ELEKTROTEHNIŠKI VESTNIK 92(3): 143-150, 2025
ORIGINAL SCIENTIFIC PAPER

The impact of three-phase connected photovoltaic power plants on voltage profiles due to insulation, external temperature and inverter efficiency

Mario Ostojić [1,*], Adnan Bosović [2], Mustafa Musić [2]

[1] International Burch University, Faculty of Engineering, Natural and Medical Sciences, Francuske revolucije bb, 71210 Ilidža, Bosnia and Herzegovina
[2] Public Electric Utility Elektroprivreda d.d. - Sarajevo, Vilsonovo šetalište 15, 71000 Sarajevo, Bosnia and Herzegovina
[*] E-mail: mario.ostojic@stu.ibu.edu.ba

Abstract. Nowadays, photovoltaic power plants are widely used because they produce low-cost insulation clean energy at lower costs, thereby contributing to energy independence and reducing CO_2 emissions. In this study, the data on network component parameters of a low-voltage feeder operating in Bosnia and Herzegovina is analysed. Also, it includes real-time data of load profiles from a control meter installed in a transformer substation. Time-series with one-hour readings of three parameters are also used: insulation (i.e. a global horizontal irradiance, external (ambient) temperature and inverter efficiency. The occurrence of the three parameters is analysed on three-phase connected photovoltaic power plants. Readings for the irradiance and ambient temperature are obtained from Solcast API Toolkit and those for the inverter efficiency with equation with the effect of the irradiance and ambient temperature simultaneously. The voltage profiles are analysed according to the EN 50160 standard. The network is modelled in the DIgSILENT powerfactory software and its analysis is made using the Quasi-Dynamic Simulation Toolbox. In total, 18 scenarios are made: nine without and nine with Normal operating cell temperature conditions, executed by Balanced Load Flow. Results show how that the three parameters affect the voltage levels of the three-phase connected photovoltaic power plants of the power network on a typical summer day with a direct impact on the network power quality.

Keywords: three-phase photovoltaic power (PV) plant, low-voltage (LV) network, power quality, Balanced Load Flow (BLF)

Vpliv trifazno priključenih fotonapetostnih elektrarn na napetostne profile zaradi izolacije, zunanje temperature in učinkovitosti pretvornika

V sodobnem času so fotonapetostne elektrarne razširjene zaradi proizvodnje čiste energije z nizkimi stroški, kar prispeva k zmanjšanju emisij CO_2 in energetski neodvisnosti. Študija analizira parametre nizkonapetostnega omrežja v Bosni in Hercegovini ter podatke o dejanski obremenitvi iz kontrolnega števca v transformatorski postaji.

Uporabljeni so enourni odčitki treh parametrov: globalna obsevanost, zunanja temperatura in učinkovitost pretvornika. Podatki za obsevanost in temperaturo okolice so pridobljeni prek Solcast API, učinkovitost pretvornika pa je izračunana glede na oba ta dva vpliva. Analiziran je tudi njihov vpliv na trifazno priključene fotonapetostne elektrarne.

Napetostni profili so ocenjeni po standardu EN 50160 v okolju DIgSILENT PowerFactory z uporabo orodja Quasi-Dynamic Simulation Toolbox. V 18 scenarijih so prikazani vplivi parametrov na napetostne nivoje in kakovost električne energije v omrežju.

Received: 28 February 2025
Accepted: 25 April 2025

1 INTRODUCTION

PV power plants are important because they reduce reliance on fossil fuels, improve the power reliability and contribute to the fight against climate changes. They can have a major impact on the system because they decentralize the power production and enable a more flexible and resilient power infrastructure. As PV power plants are becoming more and more popular, it is important to model them optimally, taking into account all the important parameters.

[1] analyses the voltage profiles in a LV distribution network near and far from a distribution transformer according to the EN 50160 standard using the Monte Carlo-based method. The findings highlight the challenges, such as the voltage rise and reverse power flows.

[2-4] uses a softwares Power System Computer Aided Design (PSCAD) and MATLAB (fixed-point algorithm using a Y_{bus} representation and the backward-forward sweep algorithm, generating the power by a three-phase grid-connected PV system towards the grid and load to

record the voltage variations and discuss the power quality.

Several works deal with the Quasi-Dynamic Simulation (QDSL) Toolbox within the DIgSILENT powerfactory software. Due to the variable load modelling with the active and reactive power, maintaining the voltage profiles is estimated according to different standards. Results show that the large penetration of the PV power plants directly affects the daily voltage variations and line losses within different calculation intervals. [9] presents a comparison of eight models used to estimate the global horizontal irradiance. Based on different parameters (direct normal irradiance, diffuse horizontal irradiance, clearness index, sun altitude, ambient temperature, relative humidity, etc.), on appropriate model can be chosen and created.

[10-11] deal with the modelling of Normal operating cell temperature (NOCT) conditions consisting of two crucial parameters: global horizontal irradiance and ambient temperature. By using their reference conditions and values compliant with the adopted rules and procedures and connected with PV-s, different simulations are performed to analyse the global horizontal irradiance and ambient temperature.

[12-14] investigate the effect of the PV variation of the ambient temperature and global horizontal irradiance at different climate conditions and load models on the inverter output, i.e. its efficiency in a grid-connected system, as well as overall losses. It is shown that in the summer season the inverter efficiency decreases because of the peak temperature value and slightly increases with the increase in the global horizontal irradiance.

[15] distributes the single-phase consumers in the LV distribution network and investigates the voltage unbalance. Using different scenario shows that a higher PV plant penetration in the network creates a higher power imbalance. Also, a higher PV penetration occurs in scenarios which need to be improved and optimized using the Phase Balance Optimization Toolbox within the DIgSILENT powerfactory software.

[16] presents the microgrids inside a stand-alone mode and outside it [17] in the QDSL Toolbox within DIgSILENT powerfactory and Hybrid Optimization Model for the Multiple Energy Resources (HOMER) software. Based on real power resource data, consumer load profiles, PV system, Wind Generator (WG) and battery sizing [16] the appropriate wind-installed power, PV and diesel power plants in combination with the battery storage [17] are estimated. The investigation of the voltage profiles proves that the system can operate with the modelled microgrids.

[18] evaluates a methodology for analysing the effects of integrated distributed generators (DG) on the distribution network of the Public Power Utility Elektroprivreda of Bosnia and Herzegovina, Sarajevo (EP in the B&H). The challenges and opportunities associated with the integration of DGs into the distribution network are considered with regard to the factors such as voltage control, power quality, network stability and techno-economic analysis. The findings are satisfactory for the power consumers and EP in the B&H, stakeholders involved in the planning, operation and control of the power distribution network.

2 METHODOLOGY

2.1 Modelling of the low-voltage feeder

A real part of the rural LV power distribution transformer substation in the vicinity of Tešanj is shown in Figure 1. The transformer power depends on the load power. The analysed LV feeder consists of 26 consumers. 19 of them are single-phase (17 are registered and two are not) and seven are three-phase and registered which is important for the analysis. Figure 1 is a precise presentation of the analysed location. The blue-pink squares are consumers. There are three locations with two consumers on each location which gives 26 consumers. As seen, the consumers are densely distributed in the middle of the network. The greater the distance between them from the transformer substation, the more significant is the impact on the power quality variation in the LV distribution network due to the changes in the consumers consumption.

Figure 1. Georeferenced representation of the network

Based on the data from EP in the B&H, from the control meter of the analysed network is processed. The day with the lowest power consumption during a high PV power plants production is determined from one-hour readings from the control meter. This is done by filtering all the consumption values around the middle of the day during the summer months June, July and August, the ones with the most sunny days. The reactive power readings from the control meter at the transformer substation are ignored for being equal to 0 MVA_r. Based on the above facts, the 02^{ND} July 2021 at 12:30 P.M. was chosen. The lowest consumption of the day read from the control meter during a high PV plant production is 2.512 kW, which is the minimum modelled load. It consists of relative values of single-phase and three-phase consumers connection power. In the model, it is distributed over three single-phase and three-phase consumers. One is in the beginning, the other one is in the middle and the third is at the end of the network. The

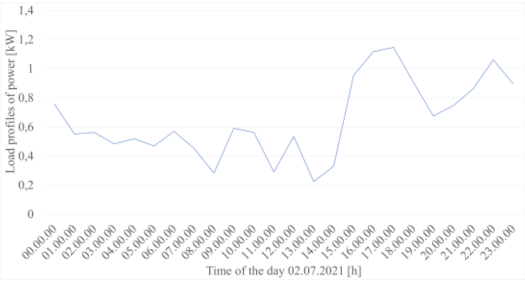

Figure 2. Day with the power load profiles during a high PV power plant production

same concept of positioning is applied to the single and three-phase consumers. Other consumers are taken to be equal to 0 kW. The consumer has a PV power plant and it produces electricity during the day. When there is nobody at home, the daily consumption is 0 kW. Figure 2 shows a graph of the submitted hourly meter values. They are measured with a control meter for a particular day with the power load profiles during a high PV power plant production.

2.2 Implementation of Normal Operating Cell Temperature Conditions and Quasi-Dynamic Simulation

The aim of our investigation is to show how distributed three-phase PV power plants affect the power quality in terms of the EN 50160 standard provisions of the observed LV distribution network. The impact of three parameters is analysed: insulation (global horizontal irradiance), external (ambient) temperature and inverter efficiency, with and without the NOCT conditions applied. For this purpose, one-hour readings during the analysed day (2^{ND} July 2021) are provided for each parameter. The Solcast API Toolkit software is used to

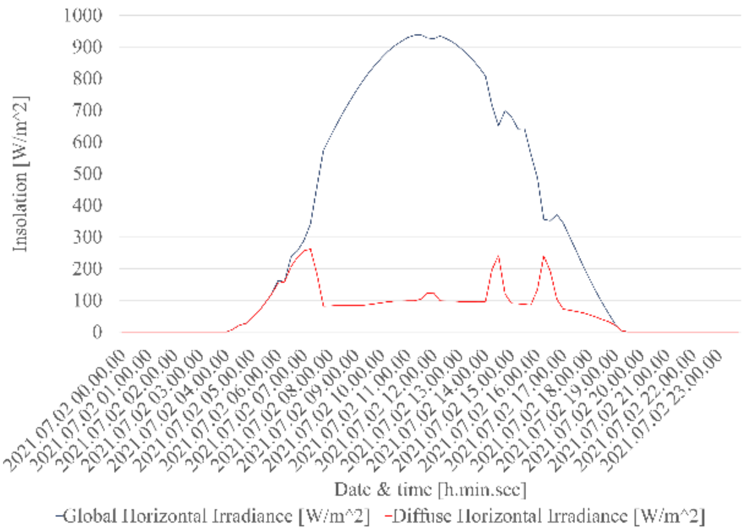

Figure 3. One-hour readings of the global and diffuse horizontal irradiance for the analysed day

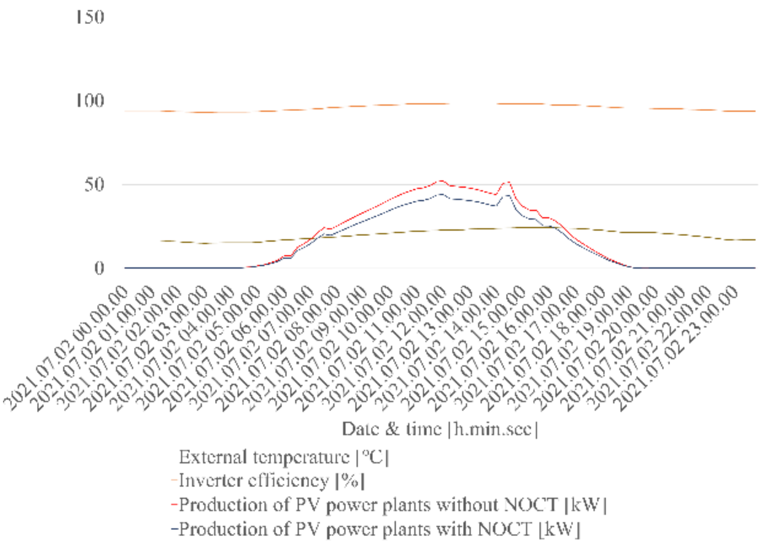

Figure 4. One-hour readings of the external temperature, inverter efficiency and production curves of the PV power plants with and without the NOCT conditions

obtain one-hour readings of the global horizontal irradiance and ambient temperature by entering coordinates of the geographical latitude and longitude of the location. Global horizontal irradiance is contained from two components: direct and diffuse. The Reindl et.al. model is used because its algorithm uses diffuse and global horizontal irradiance readings [8]. Figure 3 shows one-hour readings of the irradiance and external temperature parameters. Figure 4 shows one-hour readings of the external temperature, inverter efficiency and PV power plant production curves with and without the NOCT conditions applied.

As the analysed LV distribution network is an area where people live, it is necessary to determine the most acceptable PV module for the residential use and needs. The PV modules used for this purpose are in the range from 250W to 400W. The rooftop PV power plant installation would be the best to perform in accordance with the summarized data and analysis.

The 360W PV module is used. [19] It has the optimal values of its four most important parameters shown in Table 1:

- Voltage at the maximum point of the P-V and I-V curves (V_{MPP})
- Current at the maximum point of the P-V and I-V curves (I_{MPP})
- Voltage of the open-circuit (V_{OC})
- Short-circuit current (I_{SC})

The 360 W PV module has the capacity, i.e., the power, which is the maximum power it can produce under optimal sunlight conditions. Its surface is 1.84972 m^2, i.e. it is, 1.765m of the height and 1.048m of the width. Its thickness is 30mm as in equations 2 and 3 used to determine the output power produced by PV power plants with and without the NOCT conditions. [8, 10-13]

Table 1. 360W PV module datasheet

Short-Circuit Current (I_{SC})	8.95 A
Open-Circuit Voltage (V_{OC})	38.1 V
Maximum Power Current (I_{MPP})	8.49 A
Maximum Power Voltage (V_{MPP})	31.9 V
Module efficiency	19.46%
Dimensions (HxWxT)	1765x1048x30mm

Equation 1 represents the one-hour readings of the inverter efficiency when affected by a global horizontal irradiance and ambient temperature from the Solcast API Toolkit. It takes place simultaneously with the reference NOCT conditions of the global horizontal irradiance and ambient temperature to make the analysis realistic. A string inverter is used because of its easy performance and occupying a small space, as well as its efficience reference peak value. Coefficients for the global horizontal irradiance and ambient temperature are taken for the SMA string inverter. [12]

$$i_{\varepsilon\_1h} = \frac{\varepsilon_{ref}+[1-k_{G\_GHI}\times(i_{G\_GHI\_1h}-k_{refG\_GHI\_NOCT})]+[1-k_T\times(i_{T\_1h}-k_{refT\_NOCT})]}{100} \tag{1}$$

where:
i_{ε_1h} is one-hour inverter efficiency reading,
ε_{ref} is the reference peak value of the string inverter efficiency of 95%,
k_{G_GHI} is a coefficient of the global horizontal irradiance for the string inverter, i.e. -0.0025
$i_{G\_GHI\_1h}$ _ is a one-hour global horizontal irradiance reading,
$k_{refG\_GHI\_NOCT}$ is a coefficient representing the reference value of the global horizontal irradiance according to the NOCT conditions, i.e. 800 $\frac{W}{m^2}$
k_T is a coefficient of the ambient temperature for the string inverter, i.e. -0.37
i_{T1h} is a one-hour ambient temperature reading and
k_{refT_NOCT} is a coefficient representing the reference value of the ambient temperature according to the NOCT conditions, i.e. 20℃

Equations 2 and 3 show the production curve of the PV power plants, i.e. the output power produced by the PV power plants each for one-hour during the analysed day. Equation 2 shows the dependence of each of the three studied parameters to show the impact with no NOCT conditions applied. Equation 3 shows the impact with the NOCT conditions applied. The conditions (when the reference value of the global horizontal irradiance equals 800 $\frac{W}{m^2}$ and the reference value of the temperature equals 20°C) reduce the efficiency of the PV module by 20%. It is a general rule when the NOCT conditions are applied. The reason for applying them instead of the Standard Test Conditions (STC) is that the NOCT conditions deal only with the ambient temperature. For the analyse, this is very important because STC operates only of the temperature of the PV cell. The efficiency of the 360W PV module is 19.46%. When it is by 20% lower, i.e. 15.568%, Equations 2 and 3 are calculated with and without the NOCT conditions applied [10-11] [16].

$$P_{out_{without\_NOCT}} = \frac{A\times i_{G\_GHI\_1h}\times i_{T\_1h}\times i_{\varepsilon\_1h}}{1000} \tag{2}$$

$$P_{out_{with\_NOCT}} = \frac{A\times i_{G\_GHI\_1h}\times i_{T\_1h}\times i_{\varepsilon\_1h}\times 0.15568}{1000} \tag{3}$$

where:
A is the area of the PV module, i.e. 1.84972 m^2,
$i_{G\_GHI\_1h}$ is a one-hour global horizontal irradiance reading,
i_{T_1h} is a one-hour ambient temperature reading and
i_{ε_1h} is a one-hour inverter efficiency reading

The difference in the production curve of the PV plants with and without the NOCT conditions is because the production is higher without using the NOCT conditions. This complies with the rule that with the NOCT conditions the production efficiency drops by 20% of the PV module used. [10-11]

2.3 *Modelling scenarios*

The Toolbox used for the analysis is the Quasi-Dynamic Simulation (QDSL) contained in the DIgSILENT powerfactory software. Throughout the analysis, a Balanced Load Flow (BLF) is implemented.

Single-phase consumers are arranged by ordinal numbers according to the distance from the transformer substation. Their distance from the transformer substation, the terminal to which they are connected, the absolute and relative connection power, power and phase to which single-phase PV power plants are connected, respectively, are the following:

1. 355 m; T20; 6.7 kW; 0.2 kW; 5.36 kW; „A"
2. 395 m; T18; 6.7 kW; 0 kW; 5.36 kW; „B"
3. 423 m; T24; 6.7 kW; 0 kW; 5.36 kW; „C"
4. 445 m; T23; 6.7 kW; 0 kW; 5.36 kW; „A"
5. 450 m; T21; 6.7 kW; 0 kW; 5.36 kW; „B"
6. 472 m; T22; 6.7 kW; 0 kW; 5.36 kW; „A"
7. 472 m; T27; 6.7 kW; 0.3 kW; 5.36 kW; „A"
8. 477 m; T19; 6.7 kW; 0 kW; 5.36 kW; „A"
9. 493 m; T29; 6.7 kW; 0 kW; 5.36 kW; „C"
10. 499 m; T17'; 6.7 kW; 0 kW; 5.36 kW; -
11. 501 m; T28; 7.5 kW; 0 kW; 6 kW; „C"
12. 515 m; T35; 7.5 kW; 0 kW; 6 kW; -
13. 521 m; T34; 6.7 kW; 0 kW; 5.36 kW; „C"
14. 529 m; T30; 6.7 kW; 0 kW; 5.36 kW; „B"
15. 555 m; T39; 6.7 kW; 0 kW; 5.36 kW; „B"
16. 561 m; T40; 6.7 kW; 0 kW; 5.36 kW; „B"
17. 564 m; T31; 6.7 kW; 0 kW; 5.36 kW; „B"
18. 565 m; T32; 6.7 kW; 0 kW; 5.36 kW; „C"
19. 580 m; T17; 6.7 kW; 0.512 kW; 5.36 kW; „B"

The three-phase consumers are arranged in the same way as single-phase consumers. Their distance from the transformer substation, terminal to which they are connected, absolute and relative connection power, power of the three-phase PV power plant, respectively, are the following:

1. 233 m; T6; 23 kW; 0.4 kW; 18.4 kW
2. 383 m; T10'; 20 kW; 0 kW; 16 kW
3. 423 m; T24; 20 kW; 0 kW; 16 kW
4. 434 m; T13'; 20 kW; 0.5 kW; 16 kW
5. 435 m; T22'; 20 kW; 0 kW; 16 kW
6. 437 m; T23'; 20 kW; 0 kW; 16 kW
7. 693 m; T37; 12.5 kW; 0.6 kW; 10 kW

Each power of the single-phase and three-phase PV power plant is calculated as 80% of the absolute value of a single-phase and three-phase consumer connection power.

All scenarios are observed with and without the NOCT conditions individually for each applied scenario, which in total gives 18 scenarios. They are modelled according to the following load distributions in the network:

- 33%-33%-33%
- 40%-30%-30%
- 50%-25%-25%

Distributions of 33%-33%-33%, 40%-30%-30% and 50%-25%-25% are the distributions of the single-phase PV power plants by phases „A", „B" and „C", the number of the plants per phase in a given scenario.

The following scenarios are analysed:

1. 33%-33%-33% (10%)
2. 33%-33%-33% (20%)
3. 33%-33%-33% (50%)
4. 40%-30%-30% (10%)
5. 40%-30%-30% (20%)
6. 40%-30%-30% (50%)
7. 50%-25%-25% (10%)
8. 50%-25%-25% (20%)
9. 50%-25%-25% (50%)

10%, 20% and 50% are the penetration percentages of the PV power plants, the number of the consumers in the network having a single and three-phase PV power plant for a given scenario. The penetration percentages are applied both to the single-phase and three-phase PV power plants, so as the time characteristics with one-hour readings of the PV power plants production curves.

The numbers and the installed capacity expressed in units of kiloWatt of the single-phase PV power plants per phases, i.e. „A", „B" and „C", for the analysed scenarios are the following:

1. 1 (5.36 kW); 1 (5.36 kW); 1 (5.36 kW)
2. 2 (10.72 kW); 2 (10.72 kW); 2 (10.72 kW)
3. 5 (26.8 kW); 5 (26.8 kW); 5 (27.44 kW)
4. 1 (5.36 kW); 1 (5.36 kW); 1 (5.36 kW)
5. 2 (10.72 kW); 3 (16.08 kW); 1 (5.36 kW)
6. 5 (26.8 kW); 6 (32.16 kW); 4 (22.08 kW)
7. 1 (5.36 kW); 2 (10.72 kW); 0 (0 kW)
8. 1 (5.36 kW); 4 (21.44 kW); 1 (5.36 kW)
9. 4 (21.44 kW); 7 (37.52 kW); 4 (22.08 kW)

Scenarios 1, 4 and 7 have 1, scenarios 2,5 and 8 have 2 and scenarios 3, 6 and 9 have 4 three-phase PV power plants. The total installed capacity of the three-phase PV power plants for the scenarios 1, 4 and 7 is 18.4 kW. For the scenarios 2, 5 and 8, it is 26 kW and for the scenarios 3, 6 and 9, it is 60.4 kW.

Equation 4 represents the expression for the upper voltage limit of +10% according to the European EN 50160 standard, where U_{L-L} is the line-to-line and nominal voltage of 0.4 kV [1]:

$$\bar{U} = 0.1 \cdot \frac{U_{L-L}}{\sqrt{3}} \tag{4}$$

3 Results

This chapter deals with the voltages at the terminals with and without the NOCT conditions calculated by using BLF of the QDSL Toolbox. This is done:

- along the main feeder at a maximum load at 12 P.M. (Figure 5).
- with the three-phase PV power plants connected (Figure 6).

Scenarios 1, 4 and 7 are the same as well as scenarios 2, 5 and 8 and scenarios 3, 6 and 9. This is so because the same PV power plant penetration percentage is calculated using BLF.

Figure 5 shows that the voltage variations are the highest in scenarios 3, 6 and 9 with and without the NOCT conditions applied because of the 50% penetration of the PV power plants. This is the highest percentage of the PV power plants penetration. In scenarios 2, 5 and 8, with and without NOCT conditions applied, the highest value is recorded at terminal T_{14}. The voltage variations in scenarios 1, 4 and 7 are within the upper voltage limit of the EN 50160 standard with and without the NOCT conditions applied.

The voltage variations gradually increase from the beginning to the end of the network.

The graphs in Figure 6 show the scenarios with the three-phase PV power plants connected. They are analysed with the same PV power plants penetration percentage with and without the NOCT conditions applied. Scenarios 1, 4 and 7 have 1 three-phase PV power plant in the beginning of the network at terminal T_6. Scenarios 2, 5 and 8 have 2 three-phase PV power plants in the middle of the network at terminal $T_{13'}$ and at the end of the network at terminal T_{37}. Scenarios 3, 6 and 9 have 4 three-phase PV power plants. One is at the beginning of the network at terminal T_6, 2 are at the middle of the network at terminals $T_{13'}$ and T_{24} and one is at the end of the network at terminal T_{37}. The highest values are again at a maximum load in 12 P.M.

For scenarios 1, 4 and 7, with no the NOCT conditions applied, the highest value is the same as at terminal T_6. With the NOCT conditions, the highest value is again at terminal T_6, with a 0.6% voltage drop of the voltage profiles because of the presence of the NOCT conditions. The low penetration percentage does not violate the upper voltage limit. For scenarios 2, 5 and 8, with no the NOCT conditions, the highest values of the voltage profiles are at terminals $T_{13'}$ and T_{37}. In case with the NOCT conditions, the highest values are at the same terminals as in case with no the NOCT conditions. The voltage profile' drops the above terminals are with and without the NOCT conditions 1.8%. A higher percentage of the PV power plants penetration violates the upper voltage limit at the NOCT conditions. For scenarios 3, 6 and 9 with and without the NOCT conditions applied, the highest values are at terminals T_6, $T_{13'}$, T_{24} and T_{37}. This is as expected because at these terminals the three-phase PV power plants are connected. The voltage profiles with or without the NOCT conditions are different by 1.7%, 2.5%, 2.6% and 2.6% at terminals T_6, $T_{13'}$, T_{24} and T_{37}, respectively.

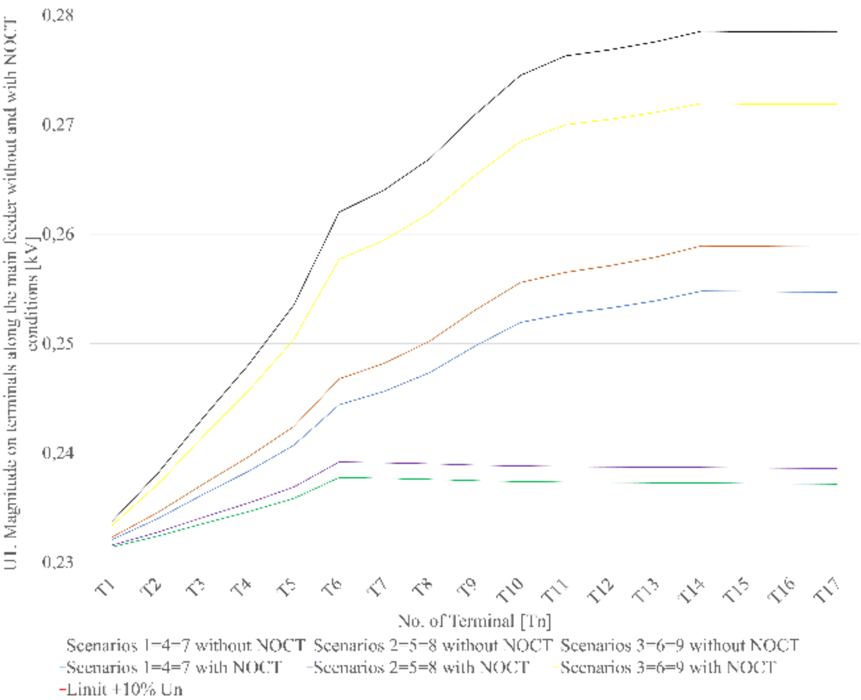

Figure 5. Voltages at terminals along the main feeder at the maximum load

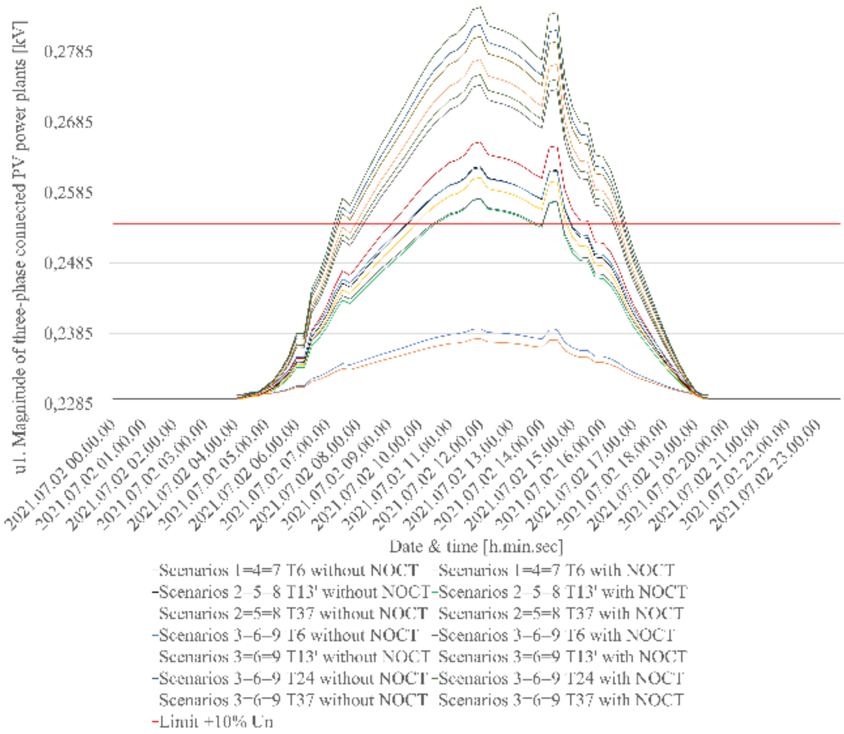

Figure 6. Voltage profiles at terminals with the three-phase PV power plants connected with and without the NOCT conditions applied

4 Conclusion

The study investigates the impact of the PV power plants on the voltage variations in the observed LV network in terms of three parameters: global horizontal irradiance, ambient temperature and inverter efficiency. The increase in the global horizontal irradiance and ambient temperature directly affect the inverter operational efficiency. In the evening and during night hours, the inverter operates less, thus decreasing its efficiency as expected. This also applies to the PV power plants production curves with and without the NOCT conditions.

This shown that the voltage profiles along the main feeder and at terminals with three-phase PV power plants connected are violated due to a higher penetration of the PV power plants in each scenario. The increased voltage variations exceed the upper voltage limit by +10% of the EN 50160 standard.

Moreover, the voltage profiles with no the NOCT conditions applied are higher than the voltage profiles with the NOCT conditions applied by some 3% due to the ambient temperature. In case of STC, it is due to the cell temperature of the PV module. To sum up, the NOCT conditions should be used instead of the STC conditions.

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Mario Ostojić received his BSc and MSc degrees in Electrical and Electronics Engineering in 2022 and 2024, respectively, from the Faculty of Engineering, Natural and Medical sciences, International Burch University, Bosnia and Herzegovina. His research interests are in renewable energy resources, distributed generation, energy efficiency and smart distribution grids. He is currently working at ETAS company, in Sarajevo, Bosnia and Herzegovina by working on the design and professional supervision of electrical power systems.

Adnan Bosović received his Dipl.eng and MSc degrees in 2009 and 2014, respectively, from the Department of Electric Power Engineering, Faculty of Electrical Engineering, University of Sarajevo, B&H. He received his PhD degree in Electrical Power Engineering from the Graz University of Technology, Austria, in 2022. He is currently working with the Department for Strategic Development at the Public Power Utility of Bosnia and Herzegovina, Sarajevo. His research interests are in the power quality, smart distribution grids and integration of electric vehicles.

Mustafa Musić received his MSc and PhD degrees in Electrical Engineering from the Faculty of Electrical Engineering, University of Sarajevo in 2002 and 2005, respectively. He is a Professor at the same Faculty. His research interests are in power system analysis and power system dynamics and stability.