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ANALYSIS OF IMPACT OF DIFFERENT DISTRIBUTED GENERATION TECHNOLOGIES ON HARMONICS AND SHORT-CIRCUITS IN REAL LOW VOLTAGE DISTRIBUTION FEEDER

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Abstract: In modern power systems, reliable electricity supply is crucial. This study analyzes the impact of small hydro power plants (SHPP) and photovoltaic (PV) systems on a low-voltage network using DigSILENT PowerFactory software tool. Results show that PV systems increase total harmonic distortion (THD), while sHPP reduces THD and significantly increases short-circuit currents during faults. These findings highlight the importance of strategic integration of distributed generation (DG) sources to maintain network quality and stability.

Keywords: Distributed Generation (DG), Small Hydro Power Plants (SHPP), Photovoltaic Systems (PV), Total Harmonic Distortion (THD), Electrical Faults

INTRODUCTION

The power system represents a complex network composed of various components, such as generators, transmission lines, distribution lines, and consumers. The main task of the power system is to generate, transmit, and deliver electricity to consumers in a reliable and efficient manner. To ensure the reliability and quality of electrical power, the system must meet certain standards, with one of the most important being the EN 50160 standard for voltage quality. This standard defines the voltage characteristics that power distributors must provide to end users.

One of the biggest issues in power systems is short circuits. A short circuit occurs when current finds an unexpected path with very low resistance, which can cause system overload, equipment damage, and interruptions in power delivery. Such situations require a quick response through protective devices, such as fuses and circuit breakers, to minimize damage and swiftly restore normal operating conditions.

Another significant issue is harmonics in the network. Harmonic distortions occur when electronic devices, such as rectifiers and inverters, generate currents with frequencies that are multiples of the network's base frequency (50 Hz). These currents cause voltage harmonics, which can lead to equipment overheating, reduced system efficiency, and problems with power quality. Harmonic distortions can be controlled by using filters and proper power system design.

The integration of renewable energy sources, such as photovoltaic systems and wind turbines, also presents challenges regarding integration into the existing grid and maintaining power reliability and quality. Given these challenges, analyzing and managing power quality are becoming increasingly important aspects of modern power systems.

In the following chapters, we will address various aspects of the power system. Chapter 2 covers faults and harmonics, explaining their impact on system performance. Chapter 3 discusses analyses by other authors on similar topics related to harmonic impacts and short-circuit currents. Chapter 4 introduces the modeling approach and problem formulation using DigSILENT PowerFactory, providing a detailed examination of small hydropower plant and photovoltaic system integration. Chapter 5 discusses the analysis results, focusing on short-circuit performance and harmonic distortion in different scenarios. Finally, Chapter 6 summarizes key findings and offers conclusions and recommendations for future integration of renewable energy sources in low-voltage networks.

1. FAULTS AND HARMONICS IN THE POWER SYSTEM

In a complex system like the power system, faults are inevitable and can significantly impact its stability and reliability. Faults in the power system can be caused by various factors, such as natural disasters, technical issues, human errors, and equipment aging. The most common and critical faults are short circuits, which occur

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when there is an unintended connection between phase conductors or between a phase conductor and the ground. Short circuits are particularly hazardous because they can produce extremely high currents that may damage equipment, cause fires, and endanger human safety. Therefore, short-circuit analysis is essential for the design, operation, and protection of power systems.

The objective of such analysis is to identify the maximum short-circuit currents that may occur in the network, enabling the proper sizing of protective devices and ensuring safe system operation. The IEC 60909 standard provides guidelines for calculating short-circuit currents at different points within the power system. This standard allows for accurate and conservative estimates of maximum short-circuit currents, taking into account various operating conditions of the system. Using software tools like DIgSILENT PowerFactory, engineers can simulate different fault scenarios and analyze their impact on the network.

In the following sections, a comprehensive discussion will be provided on the types of short circuits, methods of analyzing them, and the impact of distributed energy sources on short-circuit currents. Through theoretical approaches and practical examples, the aim is to provide a fundamental understanding of this crucial aspect of power systems [1].

1.1. Short Circuit Faults in the Power System

Short-circuit faults are common and dangerous incidents in the power system. They occur when an unintended connection between phase conductors or between a phase conductor and the ground results in extremely high currents. These currents can cause serious equipment damage, system failures, fires, and risks to human life, often triggered by natural disasters such as storms, earthquakes, or lightning strikes. Technical issues, including insulation failures, overloads, and circuit breaker malfunctions, can also cause short circuits. Human errors, such as operational mistakes or inadequate maintenance, further contribute to these faults. Additionally, the aging and degradation of materials over time increase the likelihood of short-circuit incidents.

The consequences of short circuits can be catastrophic. Extremely high currents lead to the overheating of conductors and equipment, which can cause insulation to melt, transformer explosions, and circuit breaker failures. These incidents result not only in material damage and high repair costs but also cause interruptions in electricity supply, impacting consumers and leading to significant economic losses. Moreover, high short-circuit currents generate strong electromagnetic forces that can physically damage equipment and structures within the system.

Due to the serious consequences of short circuits, conducting thorough analysis and planning is crucial to minimize their negative effects. By using advanced software tools like DIgSILENT PowerFactory, engineers can simulate various short-circuit scenarios and analyze their impacts on the network. These simulations enable the identification of critical points in the system, optimization of protection strategies, and overall improvement in the reliability and safety of the power system. Additionally, by analyzing the impact of distributed energy sources such as photovoltaic (PV) systems and small hydropower plants (SHPP), engineers can better understand how these sources affect short-circuit currents and adjust system design and operation to ensure its stability and security.

1.2. Classification of Short Circuits in the Network

There are several types of short circuits in the power system, but this work focuses on three main types: three-phase, two-phase, and single-phase-to-ground faults.

Three-phase short circuits: These occur when all three phase conductors are interconnected. This type of fault generates the highest currents and is commonly used as a reference point for analyzing and designing protective devices.

Two-phase short circuits: These occur when two phase conductors are connected while the third remains unconnected. They cause high currents, typically less intense than three-phase faults, and can be either symmetrical or asymmetrical.

Single-phase-to-ground short circuits: These occur when one phase conductor makes contact with the ground. This is the most common type of fault. The short-circuit current may be low in isolated systems but can be significant in grounded systems.

Each type requires specific analysis and protective methods to ensure system safety and reliability, including devices like fuses, circuit breakers, and relays for rapid fault detection and isolation [3].

1.3. Harmonics

Harmonics are sinusoidal components with frequencies that are integer multiples of the fundamental frequency, and they are critical for analyzing the quality of electrical signals in power systems. Under ideal conditions, voltage and current waveforms are perfect sine waves, but in reality, distortions occur due to the presence of nonlinear loads, such as various electronic devices. These distortions can be quantified using harmonic distortion coefficients (HD) for individual harmonics and the total harmonic distortion (THD) coefficient, which expresses the deviation of the actual waveform from the ideal in terms of current or voltage percentage.

Current harmonics are particularly problematic as they increase losses in power system components, such as transformers, whose transmission capacity can be halved

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at high THD values. Additionally, current harmonics can induce voltage harmonics, adversely affecting sensitive electronic devices, capacitor banks, and electric motors. Certain harmonics, like the fifth and seventh, create a rotating magnetic field that spins in the opposite direction of the fundamental harmonic, leading to heating and mechanical oscillations in motor systems [3].

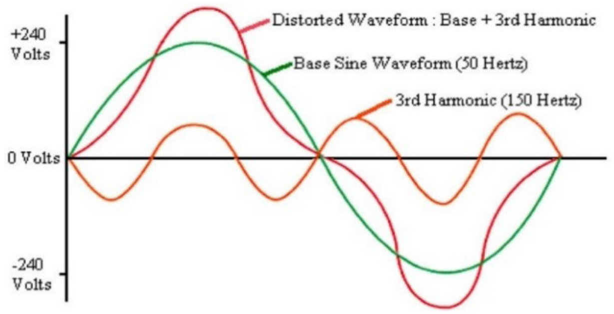

Figure 1: Distorted waveform equal to the sum of the fundamental harmonic and the third harmonic

Additionally, there are interharmonics, which have frequencies that are not integer multiples of the fundamental component. They arise due to phenomena like electric arcs and from devices such as frequency converters, caused by periodic or random changes in power. Understanding and controlling harmonics are essential for maintaining the efficiency and reliability of power systems.

1.4. Sources of harmonics

Harmonics in power systems are most commonly caused by the presence of nonlinear loads. Major sources of harmonics include electronic devices such as rectifiers and UPS systems used for converting AC to DC, as well as variable drives, like frequency converters that control motor speed. Industrial electric arcs and welding machines also generate high harmonics due to nonlinear heating processes and operation. In addition to industrial sources, computers, office equipment, modern lighting systems like LED and fluorescent lights, and capacitor banks contribute to harmonic distortion. Household electrical appliances, including microwave ovens, washing machines, air conditioners, and refrigerators, can also generate harmonics due to nonlinear components in their electronic control systems. Variable-speed motors and motor drives further contribute to harmonic issues due to nonlinear commutation. Managing and controlling these sources are essential for maintaining quality and efficiency in power systems [3].

1.5. Impact of harmonics on the network

Harmonics in power systems have a broad range of negative effects on the reliability and efficiency of the network. One of the key issues is the increase in energy losses within the system. Transformers, which are crucial for the distribution of electricity, are subject to additional heating due to harmonics. These additional losses not only reduce transformer efficiency but can significantly shorten their operational lifespan, necessitating more frequent maintenance or replacement. Additionally, cables and other conductive equipment in the power grid also suffer from the effects of harmonics. Higher-order harmonics can result in increased current losses through cables, leading to extra heating of conductors and potential overheating issues. This is especially problematic in areas with high electricity demand, such as industrial complexes or densely populated urban areas.

Furthermore, voltage harmonics can seriously impact electronic devices that require stable power. Uncontrolled harmonics may cause malfunctions in computers, medical equipment, and other sensitive devices, leading to failures or data loss with potentially serious consequences in business, healthcare, and industrial sectors.

In addition to the direct impacts on equipment, harmonics can also cause resonance in the power grid. This phenomenon may lead to voltage or current oscillations that are not only undesirable but also hazardous to system integrity. Excessive harmonics can also damage capacitor banks used for power factor correction. Capacitors exposed to resonant frequencies may become overloaded and damaged, incurring additional replacement and maintenance costs. For electric motors, which are often the core of industrial processes, harmonics can lead to extra mechanical stresses and heating. Higher-order harmonics can generate undesirable rotating magnetic fields, which not only reduce motor efficiency but also increase the risk of mechanical damage or premature wear of components.

Overall, managing harmonics is essential for maintaining stability and efficiency in power systems. This involves implementing appropriate filters and controls, as well as regular monitoring and analysis of power quality. Only through effective harmonic management can long-term stability and reliability of power grids be ensured, which is essential for various industries and the everyday functioning of modern society [4].

1.6. Total Harmonic Distortion

THD (Total Harmonic Distortion) is a metric used to quantify the level of harmonics present in an electrical signal relative to the fundamental sinusoidal signal. This measure is critical for assessing power quality and can be applied to both voltage and current signals. Total harmonic distortion is expressed as a percentage and represents the ratio between the square root of the sum of the squares of harmonic amplitudes and the amplitude of the fundamental harmonic (fundamental frequency). A higher THD indicates a greater level of distortion in the signal, which can signify the presence of more undesirable harmonics in the system.

$$THDU = \sqrt{\sum_{h=2}^{40} (Uh)^2} \frac{100\%}{U_1} \quad (1)$$

Where is:
- $THDU$: Total Harmonic Distortion (THD) for voltage, expressed as a percentage,
- $\sum_{h=2}^{40} (Uh)^2$: The sum of the squares of the RMS values of the voltage for all harmonics from 2 to 40, h: The harmonic order number and Uh the RMS value of the voltage for the h-th harmonic,
- U_1: The RMS value of the voltage of the fundamental frequency (fundamental voltage).

THD is often used as an indicator to assess the compatibility of electronic devices with voltage sources or to evaluate the degree of distortion in power systems. The total harmonic distortion of voltage (THDv), considering all harmonics up to the 40th multiple of the fundamental frequency, should not exceed 8% of the fundamental harmonic. An increase in this coefficient (THDv) also increases the likelihood of problems with consumer devices and network components [3].

- For THD up to 5%, problems are rare and of a minor scale.
- At THD levels between 5% and 7%, problems become more frequent.
- THD between 7% and 10% increases the risk of problems.
- THD greater than 10% can significantly increase the likelihood of problems, including equipment damage and improper functioning.

1.7. Harmonic Distortion

Harmonic distortion (HD) is a type of nonlinear distortion that occurs when a signal passes through a system or component that does not respond linearly to the input frequencies. This results in the generation of additional frequencies that are multiples (harmonics) of the fundamental frequency of the input signal.

Measuring harmonic distortion: Harmonic distortion is measured by analyzing the frequency spectrum of the signal and identifying the harmonics relative to the fundamental frequency.

These measurements are often performed using:
- Spectral analyzers: Devices that display the amplitudes of the signal as a function of frequency.
- Fourier analysis: A mathematical tool that decomposes a signal into its fundamental frequencies and their harmonics.

Types of Harmonic Distortion:
- Harmonic distortion of even harmonics: This includes harmonics at even multiples of the fundamental frequency (2^{nd,} 4th, 6th, etc. harmonics).
- Harmonic distortion of odd harmonics: This includes harmonics at odd multiples of the fundamental frequency (3rd, 5th, 7th, etc. harmonics).

Understanding harmonic distortion is crucial for optimizing the performance of various systems and ensuring high signal quality in different applications [5].

It is important to note that in this study, when analyzing harmonics, the THD value in the first case, without the connection of DGs (Distributed Generators), will be slightly higher, as one PV (Photovoltaic) system is already connected to the considered source network.

2. LITERATURE REVIEW

In recent decades, the rapid development of new electricity generation sources has led to significant impacts on harmonic voltages and short circuits in low-voltage power grids. This evolving landscape has stimulated growing research aimed at understanding and addressing these effects.

In [6], the research analyzes the impact of high penetration of photovoltaic (PV) systems on harmonic distortion within distribution networks. A typical three-bus distribution model was constructed in MATLAB/Simulink to investigate harmonic issues. The findings reveal that current harmonics are more prone to fluctuations compared to voltage harmonics. A proposed solution involves dynamically adjusting the inverter filter settings based on lighting levels, which effectively reduces harmonic distortion under low-light conditions.

The paper [7] investigates the effects of integrating photovoltaic systems and small hydroelectric plants on harmonic voltages in a real medium- and low-voltage grid. The study showed that photovoltaic systems generally increase harmonic voltages, while the addition of a small hydroelectric plant can reduce these distortions. Significantly, harmonic voltages remain within the EN 50160 standard limits even when both generation sources are operating.

Similar research in [8] analyzes the impact of small hydroelectric power plants (SHPP) and photovoltaic systems (PV) on short-circuit currents and harmonic distortions. The study highlights that SHPPs increase short-circuit currents and improve power quality by reducing harmonic distortions, while PV systems have minimal impact on short-circuit current strength, as their inverters typically shut down during faults.

In [9], the paper discusses the accurate calculation of short-circuit currents for doubly-fed induction wind turbines (DFIG-WTs). The study develops an analytical model that includes stator and grid-side converter (GSC) currents, emphasizing the transient behavior of the GSC

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current and the impact of second-harmonic components on transformer protection. The study stresses the importance of including the GSC effects to improve short-circuit current calculation accuracy and protection system design.

The paper [10] focuses on measuring and analyzing harmonics during electric vehicle (EV) charging. Conducted on two modern EVs and a golf cart, the research measures harmonics during single and multiple EV charging sessions. The results show that modern EVs exhibit lower total harmonic distortion in current (THDi) but higher total harmonic distortion in voltage (THDv) compared to the golf cart. It also reveals that the sum of the THDs for multiple EVs is non-linear, suggesting that the impact of EV charging on harmonics is less severe than previously assumed.

Study [11] explores the impact of grid-connected photovoltaic systems on total harmonic distortion (THD) in a low-voltage distribution grid in Egypt. Addressing technical challenges such as frequency fluctuations and power factor degradation, the study proposes solutions such as disconnecting solar panels or installing passive and active filters. Simulations and practical measurements show that these measures significantly improve the power quality in the grid.

Finally, paper [12] presents an analysis of short-circuit currents in grid-connected PV power systems, focusing on systems with voltage-source converters (VSCs). A new methodology is presented that uses an element-based approach and iterative techniques to determine the equilibrium points of short-circuit currents, taking into account VSC control modes and current saturation states. Case studies of small and large PV plants confirm the proposed method through dynamic simulations, improving the accuracy and efficiency of short-circuit current calculations, which are crucial for the design and protection of PV power systems.

In summary, the literature review highlights the complex interactions between new generation technologies and harmonics, as well as short-circuit current dynamics. It emphasizes the need for advanced analytical methods and practical solutions to manage these effects, ensuring the reliability and efficiency of modern power grids.

3. MODELING AND PROBLEM FORMULATION

In this section, we will provide a detailed description of the network model and the problem to be analyzed in this study.

3.1. Problem Formulation

In this project, using DigSILENT PowerFactory, the goal is to analyze the integration of different distributed generation (DG) technologies, such as small hydropower plants (sHPP) based on synchronous generators and photovoltaic (PV) power plants, into a real low-voltage grid. This comprehensive approach will allow us to understand the effects of DG integration on harmonic behavior and short-circuit performance in the network.

To ensure a thorough investigation, several scenarios of DG technology integration have been assessed for the analysis of harmonics and short-circuits:

- Scenario 1: PV and sHPP off
- Scenario 2: PV on, sHPP off
- Scenario 3: PV and sHPP on
- Scenario 4: sHPP on, PV off

Each scenario will be simulated using DigSILENT PowerFactory to assess their impact on the grid. The first set of scenarios will provide insights into harmonic characteristics and operational consequences, while the second set will evaluate short-circuit currents for different types of faults.

3.2. Modeling of the Real Low-Voltage Network

For the purposes of this study, information from the public electricity company Elektroprivreda Bosne i Hercegovine d.d. - Sarajevo was used. The geographical layout of the terrain and the schematic diagram of the low-voltage 0.4 kV network of Kruske (TS 10/0.4 kV Zlatici) are shown in the following Figure 2.

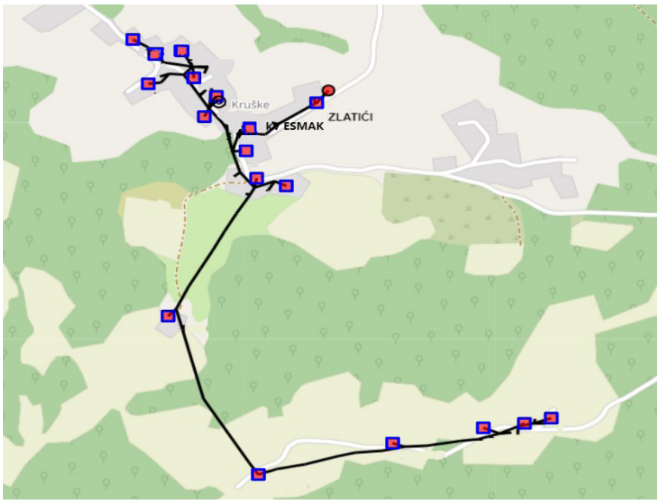

Figure 2: Geographical representation of the 0.4 kV network layout

This part of the low-voltage network is connected to the 10/0.4 kV Zlatici transformer station, which has a capacity of 160 kVA. The network consists of a total of 41 consumers and 104 nodes. Almost all consumers are categorized as households, except for 3, of which 2 are grouped under other consumption, and one is dedicated to public lighting in this part of the settlement. Only 6 of them are connected with a three-phase connection, while all others are connected with a single-phase connection. These details, along with other elements of the network, can be seen in the following Table I.

Table I. Network Parameters

Network Elements	Broj
General Loadings	41
Connections	104
Busbar (0.4 kV)	1
Busbar (10 kV)	1
Two-Winding Transformer	1
Cables	80
PV System	1

In the observed network, in addition to the consumers, a PV system is also connected. Specifically, it is a solar power plant with a capacity of 18.4 kW and a power factor of 1. The first task was to identify the day with the highest load. This information was found in the smart meter for this network. In this case, the day with the highest load was December 26, 2021. The total energy consumed that day amounted to 417.017 kWh.

Based on the provided geographical layout and the distances of various measuring points (consumers) from the transformer station, a network connection diagram was created in DigSILENT PowerFactory. Subsequently, other network parameters were entered, such as the types and lengths of cables, consumer power ratings, busbar types, and so on. The diagram of the observed network in DigSILENT PowerFactory can be seen in the following illustration.

The parameters for the transformer have been entered into the model. For all calculations, tabular data provided by the Public Electric Utility “Elektroprivreda Bosne i Hercegovine d.d. – Sarajevo” were used. Readings of active power from the main meter helped us determine the power and energy for the mentioned day of maximum load, while the reactive power throughout the year was recorded and amounts to 0 kVAr.

3.3. Sources of Harmonics

According to the literature, small hydropower plants are considered sources of electrical energy that typically have minimal or negligible harmonic emissions. This is due to the stable nature of hydropower plants and their ability to generate electricity without significant fluctuations in frequency or voltage, which could cause the generation of harmonics. Therefore, small hydropower plants are often regarded as reliable energy sources with a low impact on the power quality in the grid. Other sources of harmonics will be outlined in the following sections of this paper.

3.3.1. Harmonic Emission from PV Systems

In this study, the connections of photovoltaic systems have been analyzed and described in detail, making the input and definition of harmonics from these energy sources crucial. In our network, there is a photovoltaic system with a capacity of 18.5 kW, which requires the input of the corresponding values to ensure accurate analysis.

For successful modeling in DigSILENT PowerFactory, understanding the harmonic currents for each individual inverter is essential. For the purpose of this study, we will use the arithmetic mean of the harmonic currents for photovoltaic systems with total capacities of 18.5 kW, 20 kW, and 25 kW. A detailed table with these values can be found below [13].

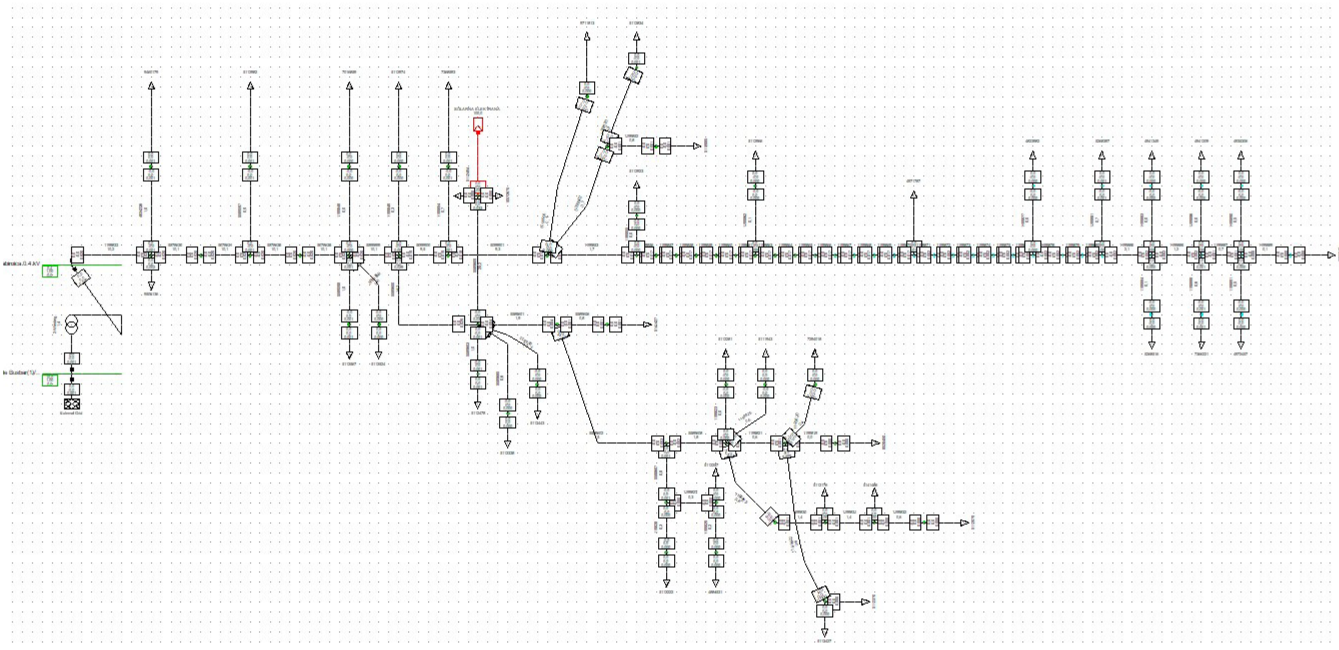

Figure 3: Representation of the Low Voltage Network in the DiGSILENT PowerFactory Tool

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Table II. Table of Values for the 5th and 7th Harmonics

5th Harmonic	PV 18,5 kW	PV 20 kW	PV 25 kW
I_F	26.72	28.87	36.09
I_A	0,1	0,1	0,1
$I_{\%}$	0.374	0.346	0.277
I_{av}		0,332	
7th Harmonic	PV 18,5 kW	PV 20 kW	PV 25 kW
I_F	26.72	28.87	36.09
I_A	0.05 A	0.05 A	0.05 A
$I_{\%}$	0.187	0.173	0.139
I_{av}		0,166	

3.3.2. Harmonic Emission from Consumers

For harmonic emissions from consumers, this research uses typical reference values of 5% for the current 5th harmonic and 1.5% for the current 7th harmonic. These values are commonly considered standard reference points in the relevant literature. Using these typical values helps ensure consistency with industry practices and allows for a more accurate assessment of the effects of harmonics [7].

3.3.3 Background Harmonics

Background harmonics were modeled using a harmonic voltage source in an external network element. The average distortion values for the 5th and 7th harmonics, expressed as percentages, were obtained from previous studies. Specifically, these distortions are 0.6% for the 5th harmonic and 0.4% for the 7th harmonic. These percentage values were then converted into per unit (pu) values for modeling purposes [7].

4. RESULTS AND DISCUSSION

4.1. Short Circuits

4.1.1. Three-Phase Short Circuit

The three-phase short-circuit in the 0.4 kV Zlatići network was analyzed in four different scenarios, which we previously outlined.

In the first scenario, the network operates without distributed energy sources. The analysis will determine the short-circuit current values and the network's response to a three-phase short circuit in this case. These results will serve as a reference point for further comparison.

In the second scenario, a 20 kW PV system is connected to the network. The goal is to analyze how the presence of a photovoltaic system affects the short-circuit current. This scenario will show all the changes in network performance during the fault.

In the third scenario, both sources, a 20 kW PV system and a 20 kW small hydroelectric plant, will be connected to the network. The analysis will help to understand the combined impact of these sources on the short-circuit current and how they affect the network in the event of a three-phase fault.

In the fourth scenario, a 20 kW small hydroelectric plant will be connected to the network. The analysis will determine the impact of this source on the short-circuit current and how it affects the network during a three-phase fault.

Below are the diagrams of the three-phase short circuits for all four scenarios. For easier examination of the results, the diagrams include only the 20 busbars. It should be noted that high values of short-circuit currents at certain busbars arise from their proximity to transformers and their position at the beginning of the network. These busbars experience higher currents because they are closer to the main busbar, which is located near the transformer, resulting in higher short-circuit currents compared to other locations in the network. The diagrams provide a clear visualization of the impact of each scenario on the short-circuit current, facilitating comparison and identification of key differences.

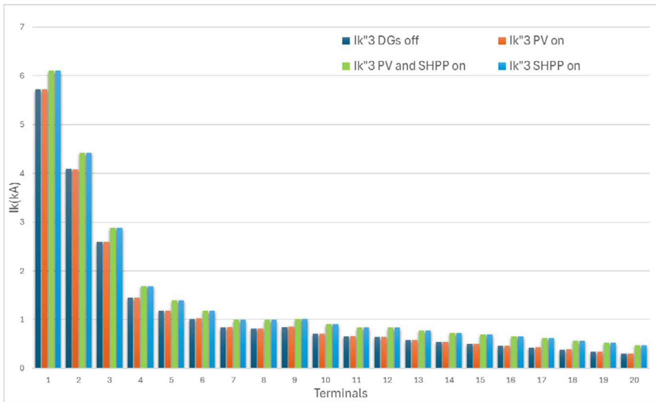

Figure 4: Comparison of Three-Phase Short Circuit Currents for Different Scenarios

The results of the three-phase short circuit are shown in the diagram above, Figure 4. It is evident that the short-circuit current in scenario 1, without distributed energy sources (DG), matches the short-circuit current in scenario 2, Figure 4, where the PV system is connected to the network. This suggests that the photovoltaic system does not significantly affect the level of the short-circuit current. On the other hand, scenario 3, where both the SHPP and PV system are connected, shows a noticeable increase in the short-circuit current, although not significantly, considering the combined capacity of the SHPP and the 20 kW PV system. This increase is the result of the SHPP supplying the network during the fault, marked in green on the diagram.

By comparing scenarios with and without DG and with the PV system connected, it is clear that the short-circuit currents are identical, indicating that PV systems do not significantly alter the short-circuit levels in the network. This suggests that the integration of photovoltaic systems into the grid does not increase the risk of higher short-circuit currents, thus maintaining the safety and stability of the network during faults.

Additionally, scenario 4 shows the same values as scenario 3, as the PV system does not affect the short-circuit currents.

However, the situation changes significantly when a small hydroelectric power plant (SHPP) is connected to the network. In this case, the short-circuit powers are considerably higher, with the maximum difference reaching up to 0.3 MVA. This increase can be attributed to the ability of the SHPP to continuously supply consumers during faults, unlike photovoltaic systems, which cannot.

4.1.2 Two-Phase Short Circuit

The analysis of the two-phase short circuit was conducted in a similar manner as the three-phase short circuit analysis. Short-circuit current diagrams will be generated for the four cases, showing diagrams for phase B and phase C, while the values for phase A will be zero, as this phase is not involved in the short circuit.

The short-circuit current diagram for phase B can be seen in the following image, Figure 5.

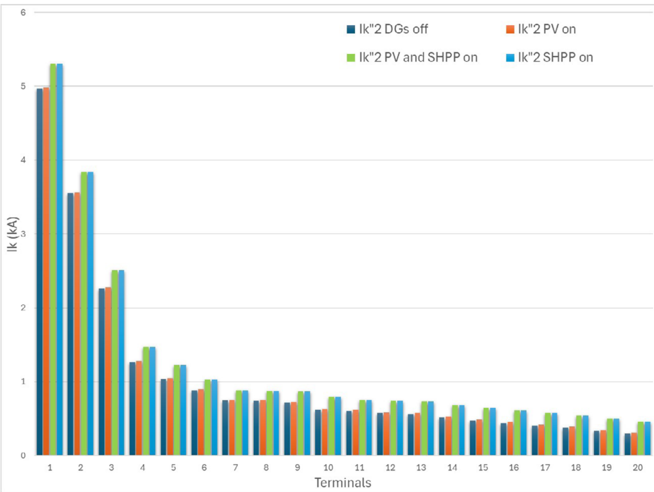

Figure 5: Comparison of Two-Phase Short Circuit Currents for Different Scenarios (Phase B)

The short-circuit current diagram for phase C can be seen in the following image, Figure 6.

Since this is a short circuit between phases, we can observe that the currents are of slightly lower values. The diagram also shows the system's behavior similar to the three-phase short circuit case. There is almost no difference between the short-circuit currents without distributed generators (DG) and the currents when the PV system is connected. However, in the case of connecting the small hydroelectric power plant, these currents are of higher intensity, as explained above..

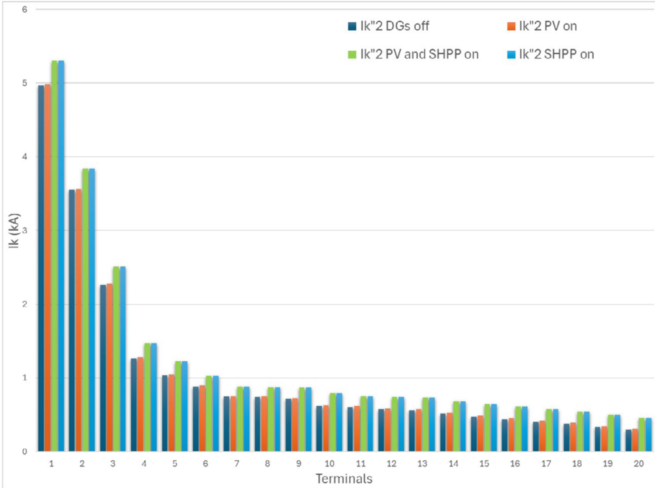

Figure 6: Comparison of Two-Phase Short Circuit Currents for Different Scenarios (Phase C)

4.1.3 Single-Phase to Ground Short Circuits

Finally, a single-phase short circuit with ground was analyzed, as shown in Figure 7. In this case, we observe that the short-circuit current is significantly lower compared to the three-phase short circuit and the phase-to-phase short circuit, as only one phase is involved in the kVAr.

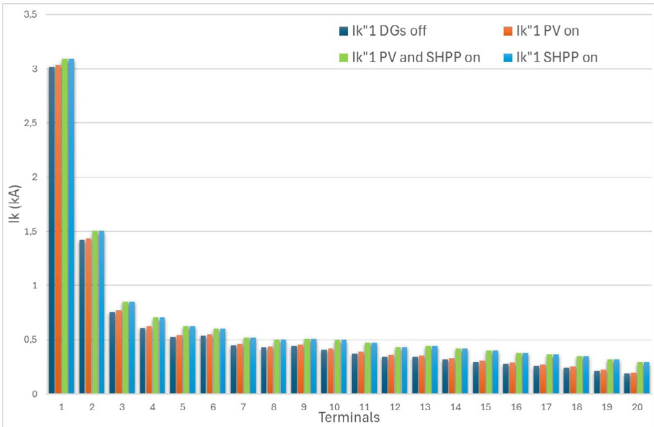

Figure 7: Comparison of Single-Phase to Ground Short Circuit Currents for Different Scenarios

This diagram also highlights differences between the cases. The addition of distributed generation sources (PV and SHPP) does not significantly alter the fundamental nature of the short-circuit current. The difference is particularly noticeable with the SHPP, as it attempts to supply the consumers and meet the demand during the fault, similar to the previous cases.

4.2. Harmonics

In this study, the total harmonic distortion (THD) graphs were analyzed. The results show that THD is highest when a photovoltaic (PV) system is connected.

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Connecting a small hydro power plant (SHPP) reduces THD, with the lowest THD observed when the PV system is disconnected and the SHPP remains connected. The analyses were conducted at busbar 41, which is located near the end of the network. Both the PV and SHPP systems are connected to node 41. Harmonic distortions for the 5th and 7th harmonics were analyzed. The 5th harmonic is a distortion component that occurs five times the fundamental frequency (e.g., 250 Hz for a 50 Hz system). It is often generated by nonlinear loads and can cause equipment overheating and interference in communication systems. The 7th harmonic occurs seven times the fundamental frequency (e.g., 350 Hz for a 50 Hz system). Like the 5th harmonic, it is generated by nonlinear loads and can cause similar problems, including degradation of power quality and equipment resonance.
The THD analysis values for the 5th harmonic are presented in Table III:

Table III. HD value for the fifth harmonic

Case	HD vrijednost za peti harmonik (%)
PV and SHPP off	1,16
Only PV on	2,08
PV and SHPP on	1,48
Only SHPP on	0,93

The THD value for the 5th harmonic in these four cases can be visualized using the diagram in Figure 8.

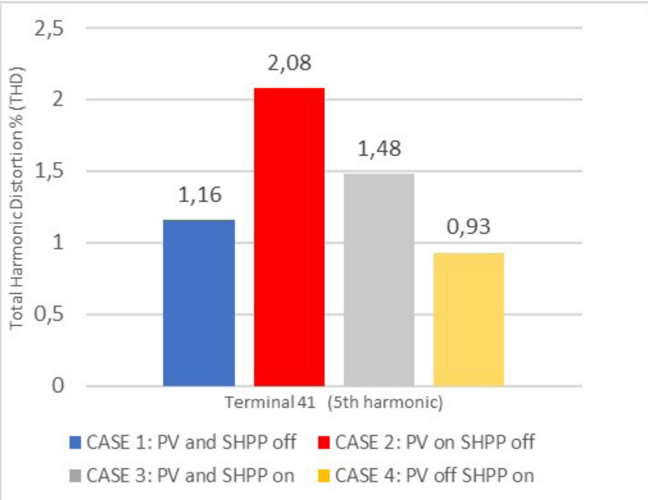

Figure 8: HD value for Busbar 41 for the fifth harmonic

The THD value for the 7th harmonic is presented in the following Table IV:

Table IV. HD value for the seventh harmonic

Case	HD value for the seventh harmonic (%)
PV and SHPP off	0,69
Only PV on	2,18
PV and SHPP on	1,46
Only SHPP on	0,53

The diagram for these 4 cases can also be seen in the following Figure 9.

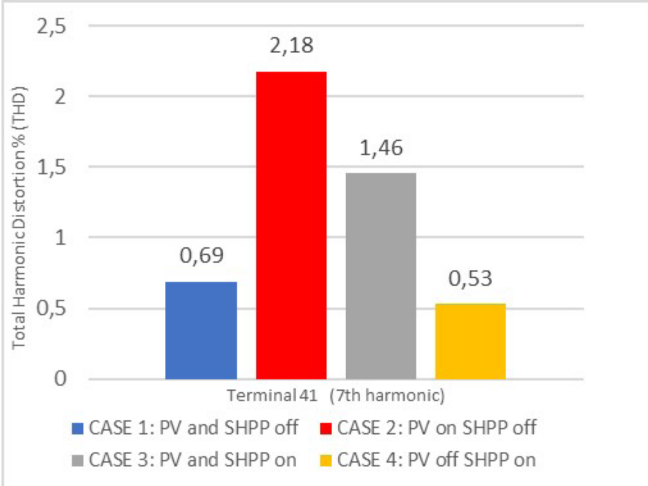

Figure 9: HD value for Busbar 41 for the seventh harmonic

According to standards, the Total Harmonic Distortion (THD) of voltage, considering all harmonics up to the 40th multiple of the fundamental frequency, should not exceed 8% of the fundamental harmonic. An increase in this coefficient raises the likelihood of issues with consumer devices and network components. The results indicate that all conditions related to the total harmonic distortion of voltage are met, as the THD in all cases is below the critical value of 8%.

Additionally, according to the EN 50160 standard, the 5th harmonic should be below 6% of the fundamental voltage, while the 7th harmonic should be below 5% of the fundamental voltage. Based on this standard, all four cases for both distributed generators meet the standard criteria.

Experiments were also conducted with different power levels of the PV system, and it was concluded that for a PV system power greater than 80 kW, the EN standard would be violated, as in this case, the THD for the 5th harmonic would exceed 6%, and the value for the 7th harmonic would be significantly exceeded. However, such a connection of a PV system to the considered network would not be possible due to other criteria checked when connecting distributed generators to the grid.

5. CONCLUSION

The aim of this study was to comprehensively analyze the impacts of integrating different distributed energy resources (DG) on short-circuit currents and harmonic distortions in the 0.4 kV Zlatici network. PV systems and small hydropower plants (SHPP) were evaluated at identical output power levels, revealing distinct effects during network faults.

Regarding short-circuit currents, PV systems showed minimal impact, maintaining similar current levels as in scenarios without DG. In contrast, the connection of SHPPs led to significantly higher short-circuit currents, surpassing the baseline levels by up to 0.4 kA. This increase was attributed to SHPP's ability to continuously supply power during faults, which is not the case with PV systems.

In the analysis of harmonic distortions, the presence of PV systems significantly increased the total harmonic distortion (THD) at the terminal, reflecting their impact near the end of the network. On the other hand, SHPPs consistently reduced the THD, which was particularly beneficial when PV systems were disconnected.

It is important to note that all measured harmonic values for the 5th and 7th harmonics remained within the acceptable limits prescribed by EN 50160 across various configurations.

These results emphasize the importance of strategic planning and management when integrating renewable energy sources into electrical grids. While PV systems can increase harmonic levels, SHPPs offer a reliable means to mitigate these effects. By carefully coordinating these sources, it is possible to improve overall power reliability, stability, and network quality in terms of sensitivity to harmonic distortions. This study provides valuable insights for future projects involving renewable energy integration, highlighting the need for a balanced approach to ensure voltage reliability and quality in distribution networks.

REFERENCES

[1] H. Saadat, Power System Analysis, McGrawHill, 1999

[2] C. L. Wadhwa, Electrical Power Systems“, New AgeInternational, 2007

[3] K. Ognjen, “Modeling and analysis of higherharmonics in simulatio interface“, M.S. thesis, Faculty of Electrical Engineering, Computer Science and Information Technology Osijek, 2018

[4] Z. V. Despotovic, „Harmonici struje i napona: uzroci nastanka i uticaj na elektroenergetski sistem (EES)“, Visoka škola elektrotehnike i računarskih studija - Višer, Beograd, 2021

[5] A. R. Hambley, Electrical Engineering: Principles and Applications, Pearson, 2019

[6] L. Xiong, M. Nour, M. Shahin, “Harmonic analysis of high penetration level of Photovoltaic generation in distribution network and solution studies“, 8 th International Conference on Modeling Simulation and Applied Optimization (ICMSAO), Manama, Bahrain, 2019

[7] E. Melić, A. Bosović, M. Musić, “Analysis of the impact of different distributed generator technologies on harmonic voltages“, Rev. Roum. Sci. Techn.– Électrotechn. et Énerg, Bucarest, 2023

[8] E. Kišija, A. Bosović, M. Musić, “ Analysis of the Impact of Different DG Technologies (SHPP vs. PV) on Short-Circuit Power and Harmonics in a Real MV Distribution Network”, ELEKTROTEHNIŠKI VESTNIK, Vol. 88, No. 1-2, pp. 17 - 25, 2021

[9] J. Li, T. Zheng, Z. Wang, “Short-Circuit Current Calculation and Harmonic Characteristic Analysis for a Doubly-Fed Induction Generator Wind Turbine under Converter Control“, Energies , Vol. 11, No. 9, Sep. 2018

[10] M. Z. C. Wanik, M. F. M. Siam, A. Ayob, Subiyanto, A. Mohamed, A. H. Azit, S. Sulaiman, M. A. M. Ali, Z. F. Hussein, A. K. M. Hussin, “Harmonic Measurement and Analysis during Electric Vehicle Charging”, Engineering, Vol. 5, pp. 215-220, 2013

[11] W. I. Gabr, W.A. Salem, “Impact of Grid Connected Photovoltaic System on Total Harmonics Distortion (THD) of Low Voltage Distribution Network: A Case Study”, 2018 Twentieth International Middle East Power Systems Conference (MEPCON), Cairo, Egypt, Dec. 2018

[12] J. Song, M. Cheah-Mane, E. Prieto-Araujo, O. Gomis-Bellmunt, “Short-circuit analysis of grid connected PV power plants considering inverter limits International Journal of Electrical Power & Energy Systems, Vol. 149, July 2023

[13] Ahmed Ahsan Latheef, “Harmonic Analysis of Photovoltaic Inverters in Electrical Distribution Systems”, M.S. thesis,University of Wollongong, 2006

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