ANALYSIS OF THE BACKWARD IMPACTS OF A PHOTOVOLTAIC POWER PLANT ON THE DISTRIBUTION SYSTEM

Radovan Šikuda[1], Miroslava Farkas Smitkova[1] Michal Vajanský[2]
[1]Slovak University of Technology in Bratislava, Faculty of Electrical Engineering and Information technology, Ilkovicova 3, 812 19 Bratislava, Slovakia,
email: xsikuda@stuba.sk,
email: miroslava.smitkova@stuba.sk
[2]Západoslovenská energetika, a. s. (ZSE), Čulenova 6, 816 47 Bratislava

Abstract

The article deals with the theoretical analysis of the backward impacts of photovoltaic power plants (PVPP) on the distribution system (DS), including phenomena such as increased voltage, changes caused by manipulations, flicker, harmonics, asymmetry, and commutation dips. The work is based exclusively on theoretical knowledge and available technical literature and is currently in the development stage [1].
The practical part will be carried out in a specific location in western Slovakia on a real network with overhead lines. Using SCADA and DECALK simulation tools, the impacts of connecting 1-phase and 3-phase PVPPs on voltage conditions in the network will be analyzed. The aim is to verify theoretical knowledge through calculations and simulations, quantify backward impacts according to the type of source, and identify critical operating states. It is assumed that single-phase sources may have up to six times greater impact on voltage quality than three-phase sources [1].

Key words

backward impacts, distribution system, photovoltaic power plants

Introduction

Photovoltaic power plants (PVPP) have become an important part of distribution systems in recent years, mainly due to the growing demand for renewable energy sources. However, with their increasing share, the occurrence of technical problems associated with backward impacts on the network is also increasing. These impacts can affect the quality of supplied electricity, operational reliability, and the possibilities for further integration of new sources [1].
Backward impacts of PVPP include increased voltage, flicker, harmonic distortion, voltage asymmetry, and commutation dips. Their character and intensity depend on the type and power of the connected source, network configuration, distance from the transformer, and other parameters [1].
The aim of this work is to analysed individual backward impacts in detail from a theoretical point of view and to prepare the groundwork for their verification in practical conditions. In the practical part, a specific section of the distribution network in western Slovakia with overhead lines will be examined. Simulations will be performed for various connection variants (1-phase vs. 3-phase source) using SCADA and DECALK tools [1].
This study is based on available technical literature, standards and regulations, as well as expert knowledge in the field of electricity quality and integration of distributed sources [1].

1. Literature review

The issue of backward impacts of photovoltaic power plants (PVPP) on the distribution system (DS) is the subject of a growing number of scientific and technical studies. The most frequently studied phenomena include voltage increase at the point of source connection, the occurrence of flicker, the formation of higher harmonic components, voltage asymmetry, and the occurrence of commutation dips [1].

In the literature, various approaches can be found, ranging from analytical models to numerical simulations of real distribution networks. Most studies focus on three-phase PVPPs with higher installed power, while less attention is paid to single-phase sources and their effect at the low-voltage level. Some works focus exclusively on the impact on voltage, while others address more complex impacts, including the impact on electricity quality according to the requirements of the EN 50160 standard [1].

Despite existing research, however, there is a lack of a comprehensive view on the comparison of backward impacts of single-phase and three-phase sources when they are connected to an existing network with a real configuration. This work focuses precisely on this area. It provides a theoretical analysis of individual types of backward impacts and prepares the groundwork for their verification through simulations of a real network section. At the same time, an extreme case is also taken into account, in which a larger number of smaller sources will be connected in a network branch. Such a configuration is often neglected in the available literature, although it can lead to more significant deviations from the standardized values of electrical quantities [1].

2. Backward impacts

Backward impacts in the distribution system manifest themselves mainly as changes in voltage, frequency, harmonic distortion, flicker, and voltage asymmetry. Their sources can be mainly electricity generation devices that are connected to the system, large loads with a non-traditional character, or specific technological processes [1].
According to the standards and technical conditions of the distribution system operator, it is necessary to monitor these impacts and keep them below the limit values [1].

2.1 Limit emission values of backward impacts

Limit values are defined based on legislation, standards, and technical manuals, and represent the limits that ensure the safe and reliable operation of the distribution network and the protection of user equipment [1].

Table 1 Limit values of back impacts in the distribution system

Parameter	Limit value	Note
Relative voltage change	≤ 2 % of nominal voltage (HV, MV) Un	For HV, LV
	≤ 3 % U_n	For LV
Long-term flicker severity P_{lt}	≤ 0.46	For HV and LV
Short-term flicker severity P_{lt}	≤ 0.8 %	For HV and LV
Voltage unbalance rate	≤ 0.7 %	For HV and LV

Source: [2]

2.2 Increased voltage

One of the most significant problems with PVPP connection is the voltage increase in the distribution system, especially in cases where the network is undersized and has long lines with a small cross-section. The paper states that these situations are critical because when power flows back towards the transformer, the voltage increases, especially at the ends of the lines [1]. This phenomenon is also examined in the practical part, where it is planned to simulate the network operation before and after the activation of a small source, assuming a maximum permissible voltage drop of 3 %. If the connection conditions are met in terms of back impacts, the production facility can be operated [1].
The relative voltage increase ΔuAn can be determined analytically. It is assumed that the electricity supply is realized to one connection point of the distribution network (e.g., multiple production facilities connected to the same point of the network) [1].

The calculation is given by the relation:

$$\Delta u_{An} = \frac{S_{rEmax}}{S_{kV}} * \cos(\Psi - \varphi_E) \;\; [\%] \tag{1}$$

Δu_{An} relatively increased voltage
S_{kV} short-circuit power at the connection point [VA]
S_{rE} maxmaximum supplied power [VA]
Ψ network impedance angle [°]

2.3 Possible measures for problems with increased voltage

If the permissible voltage value is exceeded due to the operation of the production source and it is not possible to ensure its stable operation, it is necessary to take technical measures to eliminate this back impact. The most frequently recommended solutions include [1]:

- Connection to a network location with higher short-circuit power – increasing the network stiffness reduces the voltage susceptibility to changes caused by the connection of the source.
- Increasing the short-circuit power of the network by technical modifications – for example, by changing the line, interconnections, or replacing the transformer with a more powerful one.
- Reactive power management or regulation – for example, using power electronic devices that allow dynamic voltage regulation at the connection point.
- Reducing the maximum supplied power of the source – operating the PVPP at a lower power during times of increased voltage.

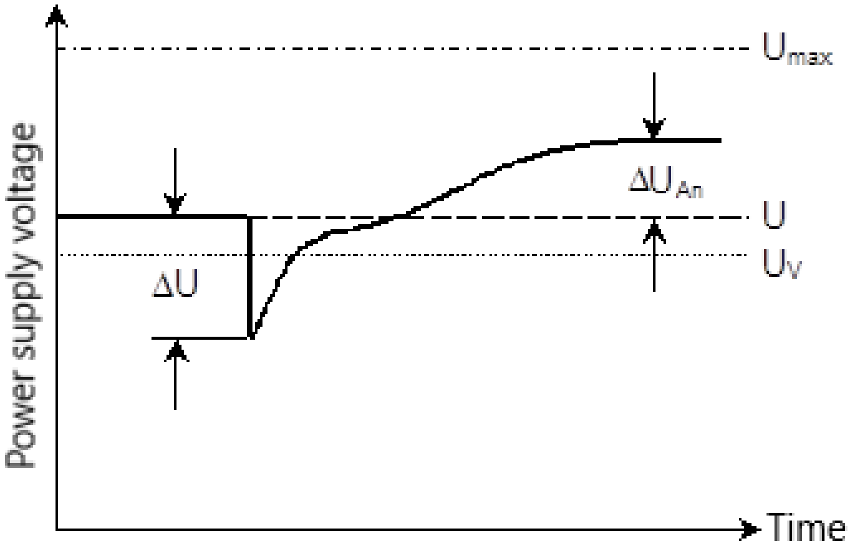
By introducing these measures, it is possible to ensure that the production facility meets the operating conditions in accordance with the applicable technical standards and operating regulations of the distribution company [1].

2.4 Changes caused by manipulations

When connecting or disconnecting decentralized sources, sudden voltage changes may occur. The impact depends on the type of generator [1]:

- Inverter sources cause a load change ΔS_A, which corresponds to their rated power. The connection usually takes place gradually, which limits the impact on the network.
- Synchronous generators, when synchronization conditions are met, do not cause significant voltage changes.
- Asynchronous generators can cause a load of up to 4 times the rated power. During the first half-wave, current surges of up to 8 times the rated current occur, which can lead to voltage fluctuations and activation of protections.

The following figure (Fig. 1) shows an example of the relationship between the short-term voltage change ΔU, caused by the connection of an asynchronous generator (e.g., during manipulation interventions), and the steady-state voltage increase ΔUAn\ ΔU, which arises due to the supply of energy to the network [1].



U_{max} maximum supply voltage [V]
U_V voltage at the connection point [V]
Un supply voltage [V]
ΔU_{An} increased voltage (in relation to the supply voltage) [%]
ΔU voltage change [%]

Fig. 1 Connection between short-term voltage change and steady-state voltage increase [1]

2.5 Flicker

The work suggests that rapid changes in PV power, e.g., due to sudden shading or changes in solar radiation intensity, can lead to voltage fluctuations. This phenomenon is particularly problematic for single-phase sources with inverters, which are prone to rapid reactions [1].
Although the work does not provide an exact calculation of the fluctuation, it emphasizes that such fluctuations can be significant, especially with a higher concentration of PV in the area. Therefore, the practical part plans to verify the behavior of the network even in "extreme cases" where "every other house has a source" [1].
Within the worst connection point in the network, the total value of long-term flicker Plt (in a 2-hour period) produced by all production facilities can be set at 0.46. For individual calculations, we will consider the formula below: For one production facility [1]:

$$P_{lt} = c * \frac{S_{rE}}{S_{kV}} * \left|\cos(\Psi + \varphi_f)\right| \tag{2}$$

In the case of multiple production facilities, the same formula is used, multiplied by the square root of the number of production facilities and without the cosine term. Flicker level assessment is usually only required for wind power plants, as devices, especially those with asynchronous generators, can reach flicker levels up to 50 [1].

2.6 Harmonics

In relation to harmonic distortion, the work states that PV systems, especially those connected via inverters, generate higher harmonic components into the grid. These harmonics can negatively affect the stability and voltage quality in the distribution system, cause equipment overheating, or disrupt the functionality of sensitive appliances. Since we will be examining the impact of connecting a small source in this work, we will focus on other reverse impacts that will have a more significant impact on the network in this case, and we will also examine this impact in individual software [1].

2.7 Commutation Dips

The relative depth of the commutation dip represents the measure of deviation of the instantaneous value of the grid voltage from the ideal waveform of its fundamental harmonic component at the moment of the largest dip caused by commutation. This deviation relates to the maximum, i.e., peak value of the fundamental harmonic voltage, thereby quantifying the level of deformation caused by commutation phenomena. In order to ensure the required quality of electricity, emission limits are set, which determine the maximum permissible value of this deviation. Production facilities can contribute a maximum of 50% to these limit values. A higher permissible value of the relative depth of the commutation dip is set for devices connected to low-voltage networks, while in the case of high-voltage networks, this value is stricter [1].

The assessment of commutation dips is carried out exclusively in the case of devices that supply electrical energy through grid inverters [1].

Production facilities can reach a maximum of 50% of the emission limits [1].

$$sieť\ LV: \mathrm{d_{Kom}} = 0{,}05 \tag{3}$$

$$sieť\ HV: \mathrm{d_{Kom}} = 0{,}025 \tag{4}$$

2.8 Asymmetry

Voltage asymmetry occurs with uneven loading or asymmetry of parameters in three-phase systems. Single-phase systems or single-phase inverters, compared to three-phase inverters, have up to six times higher reverse impact on the grid. This is because they increase the voltage in a different phase than the one to which they are connected, which significantly increases the asymmetry between the phases. It can be expressed according to the following formula, which provides a normalized measure of voltage asymmetry between individual phases. The maximum degree of asymmetry is recorded in (Table 1). This value must be set for 10 minutes [1].

Possible measures

To ensure the reliable operation of distribution systems and reduce negative reverse impacts, it is necessary to implement adequate measures, which can be divided into measures on the customer side and measures on the network side [1].

Measures for customers

- Use of motors with low inrush current or with its limitation to reduce the surge load on the network.
- Installation of inertial masses and flexible couplings to dampen surge currents and mechanical shocks.
- Introduction of blocking mechanisms to eliminate superposition dynamic effects.
- Even distribution of single-phase loads among all phases to reduce asymmetry.
- Use of compensation devices such as series reactors, adjustable reactive loads, controlled reactors, or capacitor banks for active reactive power correction.

Measures on the distribution network side

- Increasing the short-circuit power at the connection point by reinforcing lines, using points with higher short-circuit capacity, and replacing transformers with more powerful ones with lower short-circuit voltage.
- Connecting devices to a higher voltage level to reduce current load and improve stability.

2.9 Reactive Power Compensation

In situations where a network user exhibits high inductive reactive power consumption, it is usually necessary to deploy devices to improve the power factor, with compensation capacitors being the most commonly used. However, these capacitors, in combination with the network impedance, can create a resonant circuit, which poses a significant risk in terms of power quality [1].
In regulated compensation systems, the number of connected stages changes dynamically, causing a shift in the resonant frequency. Such a shift increases the likelihood of undesirable resonance in the network, which can have serious negative consequences [1].

The resonant frequency frez is given by the relation:

$$f_{rez} = 50\sqrt{\frac{S_{kQ}}{Q_V + Q_K}}\ [Hz] \tag{5}$$

S_{kQ} Short-circuit power at the common point of connection

Q_V charging power of the network

Q_K compensation power

The occurrence of resonance can lead to voltage distortions, interference with control signals, such as ripple control, as well as excessive harmonic currents. These phenomena cause increased stress on transformers and other network components, which can lead to premature failures and reduced reliability of the distribution system.

Conclusion

Theoretical analysis confirms that the impact of PV systems on the distribution network depends on the type of connection, source power, and network characteristics. These effects are not negligible, especially in the case of low-voltage networks with longer overhead lines, where significant deviations from the standardized voltage quality parameters can occur.
It has been shown that the type of source connection (single-phase vs. three-phase), its power, and the point of connection are key factors that influence the occurrence of reverse phenomena such as: increased voltage, flicker, harmonics, commutation dips, asymmetries, reactive power compensation.
For each of these influences, mathematical models and formulas were presented that allow their quantitative evaluation. These calculations are in accordance with the valid technical standards STN EN 50160 and STN EN IEC 61000-3-3 and represent the basis for the design of connecting PV systems to the distribution network. The practical part of the work will focus on the simulation and calculations of real cases and verification of these relationships in SCADA and Decalk software.

Acknowledgement

This work was funded by the EU NextGenerationEU through the Recovery and Resilience Plan for Slovakia under the project No. 09I04-03-V02-00033.
This work was supported by the Slovak Research and Development Agency under the contract No. APVV-20-0157.

References

[1] REAS ČR, ZSE, and ČEPS, *PNE 33 3430-0 – Výpočetní hodnocení zpětných vlivů odběratelů a zdrojů distribučních soustav*, 1st ed., Praha, Czech Republic, Oct. 1, 2005.
[2] Západoslovenská distribučná, a.s., Úsek technického rozvoja, *Predpisy prevádzkovateľa – Západoslovenská distribučná, a.s.* [Online]. Available: https://www.zsdis.sk/Uvod/Spolocnost/Dokumenty/Predpisy-prevadzkovatela. Accessed: Mar. 10, 2025.

GOCE DELCEV UNIVERSITY, STIP, NORTH MACEDONIA
FACULTY OF ELECTRICAL ENGINEERING

ETIMA 2025

THIRD INTERNATIONAL CONFERENCE

24-25 SEPTEMBER, 2025

TECHNICAL SCIENCES APPLIED IN ECONOMY, EDUCATION AND INDUSTRY

УНИВЕРЗИТЕТ „ГОЦЕ ДЕЛЧЕВ“, ШТИП
ЕЛЕКТРОТЕХНИЧКИ ФАКУЛТЕТ

GOCE DELCEV UNIVERSITY, STIP
FACULTY OF ELECTRICAL ENGINEERING

ТРЕТА МЕЃУНАРОДНА КОНФЕРЕНЦИЈА
THIRD INTERNATIONAL CONFERENCE

ЕТИМА / ETIMA 2025

ЗБОРНИК НА ТРУДОВИ
CONFERENCE PROCEEDINGS

24-25 септември 2025 | 24-25 September 2025

Главен и одговорен уредник / Editor in Chief
проф.д-р Сашо Гелев
Prof.d-r Saso Gelev

Јазично уредување / Language Editor
Весна Ристова (македонски) / Vesna Ristova (Macedonian)

Техничко уредување / Technical Editing
Дарко Богатинов / Darko Bogatinov

Издавач / Publisher
Универзитет „Гоце Делчев”, Штип / Goce Delcev University, Stip
Електротехнички факултет / Faculty of Electrical Engineering

Адреса на организационен комитет / Adress of the organizational committee
Универзитет „Гоце Делчев”, Штип / Goce Delcev University, Stip
Електротехнички факултет / Faculty of Electrical Engineering
Адреса: ул. „Крсте Мисирков“ бр. 10А / Adress: Krste Misirkov, 10A
Пош. фах 201, Штип - 2000, С. Македонија / PO BOX 201, Stip 2000, North Macedonia
E-mail: conf.etf@ugd.edu.mk

CIP - Каталогизација во публикација
Национална и универзитетска библиотека "Св. Климент Охридски", Скопје

62-049.8(062)
004-049.8(062)

МЕЃУНАРОДНА конференција ЕТИМА (3 ; 2025 ; Штип)
Зборник на трудови [Електронски извор] / Трета меѓународна конференција ЕТИМА 2025, 24-25 септември 2025 ; [главен и одговорен уредник Сашо Гелев] = Conference proceedings / Third international conference, 24-25 September 2025 ; [editor in chief Saso Gelev]. - Текст во PDF формат, содржи 357 стр., илустр. - Штип : Универзитет "Гоце Делчев", Електротехнички факултет ; Stip : "Goce Delchev" University, Faculty of Electrical engineering, 2025

Начин на пристапување (URL): https://js.ugd.edu.mk/index.php/etima/en. - Наслов преземен од екранот. - Опис на изворот на ден 30.10.2025. - Трудови на мак. и англ. јазик. - Библиографија кон трудовите

ISBN 978-608-277-128-1

а) Електротехника -- Примена -- Собири б) Машинство -- Примена -- Собири
в) Автоматика -- Примена -- Собири г) Инфоматика -- Примена -- Собири

COBISS.MK-ID 67297029