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ANALYSIS OF THE IMPACT OF DIFFERENT DISTRIBUTED GENERATOR TECHNOLOGIES ON HARMONIC VOLTAGES

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Keywords: Harmonic voltages; Photovoltaic (PV); Small hydropower plant (sHPP); Distribution network; Power quality (PQ).

While distributed generators (DGs) can reduce carbon dioxide emissions, they can also cause disturbances and lead to power quality (PQ) issues, with harmonic voltages being an important parameter to consider. In this paper, the impact of 14 connected photovoltaics (PVs) and a small hydropower plant (sHPP) on harmonic voltage distortions in a real medium voltage (MV) and low voltage (LV) distribution network in Bosnia and Herzegovina was analyzed. Simulation tools carried out by DigSILENT PowerFactory offer a wide range of advantages that give system operators the ability to have insight into PQ behavior in the presence of intermittent renewable energy sources (RES). Due to the inverter-based electricity generation, PV power plants inject harmonics into the LV network. The impact is relatively small and does not violate the limits from the European PQ standard EN 50160 due to the relatively small power of the modelled existing PVs. However, integrating additional PVs could lead to a violation of limits. Therefore, where a large power of PV power plants is installed, if it is possible to integrate sHPP, they will contribute to the reduction of generated harmonics without the need to reduce the power of PV. The contribution of this paper is that it compares the impact of different power generation technologies on harmonic voltages using data from a real network rather than a test network.

1. INTRODUCTION

The primary objective of power systems is to generate and distribute electrical energy to end consumers while adhering to power quality (PQ) standards such as EN 50160. In traditional power systems, production is centralized and sourced from generation units such as thermal and nuclear power plants [1].

Nowadays, distributed generators (DGs) represent various technologies that produce energy from renewable energy sources (RES), installed close to consumers in the distribution network. From the control centers, an overall system with installed DGs is monitored to control voltage levels and frequency [2]. Introduction of power electronic devices and RES inject harmonics, causing current and voltage distortion levels [3].

The increasing adoption of RES in many countries can be attributed to technological advancements and associated cost reduction. However, integrating many RES systems into power grids can lead to new PQ challenges. While grid-connected photovoltaic (PV) systems are expected to produce sinusoidal output currents from a PQ perspective, the presence of power electronics devices and varying power flow can result in the emergence of harmonics in the PV output current [4].

Also, due to DG's ability to produce energy without pollution, the rapidly growing demand for PV is significant. As more PVs and wind power plants (WPPs) are integrated into distribution networks, harmonic distortion is becoming a serious concern, requiring extensive studies to determine challenges in power networks [5].

Harmonic voltages, a key PQ parameter defined in IEC 61000-2-12, are subject to limits for European distribution networks as specified by EN 50160. These voltages result from non-linear loads injecting harmonic current into the network, leading to harmonic voltage drops on the impedance network. Such sources of harmonics can be attributed to various devices, such as PV systems and electric vehicles, which utilize power electronics [6]. To minimize the effects of harmonics, it is necessary to measure and examine them and attempt to mitigate their influence [2]. Smart grids are reliable despite increasing harmonic distortion challenges due to many power electronic devices [3]. When connecting a single PV system of small or medium size, usually ranging from 1 to 15 kW, to the network, the resulting voltage distortion can be insignificant [7]. The emission of harmonics is significantly higher at frequencies above 2 kHz, commonly called superharmonics [8].

To conduct harmonic voltage studies in this paper, two types of harmonic sources are considered: 1) background harmonics, which result from the harmonic emission in higher voltage levels of the connected networks, and 2) harmonic emissions from loads. The key distinction between the two is that background harmonics are represented as a harmonic voltage source, while harmonic emissions from loads are represented as a harmonic current source [9].

This paper aims to investigate the influence of 14 PV power plants and a small hydropower plant (sHPP), whose total installed power is equivalent to the combined power of the 14 PV power plant, on harmonic voltages in a real medium voltage (MV) and a part of low voltage (LV) distribution network. One significant contribution of the paper is that it compares the impact of different power generation technologies on harmonic voltages using data from a real network instead of a test network. This real-world analysis provides more accurate insights into the effects of PV and sHPP integration on harmonic distortions in the distribution network. Additionally, the paper suggests that integrating sHPP alongside large PVs can help mitigate generated harmonics without reducing the power output of PVs. This finding offers practical guidance for system operators and designers in managing harmonic voltages when integrating multiple power generation technologies.

The structure of this paper is outlined as follows: section 2 provides a review of the relevant literature. Section 3 presents the theoretical basis of the research and details the analysis of the real MV distribution network, as

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well as the methodology used in the DIgSILENT PowerFactory software. In section 4, the results are discussed and compared in detail. Finally, in section 5, the comprehensive simulation results are presented.

2. LITERATURE REVIEW

New DG technologies such as PV units, sHPP, electric vehicles, and WPP can significantly affect the harmonic voltages in future LV networks. Therefore the simulations for harmonic voltages are becoming increasingly important [10]. Over the past years, several studies have been carried out to analyze the impact of DG technologies on harmonic voltages. Most of the published papers refer to the analysis of the impact of PVs [5,11], while a smaller number of studies refer to the WPP [12,13]. A few research papers have been published related to harmonic voltages.

On the other hand, reference [14] investigates the effect on harmonic voltages of four types of EVs. The harmonic impact of a charging station on the MV distribution network is analyzed in [15]. Despite the increasing implementation of sHPP in power networks, limited research has been conducted on the harmonic voltage studies required for their proper integration. This lack of study raises concerns about the effectiveness and safety of sHPP implementation in power networks. Therefore, researchers must conduct further investigations on the harmonic voltage studies to ensure that sHPP can be integrated into power networks without adverse effects [16]. Most studies investigate only the odd harmonics used for the analysis, which are the 5^{th} and 7^{th} harmonic order [5,11,16].

Reference [17] studied measurements of PQ parameters of grid-connected PV systems with a size of 8 kWp and investigated the ratio between current and voltage harmonics in an LV grid. In [18], the authors analyzed the harmonic impact of PV system installation in the unbalanced distribution network by considering two types of PV inverter models.

The impact of the first 10 kW residential PV system in Croatia presented in [19] showed that the highest harmonic distortion (HD) is when all households install the PVs. The optimal penetration level of PVs in an unbalanced distorted network considering the uncertainty of load profile and solar irradiance is solved in [20] by comparing total harmonic distortion (THD) and individual HD. Using smart PV inverters, harmonic resonance problems can be reduced, as presented in [13]. Harmonic analysis considering inverter-based DGs is proposed in [21] to determine the individual influence of DGs on harmonic voltages taking into account the DG output of variable power.

To ensure optimal system performance, assessing the capacity of DGs that can be interconnected with the network is necessary. Reference [22] proposed a methodology for hosting capacity considering the harmonic current effect and impact of harmonic distortion limits. Authors of [23] pointed out the prediction of harmonic current emission of PV systems at the point of common coupling.

In [24], the effect of solar irradiance on the PV system value of THD is presented. Authors have shown that irradiance influences the current profile of THD. Paper [25] proposes THD analysis for different loading of PV systems to avoid future exceeding harmonic limits.

The analysis of the harmonic impact has become a subject of interest for many researchers due to the integration of many PV systems into the distribution network. Reference [26] proposed a comprehensive analysis of PQ challenges. The authors highlighted the important PQ challenges that arise with the integration of RES into the power grid.

Researchers have conducted numerous studies to investigate the impact of nonlinear loads on harmonic voltages [27, 28, 29]. In [30], the effect of the control strategy on operational performance is negated through a modeled PV system, represented as a current source at a harmonic frequency. Harmonic penetration analysis is executed in [13] for two cases regarding integrating offshore WPP based on the real measurements of harmonic voltages. The analysis is done when background harmonic voltages are considered and when the grid and offshore WPP emit harmonics. HD from wind power is more significant on even harmonics [13]. Reference [13] studied harmonic emission from a turbine and the public grid as harmonic studies for WPPs.

Based on the literature in the field of research, it can be inferred that the connection of PV systems to the distribution network leads to an increase in harmonic voltage distortions, while the connection of sHPP results in a decrease in harmonic voltage distortions.

To analyze the effect of PV and sHPP on the MV and LV network, the authors of this paper faced the challenging task of implementing a real harmonic simulation. Despite the task's difficulty, the authors strived to ensure the accuracy of the simulation results to achieve their research objective. Due to the inverter-based electricity generation, PV power plants inject harmonics into the LV network. The impact in the analyzed network is relatively small and does not violate the limits from EN 50160 due to the relatively smaller power of modelled existing PVs. Therefore, integrating additional PV power plants in the network could violate limits for harmonics from EN 50160. However, for such networks, where a larger power of PV power plants is installed, if there is a possibility of integrating sHPP, they will contribute to the reduction of generated harmonics in the network without the need to reduce the power of PV power plants.

3. THEORETICAL FOUNDATIONS AND MODELLING

This section presents a detailed explanation of a real MV and part of the LV distribution network, followed by a description of the problem.

3.1. PROBLEM FORMULATION

This study aims to analyze the harmonic impact of 14 PVs and one sHPP on a real MV and LV distribution network using the DIgSILENT PowerFactory software. Background harmonics are modeled as a harmonic voltage source in the external grid element to simulate the system accurately. In contrast, harmonic emissions of loads are modeled as a harmonic current source. The study focuses on the 5^{th} and 7^{th} harmonics, the network's most significant harmonics.

Four cases have been identified to study the impact of DG technologies, specifically PVs and sHPP, on the distribution level of harmonic voltage:

- Case 1: PVs and sHPP off
- Case 2: PVs on and sHPP off
- Case 3: PVs and sHPP on
- Case 4: sHPP on and PVs off

The harmonic load flow, *i.e.*, the harmonic analysis in the frequency domain, was carried out using the Harmonics/Power Quality toolbar in DIgSILENT PowerFactory.

3.2. ANALYSIS OF REAL MV DISTRIBUTION NETWORK

The required data for this study was received from the Public Electric Utility Elektroprivreda of Bosnia and Herzegovina d.d. Sarajevo. The georeferenced scheme of the analyzed part of the real distribution network in the area of Tešanj city, Bosnia and Hercegovina is presented in Fig. 1. This part of the real network is used to determine the impact of PVs and sHPP on harmonic voltages. The analysis is done on the bus 0.4 kV Žabljak Usora, which contains four connected PVs, to obtain better results required for adequate discussion. SHPP, with installed power equal to the sum of installed powers of all 14 PVs, is connected in the middle of the real part of the analyzed network at the 0.4 kV Kalim bus. Also, harmonic analysis is done on the 0.4 kV Kalim bus where sHPP is connected to see a better impact of sHPP.

This part of a real MV and part of the LV distribution network is supplied from the main 20 MVA, 110/35/10(20) kV substation, which supplies three 35/10(20) kV transformers with a rating of 8 MVA. 27 distribution transformers 10/0.4 kV are required for 27 LV networks. 10/0.4 kV transformers supply residential customers with underground cables. Loads are modeled on 0.4 kV buses. The total power demand of all the loads is 2.318 MVA with a total active power of 2.194 MW and total reactive power of 0.746 MVAr. The different components needed to simulate the MV and part of the LV network are listed in Table 1.

The total installed active power of PV power plants is 733 kW distributed among 14 locations. The sHPP has an installed power equal to the sum of all the PVs and is included in the analysis to examine the effect of a power plant with rotating machines on harmonic voltages. The general diagram of a real MV and part of the LV distribution network in Bosnia and Herzegovina is illustrated in Fig. 2. Total active losses of the analyzed network are 0.16 MW. In contrast, total reactive losses are 1.18 MVAr.

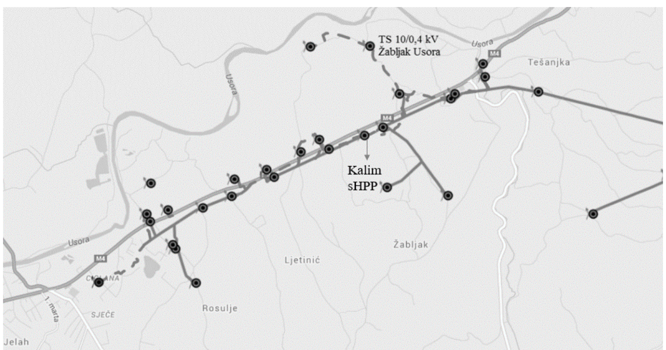

Fig. 1 – Georeferenced scheme of the analyzed location

Table 1
Network parameters

Parameters of the network	No.
Busbars	54
Lines	46
2-windings transformers	30
LV networks	27

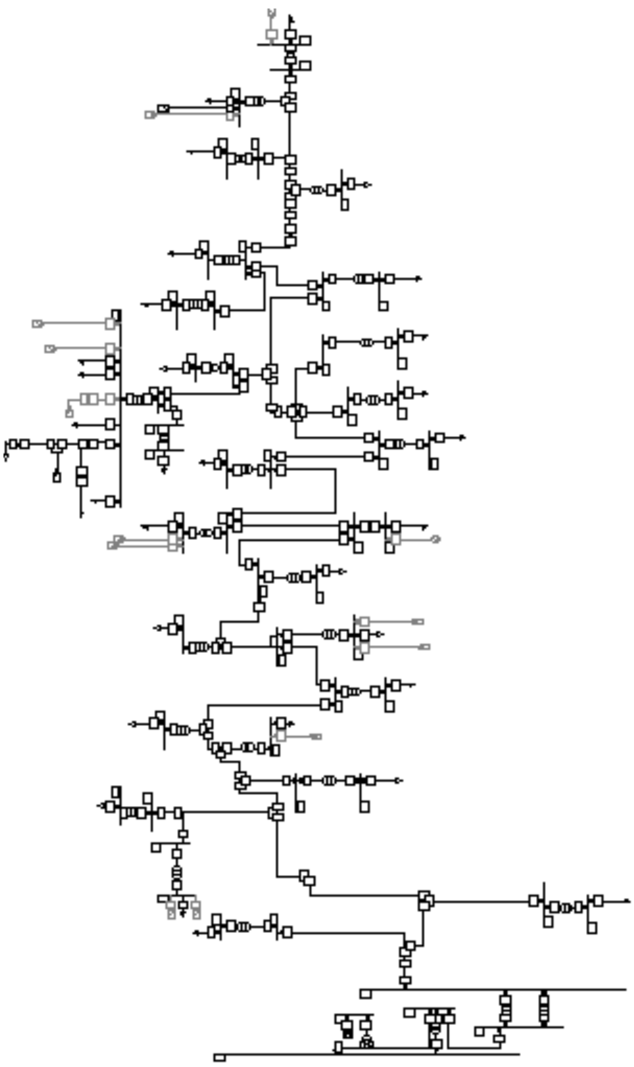

Fig. 2 – Modelled MV and part of LV network in DIgSILENT.

3.3. HARMONIC VOLTAGES

This paper studies three types of harmonic sources in the network: background harmonics as harmonic voltage sources, harmonic emissions from loads, and harmonics of PV's as harmonic current sources. According to the literature [6], sHPP falls under power generation technologies with no harmonic emissions. Harmonic voltages are calculated according to the summation law of the IEC 61000-3-6 standard [6].

The presence of background distortion in real networks must be considered. Field measurements show that the 5th and 7th harmonic voltage is the most significant harmonics, so the analysis focuses on these two orders. The 3rd harmonic, mainly generated in the LV network and forms the zero sequence, can be disregarded due to the delta winding of the MV/LV transformer as it is not transmitted to the MV network [10].

3.3.1. BACKGROUND HARMONICS

Background harmonics are modelled by a harmonic voltage source in the external grid element. The average values for background harmonics of 5th and 7th harmonic voltage distortion in percentage are obtained from the previous study [6], as illustrated in Fig. 3. These values are 0.6 % and 0.4 %, respectively. These percentage values are converted into per unit (pu) values for modelling purposes.

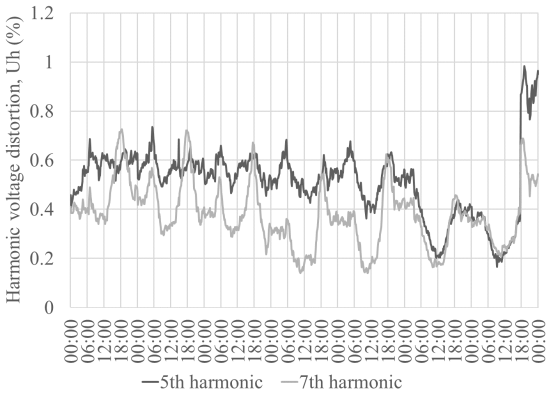

Fig. 3 – Background of the 5th and the 7th harmonic voltage distortion [6].

3.3.2. HARMONIC EMISSIONS FROM LOADS

Harmonic emissions from loads are modelled as harmonic current sources. According to the literature [5], the average 10-minute values for the 5th and 7th harmonic current as a percentage of fundamental current used for residential customer configurations in Germany are illustrated in Fig. 4 and used in this paper. Since households in Bosnia and Herzegovina typically use fewer power electronic devices than those in Germany due to the lower living standard, minimum values of $I_5 = 5$ % and $I_7 = 1.5$ % from the graph are used for the daily operation of the power plants in Bosnia and Herzegovina.

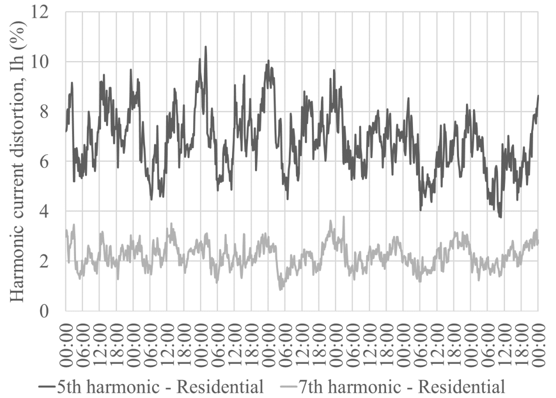

Fig. 4 – 5th and 7th harmonic current emissions as a percentage of fundamental current for configuration of residential customers in Germany [6].

3.3.3. HARMONIC EMISSION FROM PVS

Harmonic emissions from PVs are modelled as harmonic current sources. The values for the 5th and 7th harmonic current are taken from [8], where harmonic currents emitted by six PV inverters of small size are shown, measured in Dresden, Germany. Only four of the six inverters are used, as they are three-phase inverters and are more suitable for the higher power output of the PV power plant.

Table 2

Conversion of amperes into percentage harmonic current values based on fundamental current

5th harmonic	PV3	PV4	PV5	PV6
I_A	0.07	0.17	0.045	0.065
I_F	14.45087	10.83815	5.780347	14.45087
$I_\%$	0.4844	1.568533	0.7785	0.4498
Average I_{ave}	0.82			
7th harmonic	**PV3**	**PV4**	**PV5**	**PV6**
I_A	0.03	0.22	0.08	0.1
I_F	14.45087	10.83815	5.780347	14.45087
$I_\%$	0.207612	2.031394	1.384083	0.692042
Average I_{ave}	1.08			

The values for the 5th and 7th harmonic current are used as a simple arithmetic average value of four three-phase PV inverters i.e., PV3 – PV6. Harmonic current values in amperes (IA) are converted into the harmonic current in percentage (I%) based on fundamental current (IF), as presented in Table 2. Iave represents the average value.

3.4. FREQUENCY DEPENDENCY

To address the lack of known values for certain components within the analyzed network, frequency-dependent impedances of transformers, overhead lines, and cables are modeled using the DigSILENT library and frequency characteristics based on typical distribution network components. This approach allows for a more accurate network assessment despite the uncertainty surrounding specific component values. Therefore, frequency dependencies of resistance and inductance of 2-windings transformers 35/10 kV are modelled as characteristic of 108/10.5 kV, 40 MVA available in DIgSILENT PowerFactory. Distribution transformers 10/0.4 kV are modelled as frequency characteristics of 20/0.4 kV, 250 kVA transformers [5]. Frequency dependency of cables and overhead line impedances are modelled as characteristics of Cable 20 kV NEKBA 3x1x70 and Overhead Line 20 kV, respectively.

4. RESULTS AND DISCUSSION

Harmonic load flow is performed for four cases explained in subsection 3.1, and they are compared for harmonic analysis. A comparison of harmonic voltage distortion expressed in % is discussed at 0.4 kV Žabljak Usora bus, which has four connected PVs in its LV network. The results are presented in Table 3, and the graphical representation is illustrated in Fig. 5.

Furthermore, harmonic voltage distortions for four cases are compared and discussed on the 0.4 kV Kalim bus where sHPP is connected. The results are represented in Table 4. The graphical representation is illustrated in Fig 6.

According to EN 50160, the 5th harmonic must be below 6 %, while the 7th harmonic must be below 5 %. It can be inferred from the information presented in both Fig. 5 and 6 that the EN 50160 standard has been met and that the harmonic voltages fall within the acceptable range.

Case 2, PVs on and sHPP off, at the bus Žabljak Usora, indicates that connecting the PV power plant results in higher harmonic voltage distortions due to the presence of PV inverters that cause harmonic voltages. In Case 2, the absence of PV power plants connected to the 0.4 kV Kalim bus resulted in unexpected outcomes for the 5th harmonic on the Kalim bus. This is because the PVs are connected further from the Kalim bus and have less impact. However, the 7th harmonic showed an increase consistent with expectations and higher compared to Case 1, PVs and sHPP off.

To study the effects of sHPP, a model was created to analyze their impact on harmonic voltage distortion. In Case 4, sHPP on and PVs off, it was observed that the harmonic voltage distortions on both buses decreased when the SHPP was connected.

Table 3

Harmonic voltage distortion expressed in % for four cases on 0.4 kV bus Žabljak Usora

CASES	HARMONIC VOLTAGE DISTORTION [%]	
	5th harmonic	7th harmonic
Case 1: sHPP and PVs off	4.76538	2.06389

Case 2: PVs on and sHPP off	4.79861	2.16556
Case 3: PVs and sHPP on	4.74341	2.14064
Case 4: PVs off and sHPP on	4.70884	2.0394

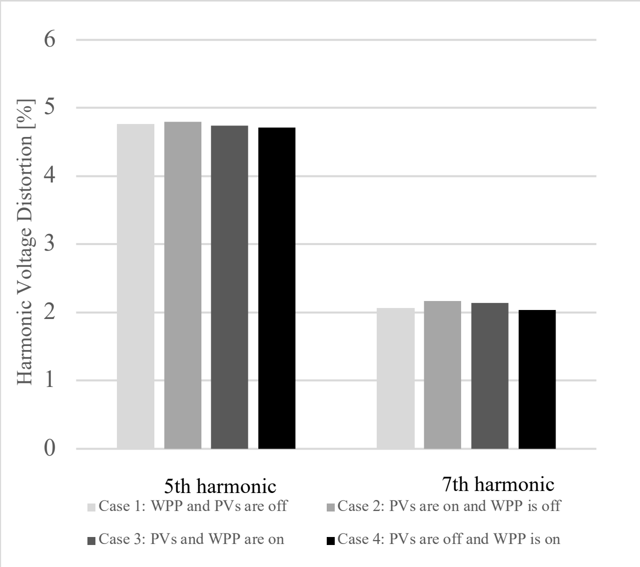

Fig. 5 – Graphical representation for four cases of harmonic voltage distortion on 0.4 kV Žabljak Usora bus.

Table 4
Harmonic voltage distortion on 0.4 kV bus Kalim

CASES	HARMONIC VOLTAGE DISTORTION [%]	
	5th harmonic	7th harmonic
Case 1: sHPP and PVs off	2.1262	1.00159
Case 2: PVs on and sHPP off	2.1104	1.00301
Case 3: PVs and sHPP on	2.09125	0.9939
Case 4: PVs off and sHPP on	2.10651	0.9923

Upon analyzing the results, it was discovered that the 5th harmonic exceeded the predetermined limits, thus necessitating a maximum power output of 13 MW to remain compliant with EN 50160. However, this power plant cannot be connected to the network due to other factors (voltage variations, rapid voltage change, etc.). here the case is that there will first be violations according to other criteria and then the harmonics.

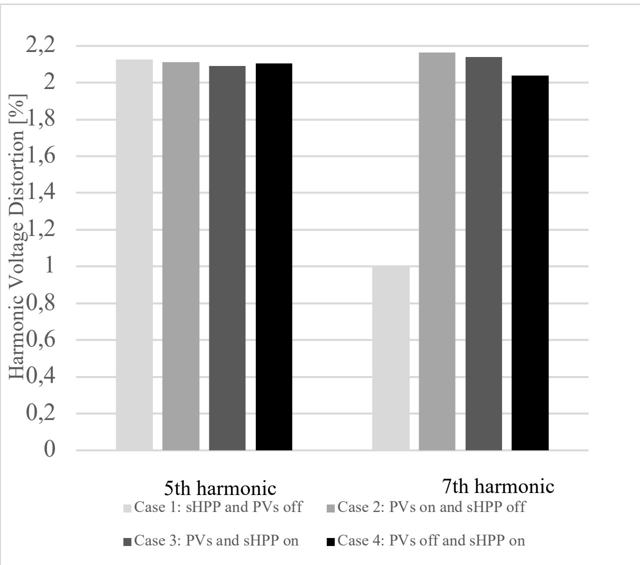

Fig. 6 – Graphical representation for four cases of harmonic voltage distortion on 0.4 kV bus Kalim.

5. CONCLUSIONS

This paper evaluates the impact of PV power plants and sHPP on harmonic voltages in a real MV and part of the LV distribution network in Bosnia and Herzegovina. All simulations are carried out by DIgSILENT PowerFactory, which proved to be a valuable platform for harmonic studies. Installing 14 PV power plants in the network (Case 2 – PVs on and sHPP off), resulted in increased harmonic voltage distortions compared to Case 1, sHPP, and PVs off. However, the harmonic voltage distortion remained within acceptable limits. It can be concluded that the inverters required for connecting the PV power plants with the network cause harmonic voltages, but contemporary PV inverters do not lead to limit violations. This is partially due to the improvements made to the PV inverters over time, resulting in reduced harmonic emissions.

None of the scenarios violates the European standard EN 50160 for 5th and 7th emission, indicating that the network can withstand the HD introduced by PVs. In Case 4, PVs and sHPP on harmonic voltage distortions are reduced, resulting in improved PQ. The standard EN 50160 is met for the 5th and 7th analyzed harmonic.

This paper can serve as a useful guide for conducting harmonic voltage simulations. Further research could focus on assessing the harmonic emissions from WPP.

Additionally, the results confirm the findings of [16], which showed that PV plant integration leads to a slight increase in harmonic voltages. In contrast, the sHPP integration leads to a slight decrease in harmonic voltages. However, the results may vary for networks of different voltage levels and configurations, making it difficult to compare similar research studies accurately.

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REFERENCES

1. A. F. Abdul Kadir, A. Mohamed, H. Shareef, *Harmonic impact of different distributed generation units on low voltage distribution system,* IEEE International Electric Machines & Drives Conference (IEMDC), Niagara Falls, ON, Canada, 2011.
2. Alma Halilovic, Lejla Mujanovic, Jasna Hivziefendic, *Influence of the distributed generation on the power quality in distribution network,* Journal of Natural Sciences and Engineering, **3**, 1 (2019).
3. R. Sinuvla, K. M. Abo-Al-Ez, M. T. Kahn, *Efficiency in distribution networks with harmonic distortion,* 17th Industrial and Commercial Use of Energy Conference, The Riverclub, Cape Town, 2019.
4. K. Fekete, Z. Klaic, Lj. Majdandzic, *Expansion of the residential photovoltaic systems and its harmonic impact on the distribution grid*, Renewable Energy, **43**, pp. 140–148 (2012).
5. I.T. Papaioannou, A.S. Bouhouras, A.G. Marinopoulos, M.C. Alexiadis, C.S. Demoulias, D.P. Labridis, *Harmonic impact of small photovoltaic systems connected to the LV distribution network,* IEEE International Conference on European Electricity Market EEM, Lisboa, Portugal, 2008.
6. A. Bosovic, H. Renner, A. Abart, E. Traxler, J. Meyer, M. Domagk, M. Music, *Validation of aggregated harmonic current source models based on different customer type configurations*, IEEE Power Quality and Supply Reliability Conference (PQ), Tallinn, Estonia, 2016.
7. S.M. Ahsan, H.A.B. Khan, A. Hussain, S. Tariq, N.A. Zaffar, *Harmonic analysis of grid-connected solar PV systems with nonlinear household loads in low-voltage distribution networks*, Sustainability, **13**(7), 3709 (2021).
8. J. Smith, S. Ronnberg, A. Blanco, M. Bollen, Z. Emin, D. Ilisiu, L. Koo, J. Meyer, D. Mushamalirwa, P. Ribeiro, N. Wilmot, *Power quality aspects of solar power – Results from CIGRE JWG C4/C6.29*, 24th International Conference on Electricity Distribution, Glasgow, 2017.
9. A. Bosovic, M. Music, H. Renner, A. Abart, E. Traxler, J. Meyer, M. Domagk, *Modelling the propagation of harmonic voltages in large medium voltage distribution network*, 25th International Conference on Electricity Distribution, Madrid, 2019.

10. S. Muller, J. Meyer, *Challenges and pitfalls of implementing realistic simulations to study harmonic levels in public low voltage network,* IEEE Power Tech Conference, Milan, Italy, 2019.

11 A. Elkholy, *Harmonics assessment and mathematical modeling of power quality parameters for low voltage grid-connected photovoltaic systems*, Solar Energy, Elsevier, **183**, pp. 315–326 (2019).

12. S.N. Guler, K.C. Bayindir, A. Tan, *Harmonic effects on an OWPP connection to Northwestern part of Turkey-A case study*, International Journal of Scientific Engineering and Science, **6**, pp. 36-45 (2022).

13. K. Yang, M.H.J. Bollen, H. Amaris, C. Alvarez, *Decompositions of harmonic propagation in wind power plant,* Electric Power Systems Research, Elsevier, **141**, pp. 84-90, 2016.

14. N. Nalo, A. Bosovic, A. Merzic, M. Music, *Analysis of the impact of electric vehicle charging on harmonic voltages in a low-voltage distribution network,* Elekrotehniski Vestnik, **88**, 4, pp. 218-226, 2021.

15. T. Pothinun, S. Premrudeepreechacharn, *Power quality impact of charging station on MV distribution networks: A case study in PEA electrical power system,* 53rd International Universities Power Engineering Conference (UPEC), Glasgow, UK, 2018.

16. E. Kisija, A. Bosovic, M. Music, *Analysis of the impact of different DG technologies (SHPP vs. PV) on short-circuit power and harmonics in a real MV distribution network,* Elekrotehniski Vestnik, **88**, *1-2*, pp.17-25, 2021.

17. A. Chidurala, T.K. Saha, N. Mithulananthan, *Harmonic impact of high penetration photovoltaic system on unbalanced distribution networks – learning from an urban photovoltaic network*, IET Renewable Power Generation, **10**, 4, pp. 485–494 (2016).

18. K. Fekete, Z. Klaic, Lj. Majdandzic, *Expansion of the residential photovoltaic systems and its harmonic impact on the distribution grid*, 2012 Renewable Energy, **43**, pp. 140–148 (2012).

19. I.C. Barutcu, E. Karatepe, M. Boztepe, *Impact of harmonic limits on PV penetration levels in unbalanced distribution networks considering load and irradiance uncertainty*, International Journal of Electrical Power & Energy Systems, Elsevier, **171** (2020).

20. S.S. Rangarajan, E.R. Collins, J.C. Fox, *Efficacy of a smart photovoltaic inverter as a virtual detuner for mitigating network harmonic resonance in distribution systems*, Electric Power Systems Research, Elsevier, **171**, pp. 175–184(2019).

21. S. Wang, X. Liu, K. Wang, L. Wu, Y. Zhang, *Tracing harmonic contributions of multiple distributed generations in distribution systems with uncertainty*, International Journal of Electrical Power & Energy Systems, Elsevier, **95**, pp. 585–591 (2018).

22. I.N. Santos, V. Cuk, P.M. de Almeida, M. Bollen, P.F. Ribeiro, *Considerations on hosting capacity for harmonic distortions on transmission and distribution systems*, Electric Power System Research, Elsevier, **119**, pp. 199–206 (2015).

23. H.A. Pereira, F.D. Freijedo, M.M. Silva, V.F. Mendes, R. Teodorescu, *Harmonic current prediction by impedance modeling of grid-tied inverters: A 1.4 MW PV plant case study*, International Journal of Electrical Power & Energy Systems, Elsevier, **93**, pp. 30–38 (2017).

24. M. Ayub, C. K. Gan, A.Fazliana, A. Kadir, *The impact of grid-connected PV systems on harmonic distortion*, IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia), Melaka, 2014.

25. A. Agrawal, D.K. Singh, *Harmonic impact of grid connected photovoltaic system on low voltage power system*, IEEE International Conference for Convergence of Technology *I2CT*, Pune, India, 2018.

26. M. Bajaj, A.K. Singh, *Grid integrated renewable DG systems: A review of power quality challenges and state-of-the-art mitigation techniques*, International Journal of Energy Research, **44**, pp. 26–69 (2020).

27. G. McLorn, D. Laverty, D.J. Morrow, S. McLoone, *Load and harmonic distortion characterization of modern low-energy lighting under applied voltage variation,* Electric Power Systems Research, Elsevier, **169**, pp. 124–138 (2019).

28. C. K. Neha, M. Hegde, V. Aher, V. Hegde, *Effect of home appliances on power quality of conventional grid*, IEEE International Conference on Circuits, Communication, Control and Computing, 2016.

29. G. Ye, M. Nijhuis, V. Cuk, J. Cobben, *Appliance-based residential harmonic load modelling,* IEEE Manchester PowerTech, 2017.

30. R. Torquato, F.C. L. Trindade, W. Freitas, *Analysis of the harmonic distortion impact of photovoltaic generation in Brazilian residential networks,* IEEE International Conference on Harmonics and Quality of Power (ICHQP), 2014.