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# PV Plant Influence on Distribution Grid in Terms of Power Quality Considering Hosting Capacity of the Grid

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## Abstract

Photovoltaic plants penetrate rapidly in distribution grid. Problems with their integration in distribution grid can exist in terms of load flow, protection settings, power quality, etc. This chapter analyzes influence of photovoltaic plants connection in distribution grid (0.4 and 10 kV voltage level) on power quality. The main focus will be on influence of photovoltaic plant connection point on distribution grid (hosting capacity—strength of the grid) in terms of power quality. Norms and regulations about influence of photovoltaic plants on distribution grid in terms of power quality will be analyzed. Influence of photovoltaic plants on distribution grid in theoretical aspects will be presented. Several case studies then will be described. Those case studies present different connection points of photovoltaic plants on distribution grid. Comparison of theoretical assumptions and real case studies will be compared. Some observations of real case studies and their impact on theoretical aspects, norms, and regulations about photovoltaic plant influence on distribution grid will be introduced.

**Keywords:** photovoltaic plant, distribution grid, power quality, hosting capacity, connection point, legal regulations

## 1. Introduction

Renewable sources (RES) (or distributed generation (DG) or embedded generation (EG)) are today one of the most actual fields in power engineering area. RES are very important factor in areas of environment protection, development of new technologies and smart grids. In the last several years, there is high penetration of RES on power grid regardless of voltage level. Those RES are with different technologies, but with same assignment: generation of renewable electrical energy. Considering source for electrical energy generation, RES can be based on sun radiation, wind power, waste utilization, exploitation of hydropower, etc. Rated power span of power plants based on RES can vary from 5 kW (microgeneration) to 150 MW (large generation) [1]. Nonrenewable sources (thermal and gas power plants and nuclear power plants) generally are connected on high voltage (HV) grid. It is due to their great rated power. In terms of that, middle- and low-voltage (MV and LV) distribution grid is generally without nonrenewable sources presence.

Without RES, distribution grid is a passive grid which transfers electrical energy from HV grid to consumers. But, penetration of RES makes distribution grid active. It is due to RES presence on all voltage levels (from HV to LV). That is due to great span of RES rated power. It means that RES can have connection in LV grid (e.g., PV plant with 10 kW) and in HV grid too (e.g., windfarm with more than 100 MW of rated power). Simply, conclusion can be derived. It is that conception of power system with RES penetration is changed. In area of electrical energy generation, RES today have great share in total electrical energy generation. But, electrical energy from, for example, PV plants and wind farms is uncontrollable and still difficult to foresee. That fact increased effort of researchers in area of storage systems development. RES created the most changes in distribution grid. Distribution grid, as already stated, became active grid. That fact made changes in distribution grid in terms of load flow conception, system protection, power quality, etc. Those changes are challenge for distribution system operators (DSOs). Distribution system operation and management becomes very difficult for those DSO. A lot of research about RES penetration in distribution grid is carried out. The results are presented in various publications. Some observations can be found in [2–7]. References [3, 4] give fundamental knowledge about RES penetration in distribution grid. Basics, in terms of grid connection, power quality, system protection, economy, and reliability concepts, are described. In [4], influence of RES on power quality and system stability was analyzed. The conditions for RES connecting were described. The authors showed that carefully selected and placed DG can have positive impact on distribution grid in terms of improving voltage profile and system losses. In [5], technical requirements for the connection of the new DG resources on the distribution grid have been analyzed. Some experiences from Greek grid were presented. In [6], technical requirements and assessment criteria for RES connection on distribution grid for power quality and system protection-related issues are presented. Reference [7] introduces statistics modeling for planning purposes of RES integration in distribution grid. One of the greatest challenges in RES connection on distribution grid is in terms of power quality. Simply, before RES penetration in distribution grid, voltage drop was the highlighted problem in distribution grids. With RES, opposite, voltage increasing is the most prominent problem in distribution grids than voltage drop. This is only one of the evidences of conception change in today's distribution grid. RES impact on power quality in distribution grid is analyzed in [2, 8–12]. Reference [8] analyzes short circuit power level with respect to power quality. Paper proposes a methodology to correlate rapid voltage changes to the load variations and to the short circuit power in point of common coupling (PCC). Presented analysis is valid for MV and high voltage (HV) grid. In [9], network impedance influence on power quality results in PCC is analyzed. Assessment procedures for connection of RES on distribution grid are presented. Registration and processing of power quality data in power grid with integrated RES is presented in [10]. In [11, 12], power quality monitoring and classification methods in distribution grids with penetrated RES are presented. There are various power quality parameters. RES penetration in distribution grid influences the most on voltage quality parameters. The impact of RES on distribution grid among voltage quality parameters such as harmonics, flicker, and voltage magnitude is presented in [4–6]. In [9], analyzed voltage parameters are voltage changes, flickers, harmonics, and commutation notches. Reference [11] analyzes voltage fluctuations and harmonics. In [12], frequency, magnitude of voltage, flicker, unbalance, and harmonics are analyzed. In [13], harmonic, unbalance, and flicker are presented. The most analyzed voltage quality parameters, among literature, on which RES can have influence on distribution grid are voltage variations, flicker, and harmonics. As the share of RES increases, the development and use of legal regulations becomes very important factor for proper function of distribution

grid. Those legal regulations depend usually on country, due to each country specifics. But, there are some common international regulations. The best known is EN 50160, made by CENELEC in the middle 1990s. The other one is IEC 61000 series regulation on power quality. The IEEE regulations are present too in engineering practice, but in Europe, IEEE regulations usually cannot have legal status. In [3], EN 50160, IEC 61000 series, and some IEEE Standards are mentioned. PV plants are power sources that rapidly penetrate in power system. Generally, they use energy of the Sun and convert it to electrical energy [2]. PV plants are present on all voltage levels, from LV (10 kW rated power) to HV (more than 100 MW rated power). This book chapter deals with influence of PV plant connection on distribution grid in terms of power quality. This chapter puts focus on dependence between strength of the grid (connection point of PV plant in the distribution grid) and PV plant rated power. In this chapter, theoretical assumptions will be analyzed. Further on, in order to reconsider theoretical assumptions, case studies will be presented too. The chapter structure is as follows:

- a. Influence of PV plant on power quality in connection point (PCC). Literature review (theoretical assumptions) and validation of it on case study.
- b. Legal regulations of power quality considering RES influence on distribution grid. Literature review and current state.
- c. Hosting capacity of the grid (strength of the grid) considering rated power of PV plant. Literature review and multiple case studies.
- d. Comparison of theoretical and practical results of PV plant influence on distribution grid. Proposal of theoretical calculation on PV plant influence on distribution grid considering practical (measured) results. Verification on case study.

First, review of already known facts in this area will be given. Further, new conclusions will be introduced. The idea of further work will be presented based on new findings. At the end of the chapter, summary conclusions will be given.

In this chapter, power quality presents voltage quality parameters.

## **2. Influence of photovoltaic plant on power quality**

PV plants can have connection in distribution grid in various PCC. That PCC potentially can be every bus in distribution grid. Generally, influence of connected PV plant in PCC (in terms of power quality) will be presented. This influence is analyzed among various literature. In [14, 15], influence of PV plants on waveform distortion in PCC was analyzed. It is concluded that if size of PV system is relatively low with respect to the short circuit power of the grid, there is no significant influence on the grid voltage quality. But, if short circuit power is relatively low, regarding PV system rated power, some problems considering power quality can be observed. According to [16], PV plants should not seriously degrade quality of supply with regard to harmonics. In [17], measurements in LV grid in PCC of PV plant connection are performed. Conclusion is that influence of PV plant in PCC is marginal in case of flicker and harmonics. This statement is valid for each measured point in grid (not only PCC). Same results for harmonics are obtained in [18]. Further on, in [19], PV plant connection on MV grid is analyzed. The result is that connected PV plant has positive contribution to the reduction of harmonic voltages distortion (with respect to the harmonic distortion occurring without connected PV



plant). Power quality problems with connected PV plants are more often in rural grids (then in urban grid) due to usually longer feeders and small cross section of conductors [20]. In [21], this is presented as a potential problem too. Limitations of PV plants penetration in distribution grids apply only in weak grids [22]. But, PV plant penetration in weak grids can cause even better performance of those grids (improving voltage profile). Each case should consider individually, as stated in [22]. Simulations in [23] with PV plant connection in distribution grid showed no violation in the harmonic values. According to [24], in period of low irradiance, harmonic distortion is greater than in period with high irradiance.

### 2.1 Case study

Considering literature review, case study results will be presented. The goal is to compare theoretical assumptions and real case study results. A measurement of power quality for one PV plant was performed. Measurement lasted a week without PV plant and a week with connected PV plant, at PCC. Measuring (periods) was performed according to EN 50160:2011 issued by CENELEC (later analyzed). The most interesting voltage quality parameters will be presented:

- voltage unbalance— $u$  (%);
- total harmonic distortion of voltage—THDU (%);
- slow voltage variations— $U$  (V); and
- long-term flicker— $P_{lt}$ .

The question about influence of PV plant on voltage quality in PCC is imposed. Rated power of PV plant is 23 kVA. Short circuit power of grid at PCC is 0.95 MVA. The PV plant is located at rural area connected to LV grid, on feeder with insulated overhead lines. The grid is in good condition (nearly reconstructed). There are two three-phase inverters in this PV plant. The goal is to find influence of PV plant connection on voltage quality at PCC. Analyzed results were in scope of 100% of measuring time periods. It is mandatory condition, so that total influence of PV plant on PCC in distribution grid can be seen.

#### 2.1.1 Voltage unbalance

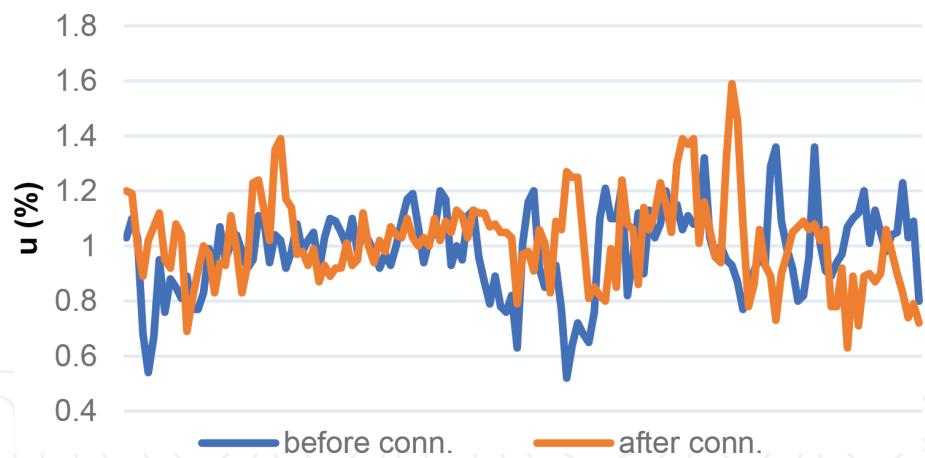
**Figure 1** presents voltage unbalance (%) before and after PV plant connection. Due to clearness, 1-day results (24 hours, 10 min periods) of voltage unbalance before/after PV plant connection are presented in **Figure 1**. Similar is for all week too.

It is quite clear that any correlation of unbalance before and after PV plant connection cannot be found. Maximum (max.) and minimum (min.) value of unbalance is quite similar before (b.c) and after PV plant connection (a.c). It is shown in **Table 1** (for all week period).

From **Table 1**, it is visible that unbalance has lower value after PV plant connection!

#### 2.1.2 Total harmonic distortion of voltage (THDU, %)

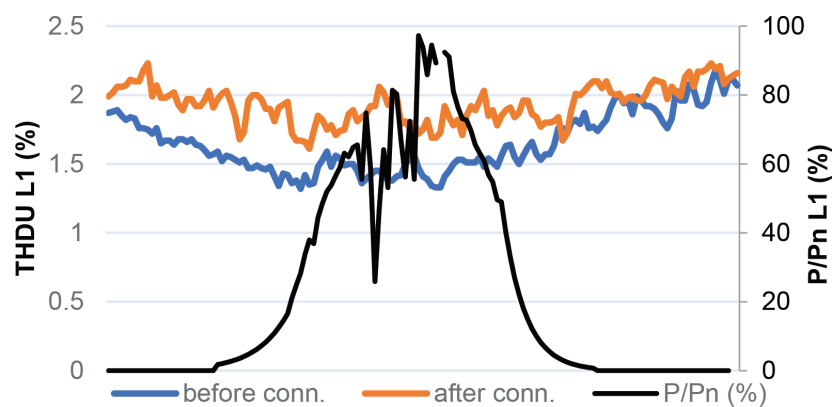
**Figure 2** presents THDU values for L1 phase regarding  $P/P_n$  (%) values of PV plant.  $P/P_n$  presents ratio of generating power ( $P$ ) and rated power ( $P_n$ ) of PV plant. Due to clearness, 1-day results (24 hours, 10 min periods) of THDU (%) before/



**Figure 1.**  
Unbalance (%) before and after PV plant connection.

		b.c	a.c
u (%)	Maximum	1.98	1.60
	Minimum	0.52	0.50

**Table 1.**  
Unbalance (%) values before and after PV plant connection.



**Figure 2.**  
THDU (%) for L1 phase before and after PV plant connection.

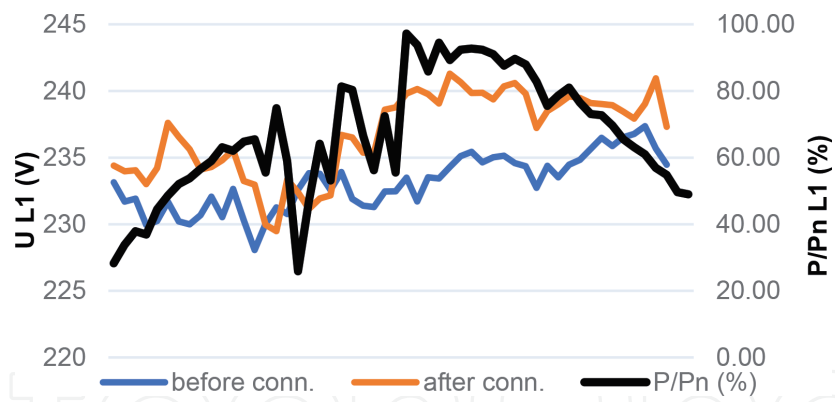
after PV plant connection are presented in **Figure 1**. Generally, results are similar for each day. Results for other two phases are similar.

It is quite obvious that after PV plant connection, THDU values are greater. Those increasing in THDU are the most presented mainly while PV plant produces electrical energy. But, analyzing 10 min values for all week period (all three phases), it is visible that max. and min. values of THDU are quite similar before (b.c) and after PV plant connection (a.c). It is shown in **Table 2**.

Both (min. and max.) values are slightly increased after PV plant connection in this case. It is mainly in period when PV plant produces electrical energy. In percent

		b.c	a.c
THDU (%)	Maximum	2.67	2.70
	Minimum	1.15	1.25

**Table 2.**  
THDU (%) values before and after PV plant connection.



**Figure 3.**  
Voltage values (V) for L1 phase before and after PV plant connection.

value, for a week period, it is negligible. Generally, THDU values before and after PV plant connection are in scope of permitted values regarding any regulation.

2.1.3 Slow voltage variations

Voltage values in V for L1 phase, compared to  $P/P_n$  value, are presented in **Figure 3**. Those voltage values are 10 min interval for one PV plant generation day, between 8.00 and 17.00 hours.

It is clear that PV plant generation increases voltage. As  $P/P_n$  is closer to 100%, voltage difference in V increases considering period before and after PV plant connection.

But, analyzing 10 min values for all week period (in all three phases), it is visible that max. and min. values of voltage values in V are quite similar before (b.c) and after PV plant connection (a.c). It is shown in **Table 3**.

In this case, both (min. and max.) values are slightly increased after PV plant connection. In percent value, for a week period, that increase looks negligible. But, 246.36 V can be potentially high voltage, depending on regulations!

**Figure 4** presents voltage values of phase L2 in V after PV plant connection, considering  $P/P_n$  (%) values. Those values present 10 min interval for 1 day of PV plant generation, between 8.00 and 17.00 hours.

It is obvious that voltage value in V is related to  $P/P_n$  (%) ratio. Generally, greater  $P/P_n$  (%) ratio means greater voltage in V (voltage increase).

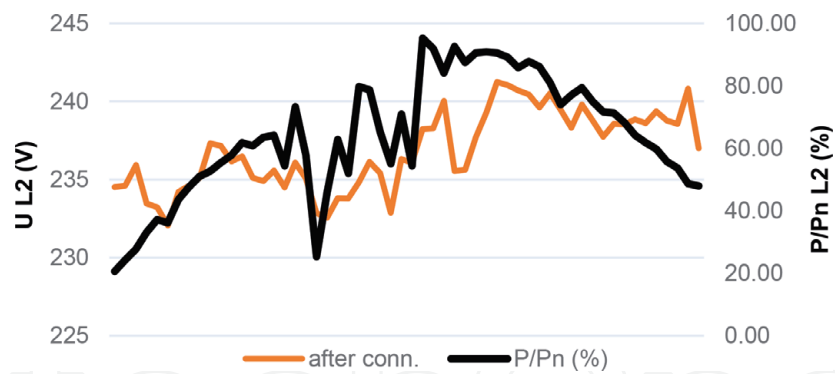
2.1.4 Long-term flicker

**Figure 5** presents  $P_{it}$  values before and after PV plant connection. On **Figure 5** is also represented current I (A) of PV plant phase L3 ( $I_{L3}$ ). Measurement period is 10 min, from 20:00 to 20:00 (24 hours).

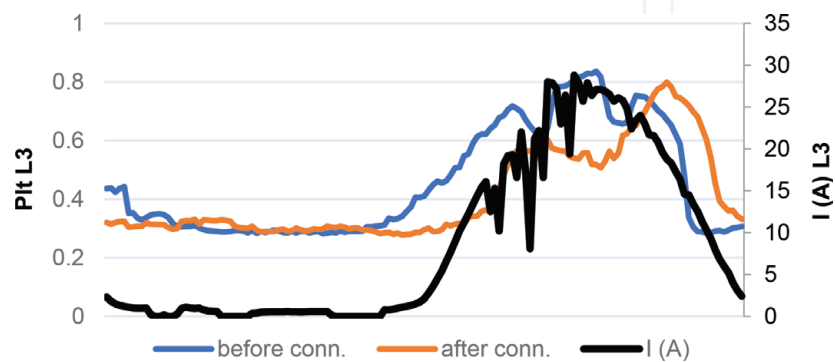
In night period, flicker values are practically the same with/without PV plant. At day period, those values are greater with/without PV plant. There was not found any correlation between PV plant energy generation and flicker values. **Table 4** presents  $P_{it}$  values in PCC before/after PV plant connection for period of 2 weeks.

		b.c	a.c
U (V)	Maximum	243.17	246.36
	Minimum	225.56	227.19

**Table 3.**  
Voltage values in V before and after PV plant connection.



**Figure 4.**  
Voltage values (V) for L2 phase considering  $P/P_n$  (%) values.



**Figure 5.**  
 $P_{lt}$  L3 values before and after PV plant period regarding  $I_{L3}$  in A.

		b.c	a.c
$P_{lt}$	Maximum	1.391	1.244
	Minimum	/	/

**Table 4.**  
 $P_{lt}$  values before and after PV plant connection.

It is obvious that PV plant does not contribute to increasing of  $P_{lt}$  at PCC.  $P_{lt}$  values have max. value before PV plant connection (not after connection) for this case study.

## 2.2 General conclusions of PV plant connection for case study

Some general conclusions for PV plant influence on voltage quality at PCC can be stated:

- Unbalance is quite similar before and after PV plant connection. From **Table 1** is visible that max. 10 min value of unbalance has lower value after PV plant connection. There is no correlation between unbalance values and PV plant generation.
- THD values are slightly increased after PV plant connection in this case. It is mainly in period when PV plant produces electrical energy. In percent value, for a week period, it is negligibly increasing. But, PV plant did have influence on THDU increasing (even slightly).



- It is obvious that voltage value in  $V$  is related to  $P/P_n$  (%) ratio. Generally, greater  $P/P_n$  (%) ratio means greater voltage in  $V$  (voltage increasing). PV plant has influence on voltage increasing due to its electrical energy generation.
- It is obvious that PV plant does not contribute to increasing of  $P_{lt}$  at PCC.  $P_{lt}$  values in this case have their max. before PV plant connection.

### 3. Legal regulations of power quality

Power quality is regulated with norms/standards. But, this area is not unique considering regulations. For this chapter, some of the most exploited norms/standards will be analyzed. Most used international norms/standards are as follows:

- EN 50160 by CENELEC,
- IEC standards, and
- IEEE standards.

These standards usually apply to normal weather conditions and exclude situations like storms, etc. Some of the most used norms/standards in terms of power quality in distribution grids will be shortly presented below. But, most of the countries exist with some legal regulations, like grid codes, in which voltage quality is exploited too.

#### 3.1 EN 50160

In Europe, the most mentioned standard is EN 50160, published by CENELEC (European Committee for Electrotechnical Standardization). First published version of this norm is from the middle 1990s. It is probably the first norm dealing with voltage quality problems. This norm gives quantitative characteristics of voltage. The norm describes characteristics of voltage parameters regarding permissible deviations. EN 50160 analyzes voltage characteristics considering frequency, waveform, symmetry, and magnitude. Measurement of voltage must be performed for 7 days. Instruments for power quality measurement are described by IEC 61000-4-30 standard. Procedure for power quality parameters measuring, according to EN 50160, is defined by IEC 61000-4-x standards. This norm gets a new issue every few years. Voltage quality limits, interesting for this analysis, are presented in **Table 5**. In **Table 5**, compliance limits for statistical evaluation of 95% of time are shown.

Supply voltage parameter	Compliance limit
Voltage variations	$\pm 10\%$
Voltage unbalance	$< 2\%$
Long-term flicker	$\leq 1$
Harmonic voltage (THDU)	$< 8\%$

**Table 5.**  
*EN 50160—voltage quality parameters.*

Supply voltage parameter	Compliance limit
Long-term flicker	$\leq 0.8$
Harmonic voltage (THDU)	$< 5\%$

**Table 6.**  
*IEEE—voltage quality parameters.*

**3.2 IEEE standards**

There is set of standards that consider voltage quality area, issued by IEEE (Institute of Electrical and Electronics Engineers). List of those standards can partly be found in [25]. Some voltage quality limits (available to authors) in scope for this analysis are presented in **Table 6**. In **Table 6**, compliance limits for statistical evaluation of 95% of time are shown. Standard that analyzes flicker is IEEE Std. 1453 and standard that analyzes harmonics is IEEE Std. 519.

**3.3 IEC standards**

IEC standards are issued by International Electrotechnical Commission. In scope of voltage quality are IEC 61000 Series Standards. Some voltage quality limits prescribed by IEC (available to authors) are shown in **Table 7**.

Now, short overview considering **Tables 5–7** can be done. It is interesting that all three published standards have some unity elements. Mainly, 95% of time, voltage parameters must be in limited area. Slow voltage variations are usually limited 10% above/below nominal value. Unbalance is limited to 2%.  $P_{It}$  is limited to 0.8 or 1. The greatest difference is, however, in THDU limits. The limited value varies from 5 to 8%.

Regarding the above-analyzed voltage quality parameters, voltage variations are the most exploited parameter. This is due to increased sensitivity of consumers on voltage values. It is a parameter of voltage quality on which consumers usually have the most complaints. Unfortunately, RES can potentially create even greater problems. Beside norms, in most of the countries exist local regulations (grid codes or similar) about permissible voltage values considering voltage level. Some of them are similar to the above-described norms, but some not.

Those regulations, based on internal country documents, can be divided into two classes. First regulation class presents permissible voltage values, which should be considered during distribution grid planning. Second regulation class considers limited voltage values during distribution grid exploitation. According to [3], permissible voltage values in LV grid are  $-10$  to  $+6\%$  of nominal value in France. In MV grid, this value is  $-5$  to  $+5\%$ . In [3] is stated that in the United States, for MV grid, permissible voltage values are from  $-8$  to  $+8\%$  of nominal value. For Canada, those values are from  $-6$  to  $+6\%$ . It is interesting according to [3], that in Brazil, in

Supply voltage parameter	Compliance limit
Voltage variations	$\pm 10\%$
Long-term flicker	$\leq 0.8$
Voltage unbalance	$< 2\%$
Harmonic voltage (THDU)	THD $< 8\%$

**Table 7.**  
*IEC 61000 series—voltage quality parameters.*

LV grid, permissible voltage variations are from  $-14$  to  $+6\%$ . The examples below are for the case of grid planning. Below, some regulations for distribution grid in exploitation will be presented. For LV customers in Hungary, 95% of the 10 min voltages should be within 7.5% of the nominal voltage value, 100% of the 10 min voltages should be within 10% nominal voltage value. Moreover, 100% of the 1 min voltages should be within 15% nominal voltage value [3]. In Norway, 100% of the 1 min voltage values should be within 10% of the nominal voltage values [3]. For Spain, 95% of the 10 min voltage values should be within 7% of the nominal voltage value [3]. Medium voltage customers in France can sign a contract that gives them a voltage within 5% of a nominal voltage [3].

It is visible great difference between individual country regulations, regarding existence of norms issued by CENELEC, IEEE, and IEC.

### 3.4 Legal regulations of power quality and RES

If one closely looks norms/standards mentioned above, the logical question can be asked. Where are RES in those regulations? Indeed, slow voltage variations are usually limited 10% above/below nominal value, no matter is or is not RES presented in PCC. Considering Section 2.1, this can be a potential problem. If voltage value is, for example,  $+9\%$  above nominal value, PV plant connection can potentially contribute to voltage increasing of, for example,  $+2\%$ . It means that now voltage increasing is  $11\%$  in that PCC—out of limit. On the other side, if voltage value is, for example,  $+5\%$  above nominal value, PV plant connection can potentially contribute to voltage increasing of, for example,  $+2\%$ . It is now voltage increasing of  $7\%$ —permitted value. But, what if on the same feeder two more PV plants should be connected. This can lead to unallowed voltage increasing. This is valid for other voltage quality parameters. Norms/standards that describe influence of RES connection in PCC, in terms of voltage quality, are not present as such.

This area is usually controlled with regulations (documents), like grid codes, where influence of RES on voltage quality in electrical grid is defined. Those regulations vary between countries, regarding RES type, grid voltage level, current state of grid, etc. Literature review of permissible voltage quality deviation in PCC by RES connection is relatively modest.

Voltage increase after RES connection in PCC can be up to max.  $3\%$  [1, 4, 5].  $P_{lt}$  value can be up to 0.65 according to [1] and 0.46 according to [4]. According to [13], compatibility level of  $P_{lt}$  in LV grid must be up to 0.8, and planning level of max. 0.4.  $P_{lt}$  must be up to 0.7 for MV grid [11]. Installed rated power of RES in LV grid can be up to 10% of rated power of transformer MV/LV [4].

It is clear that there is a wide literature approach about RES influence on voltage quality in distribution grid.

## 4. Hosting capacity of distribution grid and PV plant connection

Hosting capacity as a term can have different definitions. Considering voltage increasing, hosting capacity is max. permissible voltage increasing with connected DG, which causes max. voltage value strictly at the overvoltage limit. This leads to a conclusion that, considering voltage increasing, the hosting capacity is the amount of generation that gives a voltage increasing equal to the overvoltage margin [3].

The hosting capacity is the max. amount of generation that can be connected in some PCC without resulting in an unacceptable voltage quality or reliability for other customers. Hosting capacity can be defined as capacity of grid resistance on voltage quality changes due to RES connection in PCC. Distance between the

distributed generator and the transformer is inversely proportional to the hosting capacity. The hosting capacity is smaller as distributed generator is further away from the transformer. The feeder size and length determine strongly hosting capacity of the grid [3].

Simply, hosting capacity of distribution grid presents strength of the grid. In other words, it presents capacity potential for RES connection in one PCC. Practically, it is not the same to connect one amount of RES rated power in urban distribution grid and on the end of long rural feeder made by small cross section of conductors.

On the other side, to be able to estimate the hosting capacity, the max. permissible voltage in grid should be known. Max. permissible voltage values are analyzed in previous subtitle.

It is very probably that greater amount of RES can be connected in urban LV grid than in rural LV grid, in PCC quite distant from transformer MV/LV. But, those are assumptions that should be verified by live case studies.

#### 4.1 PV plant connection and hosting capacity of distribution grid: case studies

This section presents summarized results of voltage quality measurements in LV PCC for four PV plants. Considering hosting capacity of LV grid, PV plants are located in different places (in LV grid). Those grids are in different areas, with overhead lines and underground cables. It is all presented in **Figure 6**. PV plants are named with letters: A, B, C, and D.

PV plants A and C are placed in rural areas. PV plant A is placed not far from transformer MV/LV. PV plant C is placed at the end of the LV feeder. PV plants B and D are placed in urban areas. PV plant B is connected at LV buses of transformer station. PV plant D is set in city center near to transformer MV/LV.

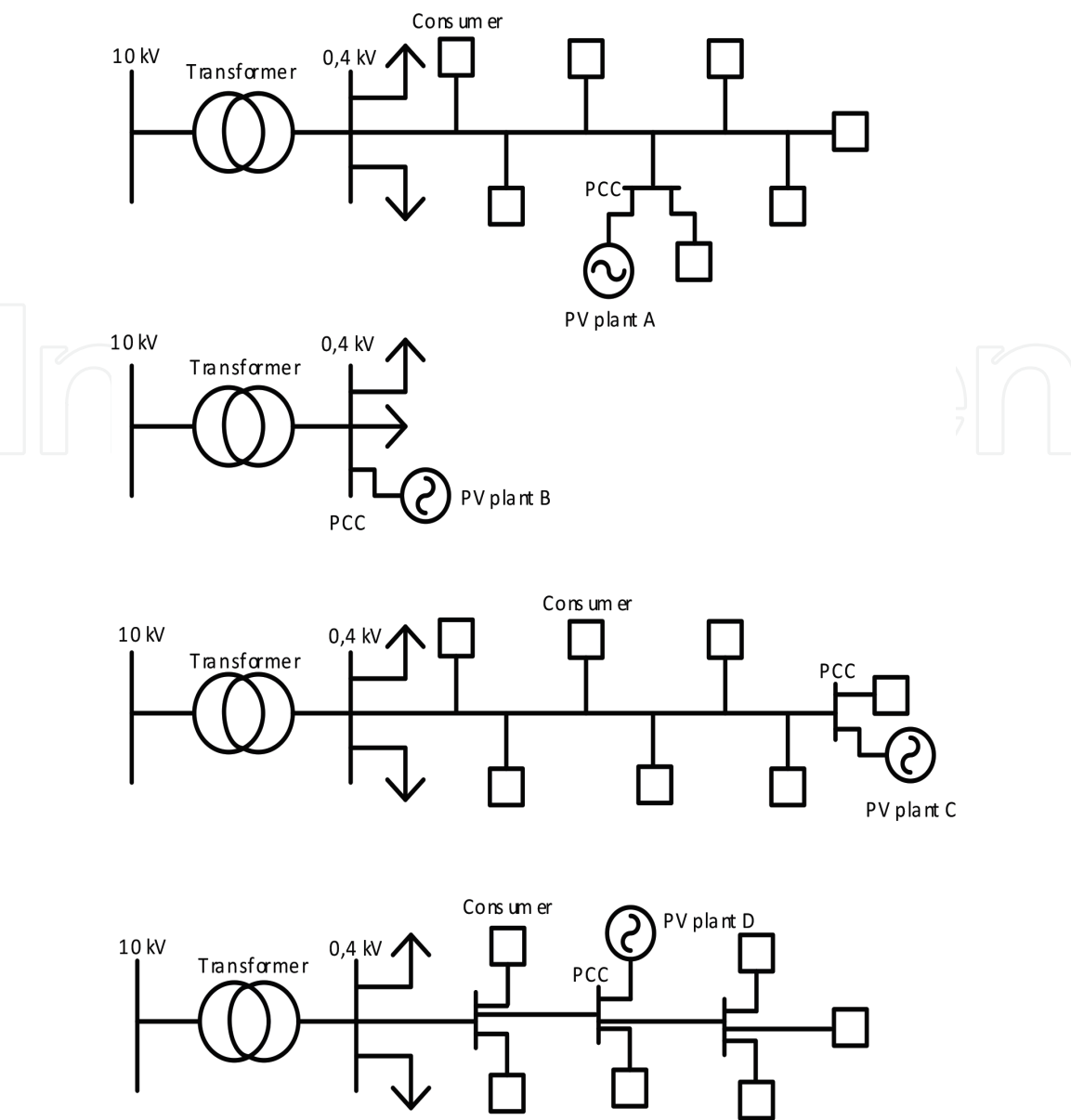
Hosting capacity of LV grid in this case will be presented by three-phase short circuit power ( $S_{sc}$ ) and PV plant rated power ( $S_r$ ) ratio. Greater  $S_{sc}/S_r$  ratio should mean stronger grid—greater hosting capacity. In other words, as PCC is closer to transformer, greater distributed generator can be connected. **Table 8** presents main characteristics of PV plants and related LV grids in PCC.

**Table 9** presents summary of voltage quality results for analyzed PV plants. Measurements were performed a week before and after PV plant connection. Measurements are in accordance with EN 50160:2011. Analyzed voltage quality parameters include slow voltage variations, voltage unbalance, long-term flicker, and total harmonic distortion of voltage. Symbol  $\Delta$  presents difference of max. values before/after PV plant connection.

Before and after PV plant connection, max. values of voltage quality parameters are given. It is due to examination of worst practical cases.

**Figure 7** presents voltage quality parameter results for PV plants, sorted by PCC weakness ( $S_{sc}/S_r$ ). Lower  $S_{sc}/S_r$  value in PCC means weaker grid (smaller hosting capacity).

Voltage increase is proportional to weakness of LV grid. As shown in **Figure 7a**, as grid becomes stronger, voltage increase is lower (there can be decreasing too). For PV plants B and D, voltage decrease has occurred. It means that voltage has lower values after PV plant connection and PV plant does not have any influence on voltage variations (values). The restriction is measurement period of only 1 week before and after PV plant connection. But, the probability of crucial result changing with longer measurement period is minor. For all other parameters such as  $\Delta u$  (%),  $\Delta P_{lt}$ , and  $\Delta THDU$ , there is no correlation between results with/without PV plant and hosting capacity of the grid.



**Figure 6.**  
Connection point of analyzed PV plants.

	A	B	C	D
Sr (MVA)	0.023	0.085	0.023	0.023
Ssc (MVA)	0.95	8.85	0.21	10
Ssc/Sr	41.30	104.11	9.13	434.78

**Table 8.**  
Main characteristics of PV plants and related LV grids in PCC.

Conclusion is that strength of the grid has influence on voltage variations in distribution grid. It means that weak grid, regarding  $S_{SC}/S_r$  ratio, can lead to voltage quality problems in subjected distribution grid.

This cannot be concluded for other analyzed voltage quality parameters. **Figure 8** presents max. voltage values (voltage increase in % of rated voltage value) for PV plants before and after connection. Green and red lines present max. permissible voltage increase in PCC (in % of nominal value), assumed 5 and 7%. Those are realistic values in practice. If permitted max. voltage increase is 5%, there could be some technical problems. For PV plant B, even before PV plant connection,



		A		B		C		D	
		b.c	a.c	b.c	a.c	b.c	a.c	b.c	a.c
U (%)	Maximum	4.99	5.11	5.52	5.32	4.03	6.45	1.4	1.04
	Δ	0.12		−0.2		2.42		−0.36	
u (%)	Maximum	1.33	1.34	0.45	0.48	1.23	1.26	0.82	0.87
	Δ	0.01		0.03		0.03		0.05	
P <sub>lt</sub>	Maximum	0.94	0.98	0.92	0.61	3.45	4.15	1.16	1.17
	Δ	0.04		−0.31		0.7		0.01	
THDU (%)	Maximum	2.67	2.7	2.65	2.7	1.81	1.85	2.39	2.41
	Δ	0.03		0.05		0.04		0.02	

Table 9.

Summary of voltage quality results for analyzed PV plants.

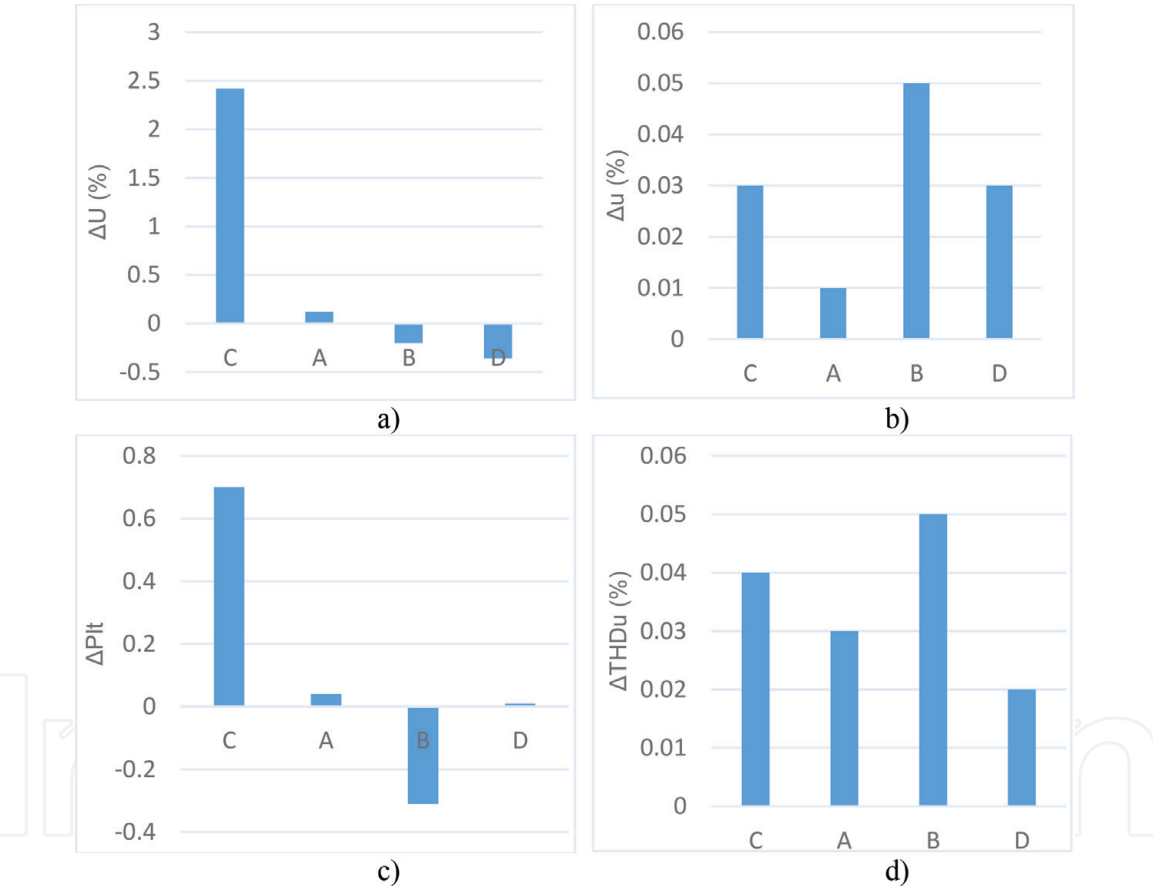


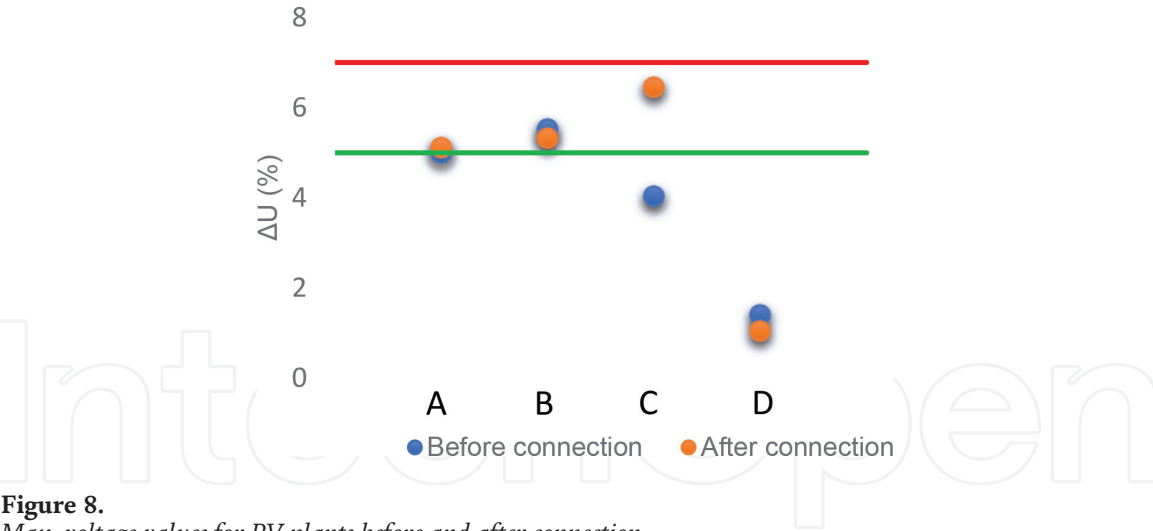
Figure 7.

Voltage quality parameter results for PV plants: (a)  $\Delta U$  (%), (b)  $\Delta u$  (%), (c)  $\Delta P_{lt}$  and (d)  $\Delta THDU$ .

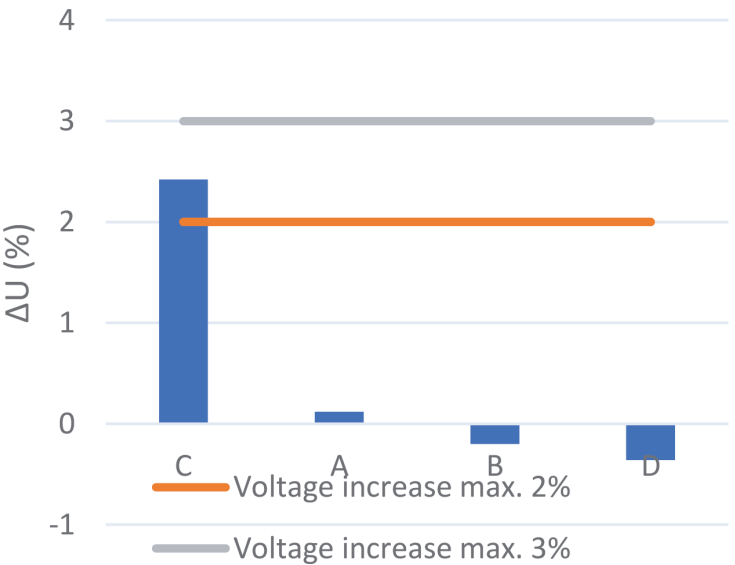
voltage values are increased. For PV plant A, voltage values are on margin. For PV plant C, after PV plant connection voltage values are increased. For permitted voltage increase of 7%, voltage values are in permitted area.

Regarding voltage variations, **Figure 9** shows max. voltage value increase ( $\Delta U$  (%)) in analyzed LV grids after PV plant connection. Permitted voltage value increase of 2 and 3% is assumed. It means that voltage increase after PV plant connection can be 2 or 3%. Those values are the most exploited in literature.

It means that if max. voltage increase in LV grid is 3%, PV plant C can operate. But, if max. voltage increase is 2%, PV plant cannot stay connected on the grid (some changes must be performed). Those changes should be in way of increasing



**Figure 8.**  
*Max. voltage values for PV plants before and after connection.*



**Figure 9.**  
*Voltage increase in analyzed LV grids with connected PV plants.*

short circuit current of the grid (greater hosting capacity of the grid) or in voltage regulations. Increasing of short circuit current in the grid means additional investment in grid (expending cross section of conductors or building new feeder for PV plant connection). Voltage regulation can be performed with inverters. This means regulation of power factor of PV plant ( $\cos \varphi(P)$  or  $Q(U)$ , for example). It is possible, but it usually means additional power losses in grid.

For example, let it be max. permitted voltage increase of 3% (considering nominal value) after PV plant connection. On the other side, let it be max. permitted voltage value increase of 5% (considering nominal value) in LV grid. It is obvious that PV plant B is out of permitted area for normal operation (**Figures 8 and 9**). But, even before PV plant connection, voltage values over permit value were increased. Moreover, after PV plant connection, voltage values were decreased. Another example is opposite. Let it be max. permitted voltage value increase of 2% for PV plant connection. On the other side, let it be max. permitted voltage value increase of 7% (considering nominal value) in LV grid. It is obvious that PV plant C is out of permitted area for normal operation (**Figures 8 and 9**). But, after PV plant connection, voltage values in PCC have permit value (regarding increase of voltage value more than 2% in PCC). This is area of sharing hosting capacity. It will be a challenge for further research.

4.2 General conclusions of PV plant connection regarding hosting capacity of LV distribution grid

Some conclusions for influence of PV plant on voltage quality at PCC, considering hosting capacity of that LV distribution grid, are as follows:

- PV plant has influence on voltage increase in PCC, considering hosting capacity of distribution grid. As the distribution grid is weaker, voltage increase is higher.
- THDU values, unbalance, and long-term flicker are apparently independent on hosting capacity of the grid.
- Contradiction is possible, in the way that voltage value increase after PV plant connection has permitted value, but in PCC, voltage value is unacceptable (increased); and in opposite, voltage value increase after PV plant connection has unacceptable value (increased voltage value), but voltage value in PCC is in limit values.

5. Comparison of theoretical and practical influence of PV plant connection in PCC considering slow voltage variations: case study

In this section, comparison of theoretical and practical results of PV plant influence in PCC considering slow voltage variations will be presented. This is important comparison, since in previous section, slow voltage variations (voltage increase) in PCC are turned out as potential problem for PV plant connection in distribution grid.

Practical results of measurements before and after PV plant connection are presented. A MV feeder (nominal voltage of 10 kV) with connected PV plant is observed. This PV plant will be named by letter E. Some basic parameters of PV plant and MV distribution grid are shown in **Table 10**.

Measurement site at 10 kV voltage level is shown in **Figure 10**.

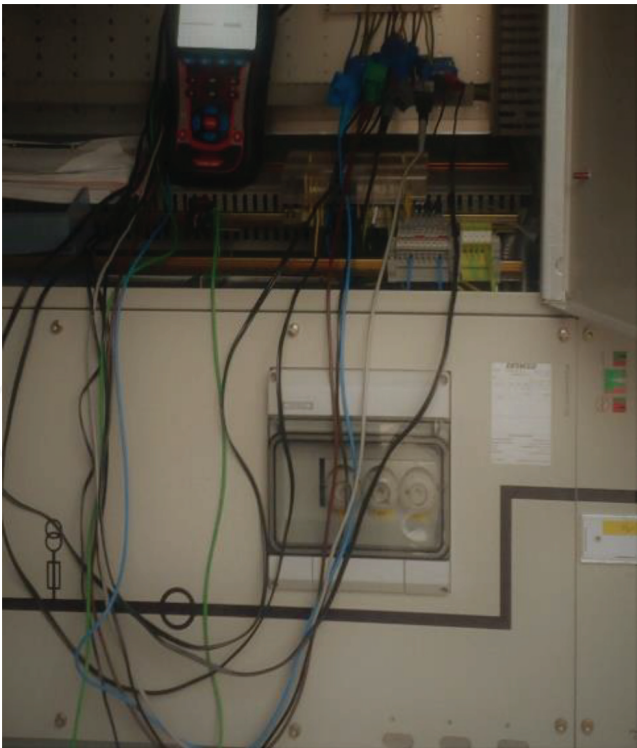
Theoretically, steady-state slow voltage variation (voltage increase) in PCC can be formulated as follows:

$$\Delta u(\%) = 100 \cdot \frac{S_r}{S_{SC}} \cdot \cos(\psi_k + \phi) \tag{1}$$

where  $\psi_k$  is phase angle of the network impedance and  $\phi$  is the phase angle of RES output current. Eq. 1 is simplified, but accurate enough for practical purposes [5]. Worst case considering voltage increase in PCC is for  $\cos(\psi_k + \phi) = 1$ . In this case study, result for voltage increase is **3.60%** (after PV plant connection) for  $\cos(\psi_k + \phi) = 1$ .

	E
Sr (MVA)	0.920
Ssc (MVA)	25.46
Ssc/Sr	27.67

**Table 10.**  
Basic parameters of PV plant and MV distribution grid.



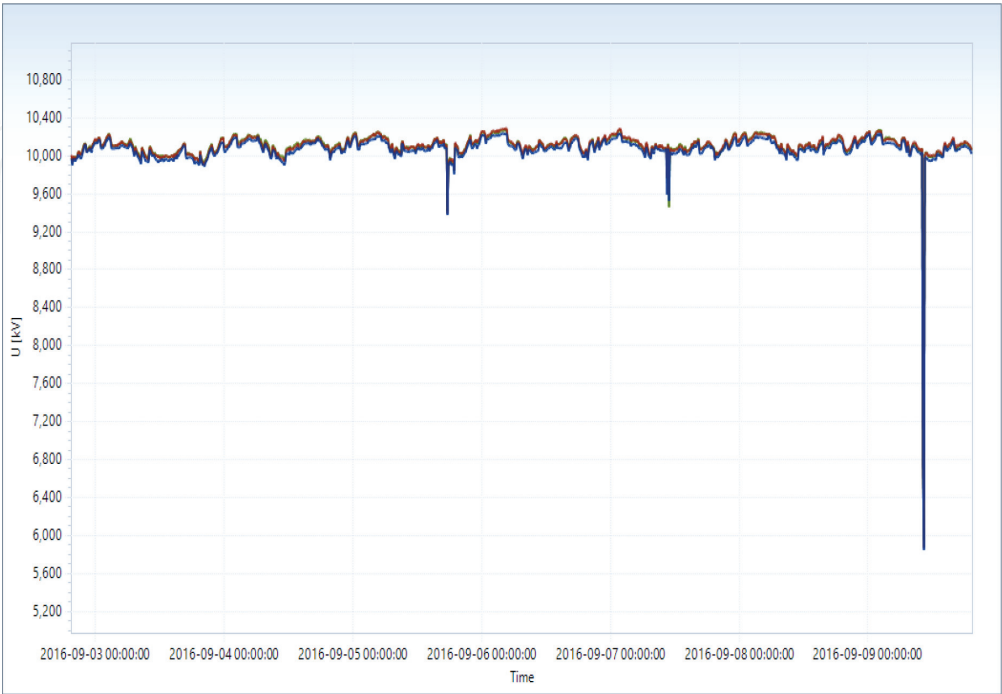
**Figure 10.**  
*Measurement site look for PV plant E.*

In **Figures 11** and **12**, practical measurement of line voltages (in kV) for a week before and after PV plant connection is shown.

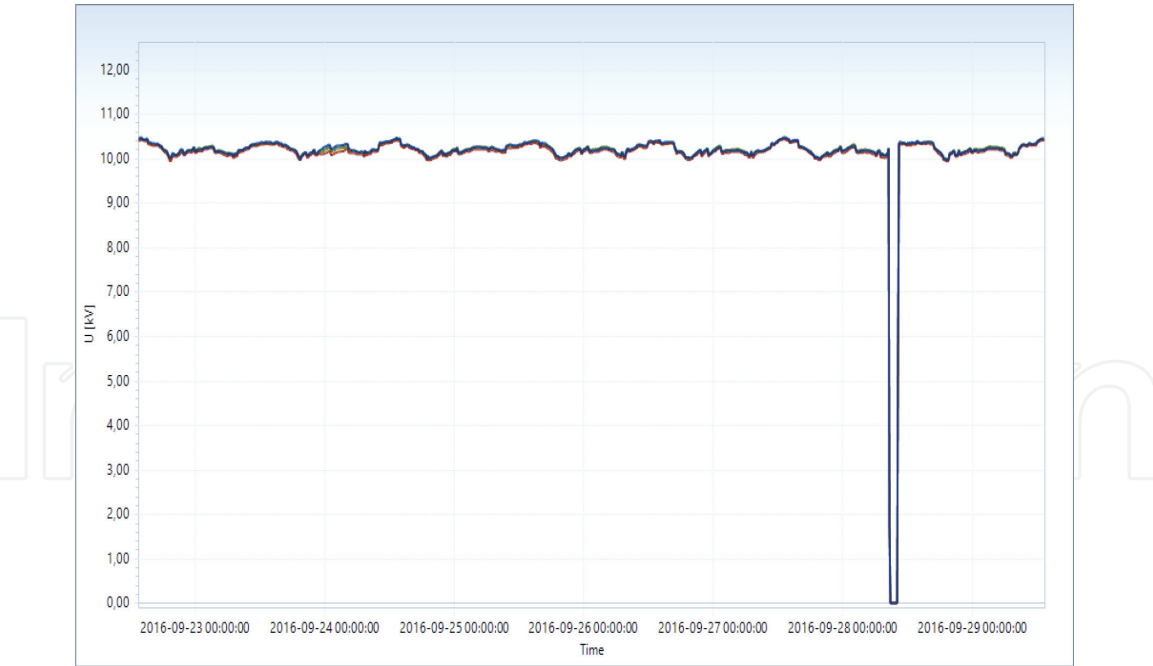
**Table 11** presents max. voltage values measured according to EN 50160:2011 (10 min value) before and after PV plant connection.

It is visible that voltage increase due to PV plant connection has max. value of **2.18%**.

Max. voltage value increase after PV plant connection is close to 5%, that is, max. value for acceptable voltage value increase in MV grids according to [3].



**Figure 11.**  
*Voltage measurement in PCC before PV plant connection.*



**Figure 12.**  
Voltage measurement in PCC after PV plant connection.

		E	
		b.c	a.c
U (%)	Maximum	2.73	4.91
	$\Delta$	2.18	

**Table 11.**  
Slow voltage variation max. values before and after PV plant connection.

Comparing of theoretical and practical voltage value increase in PCC, after PV plant connection, can be performed. It is theoretical voltage increase of 3.60% comparing to 2.18% measured in practice. It is obvious that theoretical voltage value increase is greater due to assumption  $\cos(\psi_k + \phi) = 1$ . This assumption obviously leads to max. voltage value increase, which is hard to achieve in practice.

So, if theoretical result is acceptable, there should not be any problem in practice!

**Table 12** shows other voltage quality results (u,  $P_{lt}$ , THDU) before and after PV plant E connection.

		E	
		b.c	a.c
u (%)	Maximum	0.40	0.40
	$\Delta$	0	
$P_{lt}$	Maximum	1.57	1.70
	$\Delta$	0.13	
THDU (%)	Maximum	2.29	2.51
	$\Delta$	0.22	

**Table 12.**  
Voltage quality parameters for PV plant E, before and after connection.



It is clear that for each showed parameter, there is no practically any difference in results before and after PV plant connection.

## 6. Conclusion

This chapter deals with PV plant influence on distribution grid. Literature review about PV plant influence on distribution grid is summarized. After that, case studies based on appropriate measurements are presented. The connection point of PV plant considering hosting capacity of distribution grid in terms of power quality was analyzed. Considering content of this chapter, following conclusions can be implemented:

- Power quality is regulated with some norms/standards. However, this area is not unique considering present regulations, which is presented in this chapter. There is lack of restriction condition documents for RES connection on distribution grid. In most of the countries exist local legal regulations, like grid codes, in which voltage quality is exploited in terms of RES influence on distribution grid.
- A case study of PV plant connection in LV grid is presented. The influence of PV plant on distribution grid in PCC, considering basic voltage quality parameters, was analyzed. Unbalance is quite similar before and after PV plant connection. THDU values are slightly increased after PV plant connection in this case. It is mainly in period when PV plant produces electrical energy. In percent value, for a week period of measurement, it is negligibly increasing. It is obvious that voltage value in V is related to  $P/P_n$  (%) ratio. Generally, greater  $P/P_n$  (%) ratio (greater generation of PV plant) means greater voltage value in volts (voltage increasing). PV plant has influence on voltage increasing due to its electrical energy generation. It was found that main potential problem for PV plant connection in distribution grid can be voltage increase. Finally, it is obvious that PV plant does not contribute to increasing of  $P_{lt}$  at PCC.
- A comparison of PV plants influence on distribution grid for different connection points of PV plants, considering strength of the grid, is presented. Strength of the grid is in fact hosting capacity of the grid. Four PV plants with different connection points (different  $S_{SC}/S_r$  ratio) were compared. PV plant connection point has influence on voltage increasing in PCC, considering hosting capacity of distribution grid. As the distribution grid is weaker, voltage increase is higher. THDU values, unbalance, and long-term flicker are apparently independent on hosting capacity of the grid. Contradiction is possible, in the way that voltage increase by PV plant connection has permitted value, but in PCC, voltage is increased. And in opposite, voltage increase by PV plant connection is increased, but voltage value in PCC is in limit values. This statement is valid for LV and MV grid. This area of contradiction falls in area of hosting capacity sharing and it is challenge for future work.
- Comparing of theoretical and practical voltage increase values in PCC was presented. Theoretical voltage value increase is greater due to the assumption  $\cos(\psi_k + \phi) = 1$ . This assumption obviously leads to max. voltage increase, which is hard to achieve in practice. So, if theoretical result is acceptable, there should not be any problem in practice. But, this analysis should not be only conducted analysis. It should be framework for more detailed analysis of PV

plant influence on distribution grid. For each new PV plant connection, this analysis should be implemented.

Main contributions of this chapter can be summarized as follows:

- Proving of correlation of voltage value increase considering  $P/P_n$  (%) ratio increase. As the distribution grid is weaker (low  $S_{SC}/S_r$  ratio), voltage increase is higher.
- Voltage value increase in practice should not be greater than increase obtained by calculation considering assumption that  $\cos(\psi_k + \phi) = 1$ .
- PV plant does not contribute in increasing of  $P_{lt}$  and unbalance at PCC. Increasing of THDU in PCC is negligible after PV plant connection. These parameters are apparently independent of hosting capacity of the grid.

## Acknowledgements


The authors would like to thank to JP Elektroprivreda HZ HB d.d Mostar for helping in issuing this chapter.

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