposed in [34] approach. Table 7 express comparison of the permissible current harmonics taking into consideration directly from EMC standard for the equipment [20,22] as well proposition in [34].

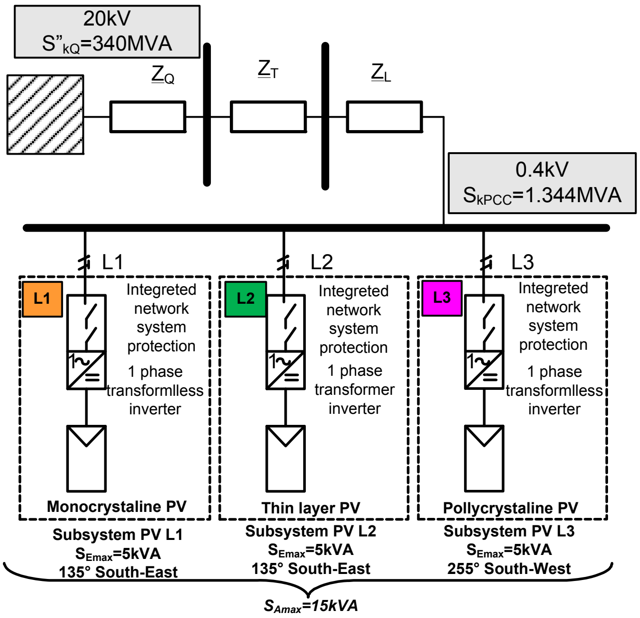

Fig. 3. Short circuit equivalent of the investigated PV system.

Table 5. Parameters of the short circuit equivalent and condition at the PCC of the investigated photovoltaic

Element	Parameters	Impedance circuit equivalent
System MV	U_{NQ}=20kV, S''_{kQ}=340MVA	R_Q=0Ω, X_Q=0.5mΩ
Transformer MV/LV	20/0.4kV, S_{NT}=630kVA, $\Delta U_{k\%}$=6%, ΔP_{Cu}=6.3kW ($\Delta P_{CU\%}$=1%)	R_T=2.5mΩ, X_T=15mΩ
PV conductor LV	Cuprum (Cu) 5x16mm2, l=100m=0.1km, γ_{Cu}=55(m/Ωmm2), R'=1.9Ω/km, x'=0.1Ω/km, C'=61nF/km.	R_L=113.6mΩ, X_L=10mΩ
PCC LV	S_{kPCC}=1.344MVA	R_{kPCC}=116.1mΩ, X_{kPCC}=25.5mΩ, Z_{kPCC}=119mΩ, $\psi_{kPCC}=12.4^0$
PV LV	S_{Amax}=15kVA	R_k=89.7

Table 6. Estimation of changes of selected power quality indices caused by connection of considered S_{Amax}=15kVA photovoltaic systems at PCC with S_{kPCC}=1.344MVA, R_k=89.7

PQ parameter	Mode of the PV regulation	Estimation of possible impact
Static voltage changes (Δu_a)	cosφ=1	1.01%
	$\cos\varphi_{cap}$=0.95	0.95%
Rapid voltage changes (Δu_{max})	k=1.2	1.22%
Asymmetry (k_{U2})	$S_{EmaxL1}=S_{EmaxL2}=S_{EmaxL3}$	0.37%
DC current injection I_{DC}	I_{rE}=21.7A	108.7mA

In order to present impact of observed PV system on power quality parameters one day data is selected with high generation level. Measurement was realized using power quality recorder class "A" in respect to standardized requirements and method of measurement specified in [27÷29]. Secondly, in order to express relation between active power generation and changes of investigated power quality parameter the construction of the figures has common manner. Bottom part of the figures contains daily shape of active power production of particular phases associated with right additional Y-axis (L1,monocrystalline, 135° South-East – black line; L2, thin layer copper indium gallium selenide, 135° South-East – brown line, L3, polycrystalline 255° South-West – gray line) also with additional line representing characteristic coordinates ($0.2P_{Emax}$=1kW red dashed line and $0.5P_{Emax}$=2.5kW red continuous line). In higher part of the figures investigated power quality parameters of particular phases are presented associated with left Y-axis (L1 – orange line, L2 – green line, L3 – magenta line). The aim of the figures construction is to represent changes of power quality parameters with relations to active power generation. Fig. 4 and Fig. 5 emphasised the rule of regulation based on standard characteristic cosφ(P). Fig. 6 to Fig. 13 depict relations between active power generation and mains frequency, static voltage changes, rapid voltage changes, short-term flicker severity, asymmetry, current harmonic distortion, dc current injection, voltage harmonic distortion.

Table 7. Limits for harmonic current emission in correspondence to limits for class A equipment [23] (R_k=33.3) and limits for harmonic current emission for considered PV system recalculated for given S_{kPCC}=1.344MVA (R_k=89.7) [35] - fragment up to 25 harmonics

Order of harmonic	Permissible harmonic current emission R_k=33.3 [23]	Relative permissible harmonic current emission related to S_{kPCC} [35]	Absolute permissible harmonic current emission related to S_{kPCC}
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
20	0.092	0.08	0.10
22	0.084	0.07	0.09
24	0.077	0.07	0.08

Presented Fig. 6÷Fig. 13 of recorded changes of power quality parameters in relation to generated active power, with additional comparison to predicted level of the disturbances in Table 6, allows to conclude following observation:

a. faint impact of the PV subsystems on mains frequency is concluded, range of frequency changes is between 49.902 to 50.111Hz,
b. visible impact of PV subsystems on voltage level at the PCC is recognized, 95% of one week 10 minute averaging voltage changes in the PCC is not higher than 1.2%, however some local extreme values of changes is 1.7% (recorded level has crossed predicted value in Table 6)

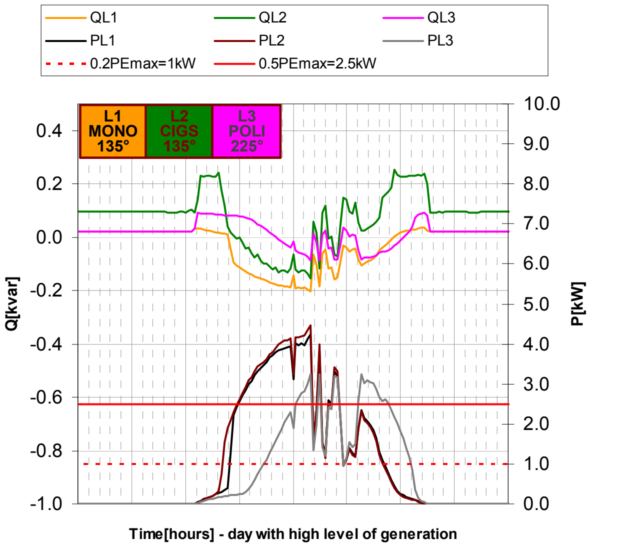

Fig. 4. Reactive power regulation in relation to generated active power - characteristic coordinates $0.2P_{Emax}$=1kW and $0.5P_{Emax}$=2.5kW

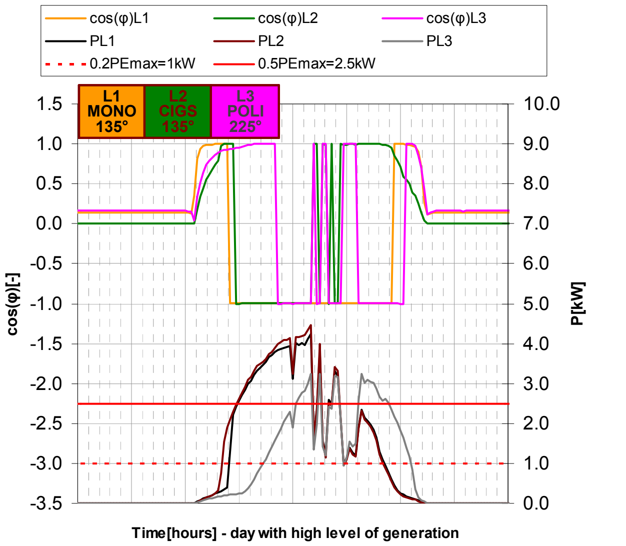

Fig. 5. Displacement power factor (**cosφ**) in relation to generated active power

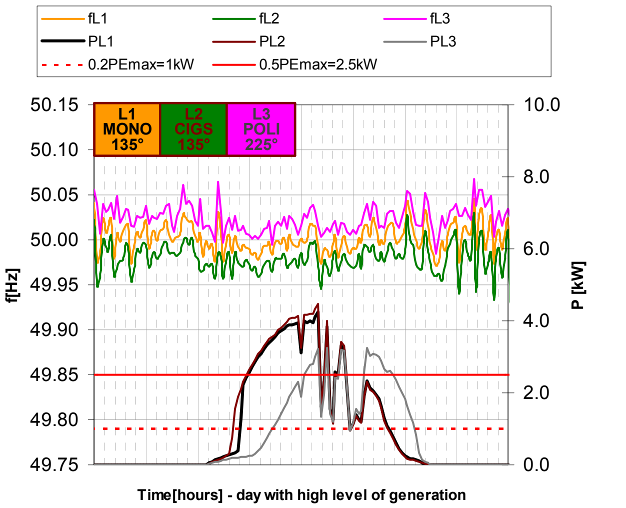

Fig. 6. Mains frequency **f** in relation to generated active power

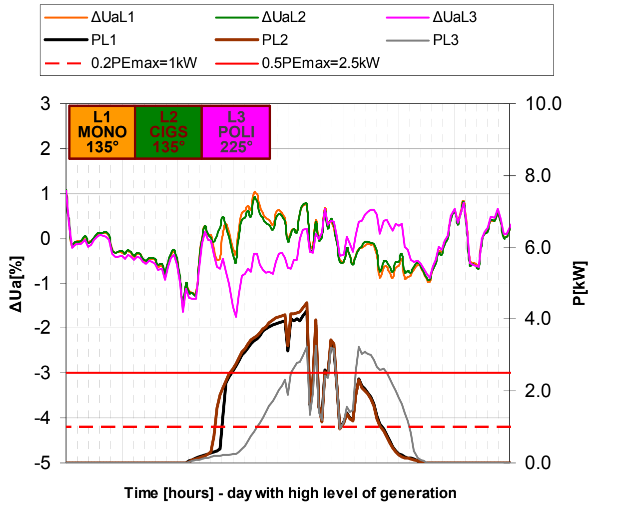

Fig. 7. Voltage level changes $\mathbf{\Delta u_a}$ in relation to generated active power

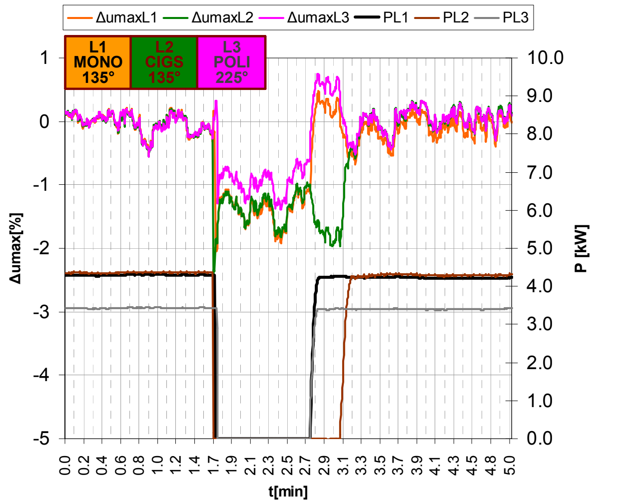

Fig. 8. Rapid voltage changes $\mathbf{\Delta u_{max}}$ caused by switching operation

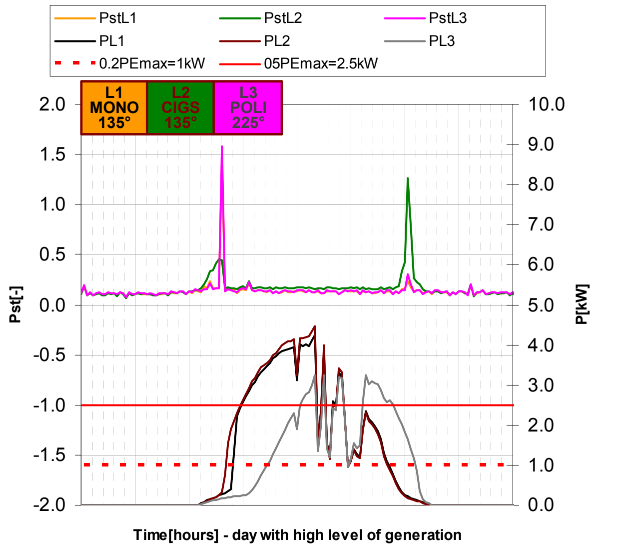

Fig. 9. Short term flicker severity $\mathbf{P_{st}}$ in relation to generated active power

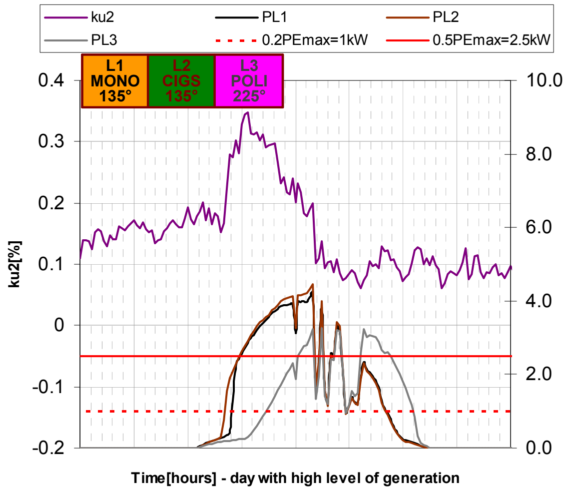

Fig. 10. Asymmetry k_{u2} in relation to generated active power

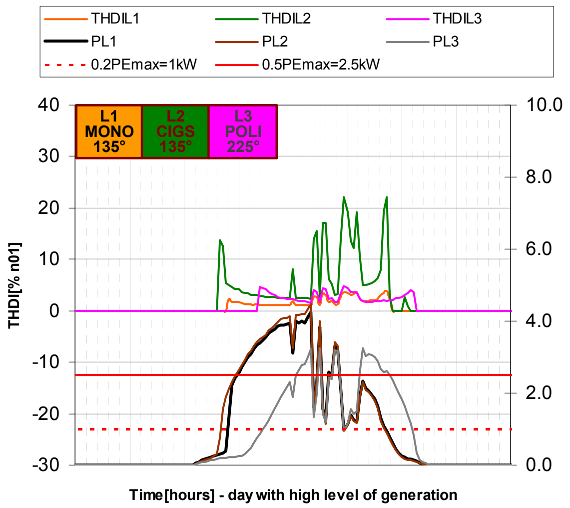

Fig. 11. Total harmonic current distortion **THDI** in relation to generated active power

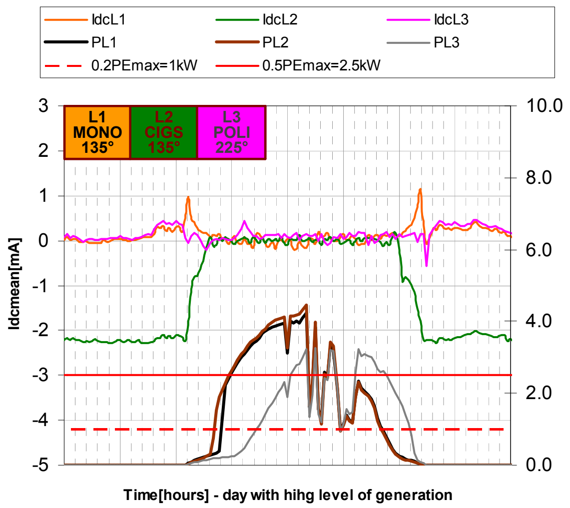

Fig. 12. DC current injection I_{dc} in relation to generated active power

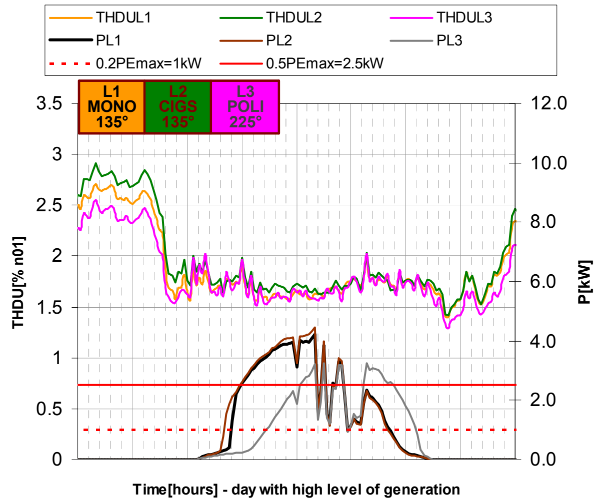

Fig. 13. Total harmonic voltage distortion **THDU** in relation to generated active power

c. visible impact of PV rapid voltage changes in the PCC is recognized, maximum rapid voltage changes caused by switching operation equals 2.4% (recorded level has crossed predicted value in Table 6),
d. it can be concluded that 95% of one week short term flicker severity index is not higher than 0.35, however some local extremes are founded which cross permissible value equals 1,
e. fact that 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) caused visible effect on asymmetry due to delay in irradiation, maximum asymmetry coefficient is 0.35% (recorded level has not crossed predicted value in Table 6),
f. total harmonic distortion index in current is high negative correlated with generated active power, it means that for higher level of generation current harmonics is reduced,
g. maximum 10 minute averaging dc current component is 1.155mA and is related with transformerless converter, in converter with transformer minimum 10 minute averaging dc current component is 0.312mA, it follows by the general reduction of the dc injection in systems used inverter with transformer,
h. faint impact of the PV subsystems on voltage harmonic distortion is recognized.

Conclusions

This work proposes to combined EMC standardization and control strategy of low-voltage DG in order to define possible impact of the DG on power quality at the PCC. Selected relations between power quality indices and parameters as well as regulation of the DG was used in order to estimate possible impact on power quality. Verification of predicted impact of the DG on power quality was performed using a field-measurement case study of power quality behaviour in real photovoltaic system connected to LV distribution network.

It can be concluded that currently there is a lack of standards for emission limits dedicated directly to distributed generation that would efficiently cover all problems of the unconditional decision about connection of DG to low-voltage network as it is practised in case of equipment. Discussed in the paper trend to treat low-voltage DG as the low-voltage equipment seems to be not sufficient due to significant rule which plays generation for power systems in meaning of control as well as protection regimes. That is why the impact of distributed generation on power quality is proposed to be supplemented by estimation of possible influence with reference to condition of point of common coupling where the generation is planning to be connected.

Presented real measured relations between power quality parameters and modes of photovoltaic control strategy shows visible impact of the DG on power quality. Prominent example is implementation of cosφ(P) characteristic which has a direct influence on level of power quality.

Therefore it is necessary to intensify efforts to specify standards for emission limits and method of measurement for distributed low-voltage generators. Additionally new appearing problems of power quality should be adapted in mentioned area like effect of multisource low-voltage network or method of measurement for dc injection as well as supraharmonics.

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Standards:

[20] EN 50160, Voltage characteristics of electricity supplied by public distribution networks.
[21] EN 50438, Requirements for the connection if micro-generators in parallel with public low-voltage distribution networks.
[22] IEC 61000-2-2, Part 2-2: Environment - Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems.
[23] IEC 61000-3-2, Part 3-2: Limits – Limits for harmonic current emissions (equipment input current ≤ 16 A per phase).
[24] IEC 61000-3-12, Part 3-12: Limits – Limits for harmonic currents produced by equipment connected to public low-voltage systems with input current > 16 A and ≤ 75 A per phase.
[25] IEC 61000-3-3, Part 3-3: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤ 16 A per phase and not subject to conditional connection.
[26] IEC 61000-3-11, Part 3-11: Limits – Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems – Equipment with rated current ≤ 75 A and subject to conditional connection.
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