Journal of Natural Sciences and Engineering, Vol. 3, Issue 1 (2021)
DOI number: 10.14706/JONSAE2021322

Influence of the distributed generation on the power quality in distribution network

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Abstract – **The aim of this paper is to present and discuss the influence of distributed generation on power quality. Nowadays, interest in power quality has increased since it has become a very important issue in power system delivery. One of the major problems of ensuring a certain level of power quality are harmonics. The aim of this project is to investigate an impact of photovoltaic (PV) on harmonic voltage distortion (HD) in real MV distribution network. Different scenarios will be implemented where solar power plant is going to be modelled with high variability of load and generation to see their effects on the systems power quality (PQ). Those scenarios are when PV is disconnected from the grid and PVs are connected with 2 different powers. Results presented below showed that PV improves power quality of the system, because their inverters are source of harmonics and they increase HD. However, that impact is not very significant and harmonic limits are not violated. A load flow analysis is done for the model of test system 110/35/10kV in which a distributed generator is added, that is on-grid or off-grid. The network modelling and simulation is done in DIgSILENT PowerFactory software.**

Keywords* – *DIgSILENT*, *power system harmonics, PVs, power quality, harmonic distortion.

1. Introduction

In traditional power systems, most of the power is produced in large power plants, placed at appropriate geographical locations, which is then transmitted over a long distance toward large consumption centers through transmission lines. A large amount of dispersed generation is being developed, including both, renewable and nonrenewable energy sources, such as: photovoltaic (PV) generators, hydro generators, wind turbines, wave generators, fuel cells, gas powered combined heat power stations, etc. [1] Distributed generation (DG) refers to the various technologies that produce electrical energy from renewable sources, typically up to 1 MW, which are installed in distribution electrical network. There are many ways they affect the power system, like improving reliability and decreasing the losses. The main objective of all power systems is to produce and carry reliable, high quality electric power to the consumers, at the reasonable price, with the primary aim to maintain the continuous supply of the power. The system is continuously monitored and controlled by the system control centers to ensure the power quality, controlling frequency and voltage levels.

Power quality has become a very important issue in power system delivery, especially in the second half of the 1990s in connection with high voltage DC (HVDC) systems and static var compensators (SVC). [1,2]

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It was an issue on which improvement utilities all over the world have worked for decades before, but it was not known as power quality issue. In generally, the power quality research refers to the voltage fluctuations, harmonics, voltage sag/swell, flickers, and many other issues followed by the integration of distributed generation in a electrical distribution network.

There are many reasons why the interest in power quality has increased nowadays. Not only that electronic and power electronic equipment has become more sensitive to voltage disturbances, but it also causes voltage disturbances for other customers. Power utilities view end-user modern equipment as the main source of disturbances and so, the main power quality problem. The reason for that is increased use of electronic equipment (converters, inverters, UPS) which can cause nonsinusoidal characteristic of current. It contains a power frequency component and also harmonic component, which frequency is a multiple of the power frequency. The harmonic distortion of the current leads to harmonic components in the supply voltage. Another reason for growing interest in power quality is growing need for standardization and performance criteria. Nowadays consumers are viewed as customers and electrical energy as a product which can be measured, predicted, improved, etc. Therefore, all of this led to privatization, deregulation of the electricity industry and open competition, which made situation even more complicated. It is no longer clear whose responsibility is the reliability and power quality. Utilities want to deliver a good product and the power supply has become too good. Customers have, wrongly, gotten the impression that electricity always has to be available and of high quality, because long interruptions have become rare in most industrialized countries. The fact that there are some, almost impossible to eliminate, imperfections in the supply is easily forgotten. The availability of electronic devices which can measure the power quality has certainly contributed to the interest in power quality. [1]

Harmonics are one of the major problems of ensuring a certain level of power quality and this requires harmonic generation analysis and measurements, study of their effects and limitation to acceptable levels. The main objective of this project is to analyze an impact of DG technology –photovoltaic (PV) on harmonic voltage distortion (HD) in real MV distribution network.

In the following chapter harmonics, as the main power quality problem, are explained, including their definition, causes and effects. In the third chapter results and discusson are presented and in fourth chapter modelling and simulation. Conclusion of the work is in chapter five. Practical part and simulation, explained in fourth chapter, include:

- Modelling a part of MV distribution network feeder with real network parameters in software tool
- Analyzing the impact of DG technology (PV) on harmonics in the real MV distribution network
- Performing harmonic load flow in Power Quality and Harmonic Analysis toolbox (DIgSILENT PowerFactory)

2. Power System Harmonics

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A. Basic definitions

Power systems normally operate at constant frequencies of 50Hz or 60Hz. However, when nonlinear device or load is connected to the source of sinusoidal voltage, there is the current distortion in the system and its characteristic is not perfectly sinusoidal. This current, in connection with the system impedance, create a non-sinusoidal voltage drop what will further cause voltage distortion at the load terminals. Furthermore, the current harmonics increase the rms current in the electrical circuit and affect on the power losses by increasing them. [3]

Harmonic distortion (HD) is degree to which waveform deviates from its pure sinusoidal values. The periodic nonsinusoidal waveform can be presented mathematically in terms of Fourier series. Each term of the series is called harmonic component of distorted waveform, and for voltage and current, those waveforms can be defined in equations (1) and (2) as:

$$v(t) = V_{DC} + \sum_{n=1}^{h} \quad V_{rms}^{n} \cos\cos(n\omega t + a_n) = V_{DC} + v^{(1)}(t) + v^{(2)}(t) + v^{(3)}(t) + \cdots \tag{1}$$

$$i(t) = I_{DC} + \sum_{n=1}^{h} \quad I_{rms}^{n} \cos\cos(n\omega t + \beta_n) = I_{DC} + i^{(1)}(t) + i^{(2)}(t) + i^{(3)}(t) + \cdots \tag{2}$$

where ω is the fundamental frequency, n is harmonic order and V, I, a, and β are rms amplitudes and phase shifts of voltage and current for the certain harmonic. [4] Total harmonic distortion (THD) is defined as root mean square (rms) of harmonics expressed as percentage of the fundamental component in equation (3):

$$THD = \frac{\sqrt{\sum_{n=2}^{N} \quad V_n^2}}{V1} \tag{3}$$

Where Vn is the single frequency rms voltage at harmonic n, N is maximum harmonic order to be considered and V1 is fundamental line to neutral rms voltage. For most applications, the harmonic ranges from 2nd to 25th is considered, but most standards specify up to 50th. [3] Compatibility levels for harmonic voltages for public MV networks are defined in IEC 61000-2-12 and limits for public distribution networks in Europe are defined in EN 50160. [5]

Harmonics are caused by various operations, such as: ferroresonance, magnetic saturation, subsynchronous resonance and nonlinear and electrically switched loads, which are the most dominant source of harmonics in power systems. There are plenty devices that are really sensitive to harmonics, including the inverters that cause the harmonics. [6]

B. Nonlinear Load

Harmonics are produced by non-linear loads that insert harmonic currents in the networks, which produce harmonic voltage drop on the network impedances. However, when a nonlinear device or load is connected to the source of sinusoidal voltage, the resulting current is not perfectly sinusoidal. This current, in the presence of system impedance, causes a non-sinusoidal voltage drop and produces voltage distortion at the load terminals. These loads do not display constant impedance during the entire cycle of applied sinusoidal voltage and they draw a current that may even be discontinuous or flow in pulses for a part of sinusoidal voltage cycle. The number of nonlinear loads is constantly increasing and it is estimated that, more than 60% of loads will have nonlinear characteristic during the next 10 years. [2] A growing number of loads are sensitive to power quality, which gets worse with the increased number of nonlinear loads. Some examples of nonlinear loads are:

- HVDC transmission
- Light emitting diodes (LED)
- Fluorescent lighting
- Electrical vehicle charging systems
- Static var compensators (SVC)
- Thyristor controlled reactors
- Wind and solar power generation

C. Effects of Harmonics

Distortion of the current and voltage waveforms, caused by harmonics, have adverse effects on electrical equipment. Some of the effects are:

- Increase of line current
- Overheating of transformers, motors, generators, capacitors, cables, etc., which can cause premature failure
- Misoperation of protective devices (circuit breakers)
- Malfunction of electronic equipment and instruments (including medical instruments)
- Incorrect meter readings
- Premature failure of power supplies
- Low power factor
- Power quality has drastic effect on power regulation and consumption [7]

Since power quality has become a very important issue in power system delivery, it has been a point of interest for many researchers. In [8] an impact of residential PVs on harmonics and power quality in low-voltage distribution network is analysed. The results showed that the greatest voltage total harmonic distortion (THDu) occurs in the scenario when all the households install PV plants. An overall contribution of all installed PV plants to the THDu is higher than 2% but does not violate harmonic limit, stated by EN50160 – THDu<8%. [9] The same is concluded by authors of [10-11], there is an impact but harmonic limits are not violated.

3. Results and Discussion

The aim of this project was to analyze an impact of DG technology on harmonic voltage distortion level and the analysis in this project is done for three scenarios: PVs are connected with 2 different powers and PV disconnected from the grid. The different analyses have been performed to identify the level of the PQ issue. In this study, the software tool DIgSILENT Power Factory is used, performing harmonic load flow in Power Quality and Harmonic Analysis toolbox. Between first and second scenarios there are not any major disimilarities, they are at least the same, except third scenario where we have a difference because PV is connected with higher power of 5700kW. As mentioned earlier, PVs cause harmonics because of the inverters, but technology has advanced and nowadays there are inverters which do not cause so much harm in the network. Harmonic voltage distortion increases when PV is connected to the system and in that way improves power quality. Harmonic distortion increases but not to the point that is not acceptable. However, their impact will be sensed, especially in the bigger systems with the greater power. Results are similar for the first two scenarios and these results are still good and the difference can be justified by the third scenario with higher power. The results are done descriptively, graphically and in a tabular manner and it will show how a PV power plant is going to affect the grid.

4. Modelling and simulation

A. Problem Formulation

Problem of harmonics, described in previous chapters, is shown on the example of MV distribution network. The problem is based on determination of harmonic voltage distortion level of 5th to 31th harmonics at the bus marked in Figure 1. An impact of DG technology (PV) on HD level is analyzed. Analysis is done for three scenarios: (i) PV disconnected (210kW), (ii) PV connected (210kW) and (iii) PV connected (5700kW). In this study, the software tool – DIgSILENT Power Factory is used, performing harmonic load flow in Power Quality and Harmonic Analysis toolbox. In the calculation of harmonic load flow, PowerFactory performs a steady-state network analysis at each frequency at which harmonic sources are determined. [12] PowerFactory harmonic power flow calculates indexes related to current and voltage distortion and harmonic losses caused by harmonic sources (usually nonlinear loads). For analyzing the impact of harmonics in power systems, DIgSILENT PowerFactory provides Harmonics Load Flow. [13]

The analysis is done using the model of distribution network 110/35/10kV. The test system has one 3-winding transformer, four 2-winding transformers, 5 loads and 6 power lines. Components of the network are presented in Table 1. PV is connect at bus bar called "10kV Busbar" where the load is in allowing limits with active power of 2MW and reactive power of 1MVar. PV has apparent power of 210kVA and active power of 300kW. An impact of integration of Photovoltaic system in the distribution network is analyzed. The model of the network is designed in DIgSILENT, with the marked bus of interest, as shown in Figure 1.

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Table 1. Components of the network

Busbars	13
Power lines	6
Transformers	5
Loads	5

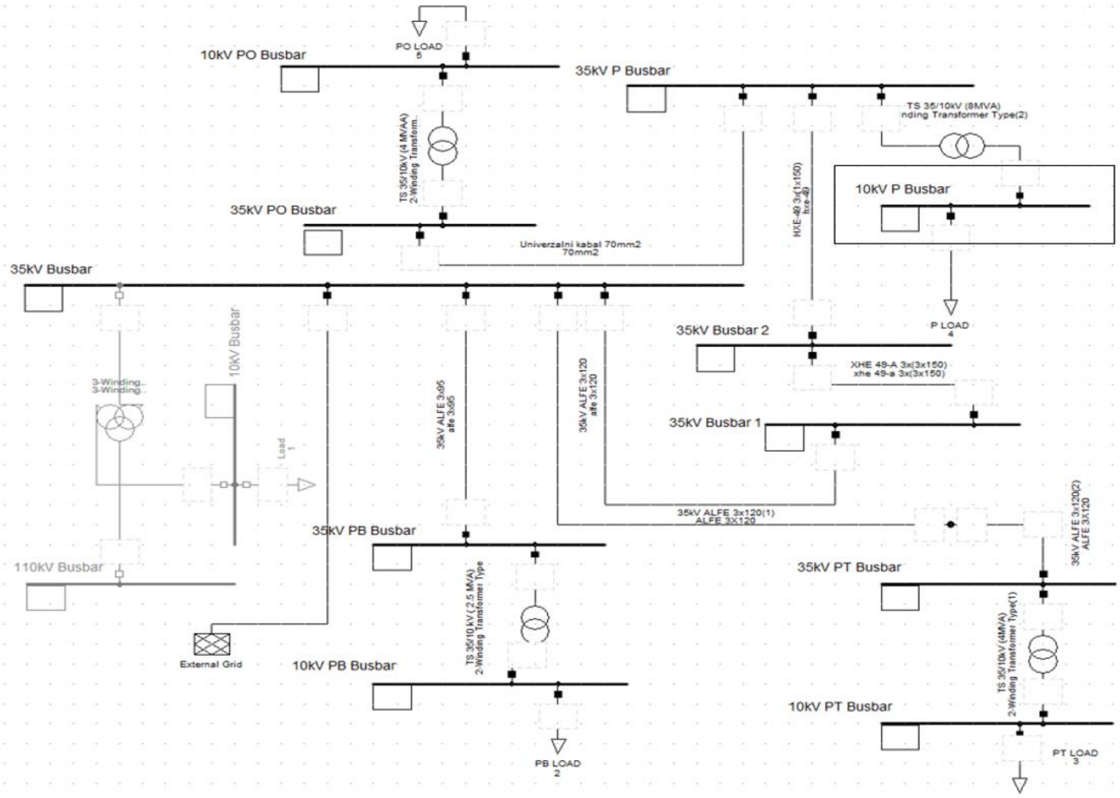

Figure 1. Model of the analyzed network

We will have here 2 scenarios of harmonics modelling, first when is used Load Flow Balanced and second when is used Load Flow Unbalanced (3 Phase: A, B, C). We take into consideration two busbars: 10kV P Busbar (the bus of interest) and 10kV PB Busbar with 31th harmonic order.

a) Load Flow Balanced

Balanced - characteristic harmonics occur in the positive sequence component (7th, 13th, 19th, etc.), or in the negative sequence component (5th, 11th, 17th, etc.) in the case of a symmetrical network with balanced harmonic sources. Hence, a single-phase equivalent (either positive or negative sequence) can be used for the analysis at all frequencies. Figure 2. shows HD in % for 2 busbars: 10kV P Busbar and 10kV PB Busbar. For searching the bus of interest, these 2 busbars have the lowest HD in % in the entire network.

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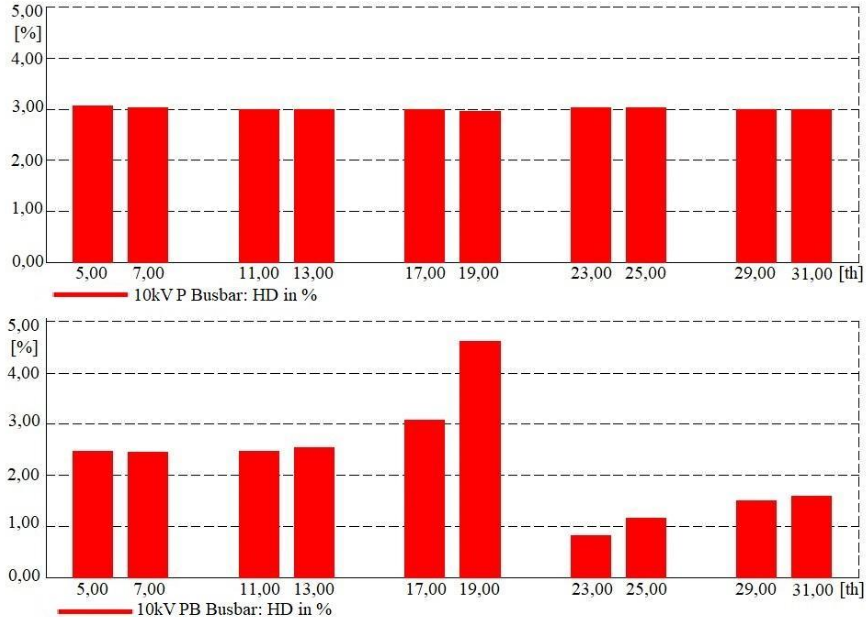

Figure 2. Harmonic Distortion in % for 2 busbars

b) Load Flow Unbalanced (3 phase – ABC)

Unbalanced, 3-phase (ABC) for analyzing non-characteristic harmonics (3rd order, even-order, interharmonics or harmonics in non-symmetrical network), this uncommon option for modelling the network in the phase-domain should be chosen. Figure 3 shows HD in % for 2 busbars: 10kV P Busbar and 10kV PB Busbar including 3 phases-(ABC).

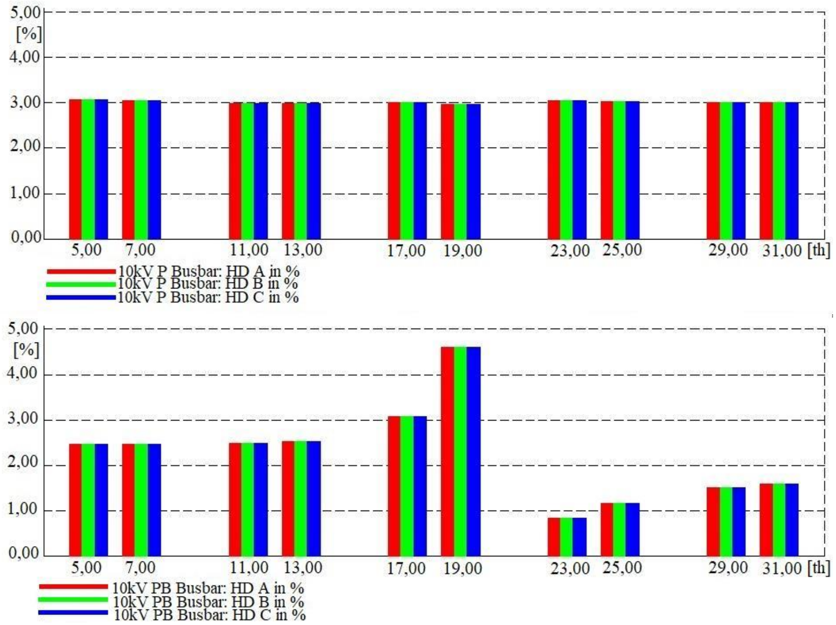

Figure 3. Harmonic Distortion in % for 2 busbars

Table 2. represents the HD in % for 2 busbars: 10kV P Busbar and 10kV PB Busbar which are shown from the Figure 2. and Figure 3., when entire network is analyzed without any PV connected.

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Table 2. Harmonic Distortion in % for 2 busbars

Harmonic Distortion (HD) in %		
Harmonic orders	10kV P Busbar	10kV PB Busbar
5th	3,0643	2,4660
7th	3,0307	2,4584
11th	2,9900	2,4795
13th	2,9879	2,5403
17th	2,9973	3,0751
19th	2,9529	4,6039
23th	3,0364	0,8281
25th	2,0206	1,1645
29th	2,9968	1,5049
31th	3,0026	1,5987

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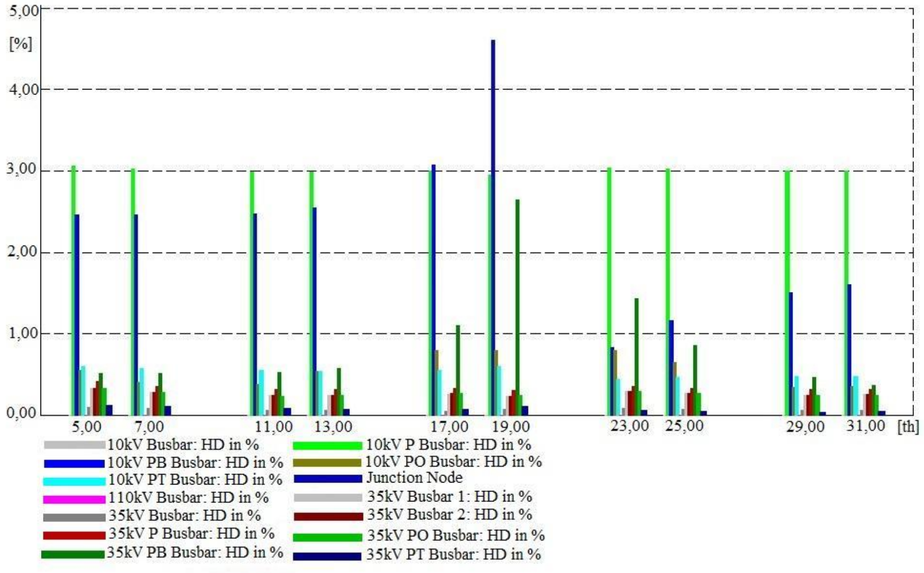

Figure 4. Harmonic Distortion in % for all busbars without PV

Figure 4. shows HD in % for all busbars in the whole network without solar power plant. Figure 5. represents waveform plot for 2 busbars, where x-axis shows values in seconds [s], while y-axis shows values in amplitudes [A]. The red color is 10kV P Busbar and form figure we can see that waveform plot is a real harmonic distortion, while the blue color is 10kV PO Busbar and it shows that there barely exist harmonic distortion.

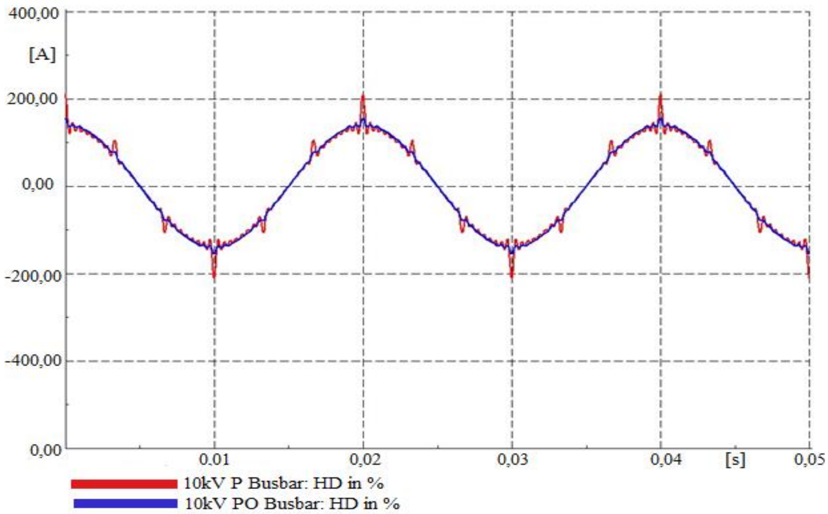

Figure 5. Harmonic Distortion in % for 2 busbars – waveform plot

Table 3. shows HD in % for all busbars with 3 scenarios:

1. PV disconnected from the network
2. PV connected with active power of 210kW
3. PV connected with higher power of 5700kW

This table includes the complete topology of the network. The results that we get from table, the highest HD in % has 10kV P Busbar, while the lowest has 110kV Busbar for all these 3 scenarios.

Table 3. Harmonic Distortion in % for all busbars with 3 scenarios

Name of Busbars	PV disconnected	PV connected (210kW)	PV connected (5700kW)
	HD in %	HD in %	HD in %
10kV P Busbar	5,57167	5,57056	5,54416
10kV PB Busbar	4,840274	4,844502	4,948635
10kV PO Busbar	2,942774	2,945297	3,006322
10kV PT Busbar	3,001534	3,002078	3,012993
10kV Busbar	1,242805	1,243834	1,267714
35kV P Busbar	2,830056	2,830905	2,850502
35kV PB Busbar	3,112159	3,114321	3,166598
35kV PO Busbar	2,774163	2,775247	2,800827
35kV PT Busbar	2,594297	2,59570	2,629479
35kV Busbar	2,565647	2,567134	2,603111
35kV Busbar 1	2,768072	2,769138	2,794252
35kV Busbar 2	2,769446	2,77051	2,795583
110kV Busbar	0,1377921	0,137895	0,1402935
Junction Node	2,593119	2,594538	2,628716

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And this Figure 6, is represented like as a profile (HD in % versus busbars). From figure we can see that the highest HD in % has 10kV P Busbar, while the lowest HD in % has 110kV Busbar (including all these 3 scenarios).

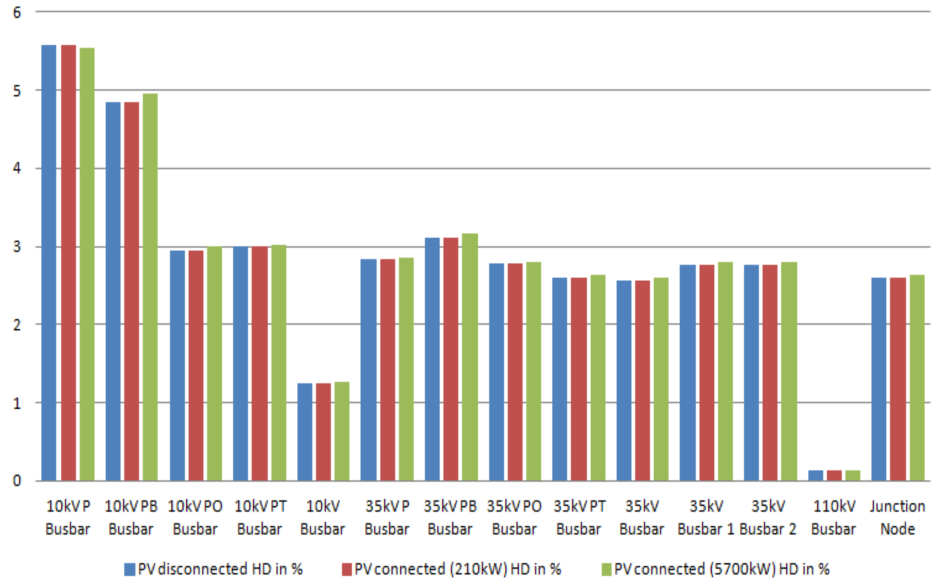

Figure 6. Harmonic Distortion in % for all busbars with 3 scenarios

Now, Table 4. shows THD in % again for all busbars with 3 scenarios:

1. PV disconnected from the network
2. PV connected with active power of 210kW
3. PV connected with higher power of 5700kW

Table 4. Total Harmonic Distortion in % for all busbars with 3 scenarios

Name of Busbars	**PV disconnected**	**PV connected (210kW)**	**PV connected (5700kW)**
	THD in %	**THD in %**	**THD in %**
10kV P Busbar	17,00853	17,03875	17,86122
10kV PB Busbar	17,66484	17,72377	19,33891
10kV PO Busbar	10,64375	10,67948	11,78201
10kV PT Busbar	11,18484	11,21511	12,14207
10kV Busbar	4,20437	4,221194	4,70948
35kV P Busbar	10,65629	10,68914	11,7416
35kV PB Busbar	14,70096	14,75297	16,35328
35kV PO Busbar	10,58144	10,61473	11,685592
35kV PT Busbar	10,50223	10,53536	11,63015
35kV Busbar	10,27017	10,30385	11,38961
35kV Busbar 1	10,57307	10,60631	11,67553
35kV Busbar 2	10,57476	10,6080	11,67723

110kV Busbar	0,506839	0,5087155	0,565915
Junction Node	10,49684	10,53001	11,62602

THD in % for all busbars with 3 scenarios are shown in Figure 7, and it is also represented as a profile (THD versus busbars). From this figure we can see that the highest THD in % has 10kV PB Busbar when PV is installed with higher power (active power of 5700kW and nominal apparent power of 6000kVA), while the lowest THD in % has again 110kV Busbar (including all these 3 scenarios).

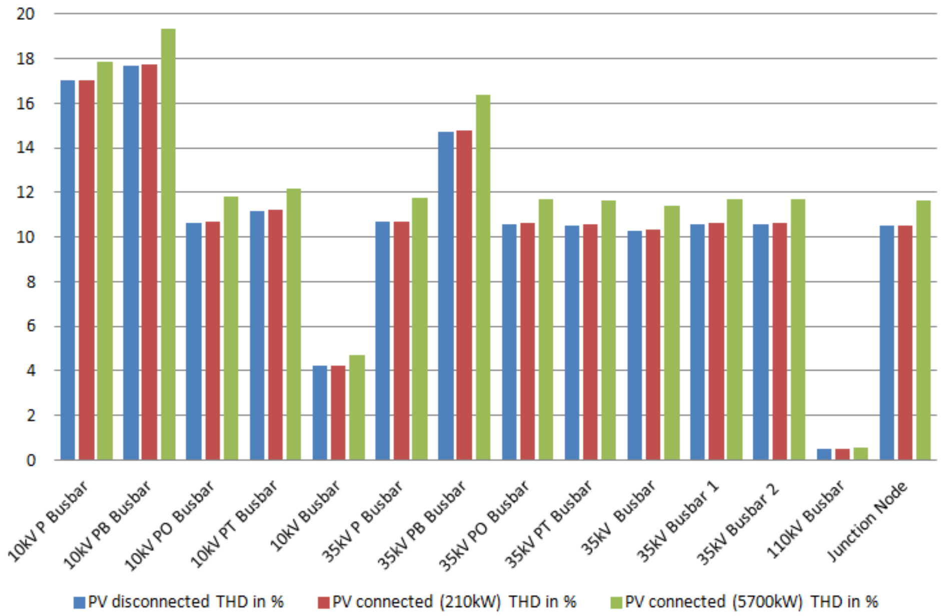

Figure 7. Total Harmonic Distortion in % for all busbars with 3 scenarios

Table 5. Values of harmonic sources in the network in % of fundamental values

Source	**Harmonic Sources**			
	Harmonic current		***Harmonic voltage***	
	5th	7th	5th	7th
External grid	/	/	1.9919	1.2647
PVs	0.2085	1.3266	/	/
Load 1	6.82	2.2	/	/
Load 2	7.94	2.97	/	/
Load 3	7.87	3.04	/	/
Load 4	6.97	3.06	/	/
Load 5	7.71	3.51	/	/

Analysis is done for 3 scenarios: PV disconnected from the grid, PV connected with power of 210kW, and PV connected with higher power of 5700kW on the grid. The resultant harmonic voltage distortion obtained on the bus of interest (10kV P Busbar) after performing harmonic load flow are presented in Table 6.

Table 6. Harmonic voltage distortion for three scenarios

Scenarios	**Harmonic Voltage Distortion**	
	5th harmonic	***7th harmonic***
PV connected (210kW)	3,0643	3,0307
PV connected (5700kW)	3,1525	3,0898
PV Disconnected	5,4571	4,9669

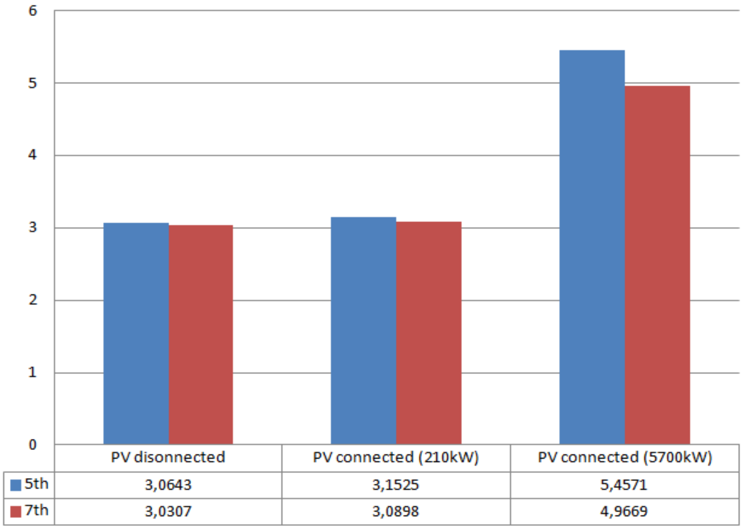

Figure 8. Harmonic voltage distortions for three scenarios - graphical representation

5. Conclusion

Therefore, this project focuses on the analysis and estimation of the PQ phenomena. The aim of this project was to model and analyze an impact of DG technology on harmonic voltage distortion level in one part of a real MV distribution network of test system 110/35/10kV. Analysis is done for 3 scenarios: PV disconnected from the grid, PV connected with power of 210kW, and PV connected with higher power of 5700kW to the grid. In this study, the software tool DIgSILENT Power Factory is used, performing harmonic load flow in Power Quality and Harmonic Analysis toolbox. From results presented in Table 6, where shows harmonics voltage distortion for 3 scenarios, it can be concluded that solar power plants improve the power quality of the system, because harmonic distortion is higher when they are connected with higher power. So, conclusion is that there is no big difference between HD when there is no generation connected to the system and when PVs are connected as we can see from Figure 8 where which shows the comparison of results of these 3 scenarios.

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