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Analysis of the Impact of Different DG Technologies (SHPP vs. PV) on Short-Circuit Power and Harmonics in a Real MV Distribution Network

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Abstract. The key process of all power systems is providing a continuous electricity supply and the main challenge of that process are electric faults. Faults are mostly caused by natural disasters or accidents, so their occurrence is hardly predictable or avoided. The knowledge about short-circuit currents is very important since the selection of the equipment, protection measures and circuit-breaker size depends on them. Nowadays, the interest in the power quality has increased, since it has become a very important issue of the power system supply. One of the major problems of ensuring a certain level of the power quality are harmonics. The aim of the paper is to investigate the impact of small hydro power plants (SHPPs) and photovoltaics (PVs) of the same power, on short-circuit faults and harmonic distortion (HD) in real 46-bus MV distribution network in Bosnia and Herzegovina. There are three harmonic sources in the analyzed network: background harmonics, harmonic emission of loads and harmonics from PVs. Results show that SHPPs improve the short-circuit power and power quality of the system since they increase short-circuit currents for about 0.2 kA feeding the network in the direction of the fault, and decrease HD. On the other side, PVs don't significantly affect the short-circuit power since inverters turn them off at fault occurrence. Their impact on the power quality of the system is negative because inverters are a source of harmonics and they increase HD. However, the impact is not very significant and harmonic limits are not violated.

Keywords: short-circuit power, harmonic distortion, power quality, small hydro-power plant, photovoltaic system

Analiza vpliva razpršenih virov energije na kratkostični tok in višje harmonike v elektroenergetskem omrežju

Ključni pomen vseh elektroenergetskih sistemov je zagotavljanje neprekinjene oskrbe z električno energijo. Pri oskrbi z električno energijo lahko pride do motenj, še zlasti v primeru naravnih nesreč. Ena od največjih težav pri zagotavljanju določene ravni kakovosti električne energije so višji harmoniki. V prispevku analiziramo vpliv malih hidroelektrarn (MHE) in fotovoltaičnih sistemov (PV) enakih moči na napake zaradi kratkostičnega toka in harmonsko popačenje (HD) napetosti v elektroenergetskem omrežju v Bosni in Hercegovini. Analizirali smo tri izvore višjih harmonskih komponent. Dobljeni rezultati so pokazali, da MHE izboljšajo moč kratkega stika in kakovost elektroenergetskega sistema, saj povečajo tokove kratkega stika za približno 0,2 kA, napajajo omrežje v smeri napake in zmanjšujejo HD. Sistemi PV nimajo pomembnega vpliva na moč kratkega stika, saj jih pretvorniki v primeru napake izklopijo.

1 INTRODUCTION

In traditional power systems, most of the power is produced in large power plants, placed at appropriate geographical locations near energy sources such as coal mines, rivers, etc. The power is then transmitted over a long distance toward large consumption centers through transmission lines. Nowadays, a large amount of dispersed generation (DG) is being developed, including both renewable and nonrenewable energy sources, such as: photovoltaic (PV) generators, hydro generators, wind turbines, wave generators, fuel cells, gas-powered combined heat power plants (CHPP), etc. DG is an application of small generators, typically up to 1 MW, scattered throughout a power system to provide electric power closer to consumers.

The main objective of any power systems is to produce and transfer a reliable electric power to consumers, maintaining its quality in accordance with the standard EN 50160, at a reasonable price, with the

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primary aim to maintain a continuous power supply. Under normal operating conditions, all elements of the electric power system conduct a normal load current, within the set limits, compliably with the rated values of system elements. However, this condition can be interrupted due to faults in the power system. A fault in the power system is any failure that stands in the way of a normal system operation and a normal current flow. Natural events, such as ice, wind, lightning, heat, animals, etc., or equipment failure and many other uncertain factors may cause undesirable situations, so called faults [1]. In order to prevent these undesirable situations, power-system fault analysis is used. The power-system fault analysis is a process of evaluating voltages and currents of the system at different types of short circuits. Such analysis leads to a proper computation of the protection setting to ensure a suitable fuse, circuit-breaker size and relay type. The short-circuit power defines the natural power and capacity of the network.

The power quality is another very important issue of the power supply. This was particularly noted in the second half of the 1990s in connection with the high-voltage DC (HVDC) systems and static var compensators (SVC) [2,3]. At the time it was recognized as a power-quality issue on which improvement utilities all over the world were working intensively for decades. There are many reasons why the interest in the power quality has increased nowadays. Despite becoming more sensitive to voltage disturbances, the electronic and power electronic equipment also affect the power quality. Power utilities view the end-user modern equipment as the main source of disturbances and consequently the main power-quality problem. The reason for that is the increased use of converter-driven equipment (consumer electronics and computers) and the main issue is the nonsinusoidal current of rectifiers and inverters. It contains a power frequency and also a harmonic component whose frequency is a multiple of the power frequency. The current harmonic distortion leads to harmonic components in the supply voltage. Another reason for the growing interest in the power quality is the growing need for standardization and performance criteria. Nowadays consumers are viewed as customers and the electric energy as a product which can be measured, predicted, improved, etc. Therefore, all of this has led to privatization, deregulation of the electricity industry and open market competition which have made the situation even more complex. Utilities wanting to deliver a good product have made the power supply become too good. Customers have gotten a wrong impression that electricity can be always made available and of a high quality, because long interruptions have become extremely rare in most industrialized countries. The availability of electronic devices which measures the power quality has certainly contributed to the interest in the power quality [2].

Harmonics are one of the major problems of ensuring a certain level of the power quality and this requires a harmonic-generation analysis and measurements, study of their effects and their limitation to an acceptable level.

The main objective of the paper is to analyze the impact of different DG technologies, SHPP and PV of the same power, on different types of short-circuit faults and HD in a real MV distribution network. In Section 2, short-circuit faults and power-system harmonics are explained. In Section 3 the related literature is reviewed. In Section 4 the used methodology is described. In Section 5 results are presented. Section 6 draws conclusions of our work.

2 POWER-SYSTEM FAULTS AND HARMONICS

2.1 *Faults*

In the power system, a fault is defined as s failure which causes the massive current to be distracted from the intended path. It is a deviation of voltages and currents from their nominal values [4].

Faults can occur anytime and at any part of the electric power system. Unfortunately, in most cases faults cannot be predicted, because they may be caused by various natural disturbances, such as lightning, earthquake, high-speed wind, etc., or accidents such as tree falling, vehicle colliding, airplane crashing, etc. Inappropriate insulation and critical weather conditions, in combination with high-voltage levels, can also result in faults. In such situations, a phase establishes a connection with another phase of a different potential, the ground or both, and the direction of the current changes. The electric-fault effects are presented in Table 1.

Table 1. Electric faults effects.

Over-Current Flow	A fault creates a very low impedance path for the current flow. As a result, a very high current is being drawn from the supply, causing tripping of relays and damaging the insulation and equipment.
Danger to Personal Operating	A fault occurrence can also cause shocks to humans. The shock intensity depends on the current and voltage at the fault location and may even lead to death.
Loss of Equipment	A high current causes the components to burn completely, leading to an improper working of the equipment or device, sometimes even burnout of the equipment.
Disturbance of interconnected active circuits	Faults do not only affect the location at which they occur, but also disturb the active circuits, interconnected to the faulty line.
Electrical Fires	Sparks can be caused by ionization of the air between two conducting paths and may lead to fire.

Power system faults are mainly divided into two groups: open-circuit and short-circuit faults. In the paper, short-circuit faults are analyzed.

2.1.1 Short-circuit faults

A short circuit fault occurs when conductors of different phases come in contact with each other, power line, power transformer or any other element in the circuit, resulting in a low impedance path, whether between phases or phase(s) to ground. [1] What is actually happening is the connection between two nodes which forces them to be at the same voltage level, and because there is almost no resistance in between, the current is limited only by the resistance of the rest of the circuit.

Prior to a fault occurrence, only AC voltages and currents are present, but immediately after a fault, both AC and DC currents occur. The short circuit current is a sum of these two components. The circuit-breaker is a switching device that interrupts a certain amount of the short-circuit current in order to prevent the system from a damage. It takes some time for the relay to detect the fault and send commands to a circuit-breaker and therefore, its size is less than the peak short-circuit current. The maximum value of the short-circuit current is calculated according to the intensity of the currents in a sub-transient period. This current can be as much as ten times the steady-state fault current [5]. “Subtransient” refers to the fact that this quantity operates extremely fast, even faster than “transient”. Because of the short-circuit protection, this current will be cut-off very fast. If components in an electrical installation are insufficiently short-circuit proven, this can cause a lot of damage, even if a short-circuit current exists only briefly. Therefore, taking the short-circuit capacity on an electrical installation into account is extremely important.

Short-circuit faults can be either symmetrical or asymmetrical. Symmetrical faults involve all the three phases which remain balanced even after a fault occurrence. The information about a three-phase balance fault is used to set phase relays. Such faults are sub-categorized into L-L-L (line-line-line fault) and L-L-L-G (line-line-line-ground fault). Symmetrical faults are the most severe, but fortunately only about 5% of the faults that occur in the system are symmetrical [6]. Asymmetrical faults do not affect neither of the three phases equally, so the currents of these faults differ in their magnitude and phase in the three phases of the system. The system is unbalanced and based on the number of phases involved and contact of the ground, faults can be divided into three sub-categories: L-G (single line to ground with the occurrence of 70-80%), L-L (line to line with the occurrence of 2%) and L-L-G (double line to ground with the occurrence of 17%) [7]. The paper analyses each type of the short-circuit fault.

2.2 Harmonics

Electricity generation is normally done at constant frequencies of 50 Hz or 60 Hz and the generator e.m.f. can be considered practically sinusoidal. However, when a nonlinear device or load is connected to the source of a sinusoidal voltage, the resulting current is not perfectly sinusoidal. This current, in the presence of a system impedance, causes a non-sinusoidal voltage drop and produces voltage distortion at load terminals. Power-system harmonics are defined as a sinusoidal voltage and currents at frequencies that are integer multiples of the main generated (fundamental) frequency [8].

HD is a degree to which a waveform deviates from its pure sinusoidal values. The periodic nonsinusoidal waveform can be presented mathematically in terms of the Fourier series. Each term of the series is called a harmonic component of a distorted waveform. For most applications, the harmonic range from the 2nd to the 25th is considered, but most standards specify those up to the 50th [8]. The compatibility levels for harmonic voltages for public MV networks are defined in the IEC 61000-2-12 standard and limits for public distribution networks in Europe are defined in the EN 50160 standard [9].

Harmonics are caused by various operations, such as ferroresonance, magnetic saturation, subsynchronous resonance and nonlinear and electrically switched loads.

Nonlinear and electrically switched loads are the most dominant source of harmonics in power systems (HVDC transmission, light emitting diodes - LED, fluorescent lighting, static var compensators - SVC, thyristor controlled reactors, wind and solar power generation, computers, copy machines, television sets and home appliances, air conditioning, heat, etc.)

Distortion of the current and voltage waveforms caused by harmonics adversely affects electrical equipment. Some of the effects are:

- Increase in the line-current value,
- Overheating of transformers, motors, generators, capacitors, cables, etc., which can cause a premature failure,
- Misoperation of protective devices (circuit breakers),
- Malfunctioning of electronic equipment and instruments (including medical instruments),
- Incorrect meter readings,
- Premature failure of power supplies,
- Low power factor and
- Power quality drastically affects the power control and consumption.

3 LITERATURE REVIEW

DG applications in the power distribution system are investigated in terms of the short-circuit current in many papers. With the integration of different types of DGs, the values of short-circuit currents increase by up to 164.18% [10,11]. The impact of a large-scale PV system integration on the short-circuit level of a power distribution system is done in [12] by comparing four different scenarios of various PV sizes and locations. The difference between short-circuit currents of connected and disconnected PVs is insignificant [13]. In [14], the variation in the DG size and location does not significantly affect the short-circuit level. On the other side, it is shown that small hydro power plants increase the short circuit current levels, especially if a short circuit occurs close to a plant.

Since the power quality has become a very important issue in the power supply, it has been a point of interest for many researchers. In [15], the impact of residential PVs on harmonics and power quality in a low-voltage distribution network in Croatia is investigated. The results show that the greatest voltage total harmonic distortion (THDu) occurs in the scenario when all the households install PV plants. The total contribution of the installed PV plants to the THDu is above 2% but does not violate the harmonic limit, laid down by the EN50160 standard (THDu<8%). [16] In [17-20], the authors come to the same conclusion.

4 METHODS

4.1 *Problem formulation*

The problems of the short-circuit faults and harmonics in a power system described above are analyzed on an example of an MV power distribution network. The first problem is determination of short-circuit current values, which is a crucial standard in selecting the mandatory safety measures, electrical equipment and circuit-breaker size.

The second problem is determination of the harmonic voltage distortion level of the 5th and 7th harmonics at the bus marked in Figure 1.

The impact of different DG technologies (SHPPs and PVs) on the short-circuit currents and HD level is analyzed. In both cases, three scenarios are considered:

1. Both SHPPs and PVs disconnected (DGs off),
2. PVs connected and SHPPs disconnected (PVs on),
3. SHPPs connected and PVs disconnected (SHPPs on).

The software tool DIgSILENT Power Factory is used to perform the short-circuit analysis in the Base package and the harmonic load flow in the Power Quality and Harmonic Analysis toolbox.

4.2 *MV power distribution network modelling*

The analyses are done using a model of a part of the power distribution network Goražde, supplying its customers from the 110/35/10(20) kV Goražde 1 transformer substation. The voltage levels are: 35 kV, 20 kV, 10 kV and 0.4 kV. The whole 20 kV power distribution network in the analyzed area belongs to the 20 kV Prača line. The line is 60 km long. The network components are presented in Table 2. The impact of two different DG technologies, SHPPs (Čemernica, Kaljani) and PVs of the same power is analyzed. SHPPs are the existing facilities and PVs are modelled for the analysis purposes. A georeferenced scheme of the analyzed part of the Goražde MV power distribution network is shown in Figure 2. The harmonic analysis is done at the bus which connects the bus at which DGs are connected to the rest of the network. Figure 1 shows the network model designed in DIgSILENT Power Factory for harmonic analysis.

Table 2. Network components.

BUSBARS	46
LINES	39
TRANSFORMERS	5
GENERATORS	3
LOADS	32

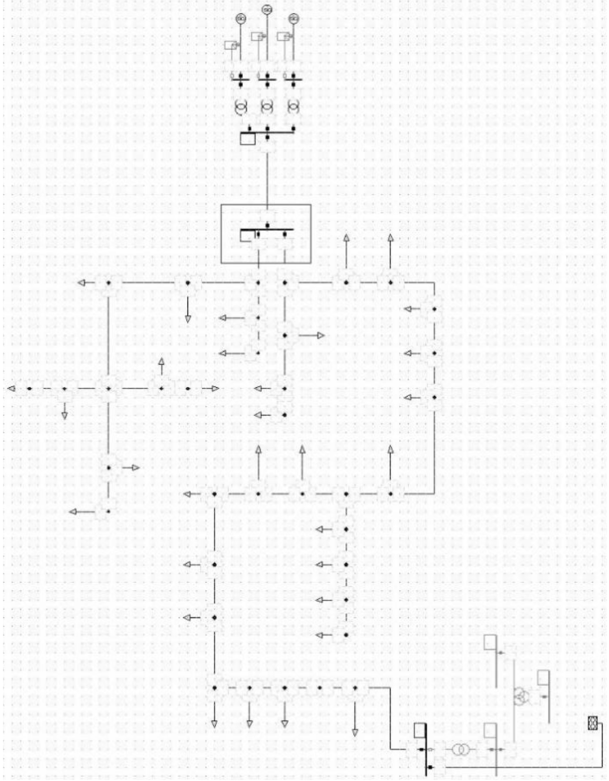

Figure 1. Model of the analyzed network.

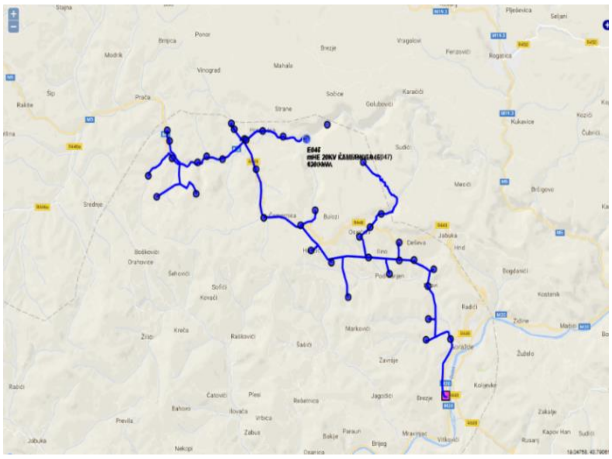

Figure 2. Georeferenced scheme of the analyzed network.

4.3 Harmonics modelling

There are three types of the harmonic sources for harmonic voltage studies in this network: background harmonics from higher voltage levels, harmonic emission from loads connected to the network and harmonics from PVs. Modelling and summation of the harmonic sources is done according to the summation law of the IEC 61000-3-6 standard.

4.3.1 Background harmonics

Background harmonics are usually modelled as a voltage source in an external grid element. The study makes use of harmonic voltage measurements performed by the Bosnia and Herzegovina Electric Power Utility (Elektroprivreda). The values for the 5th and 7th harmonics are presented in Table 3.

4.3.2 Harmonic emissions from loads

Harmonic emissions from loads are often modelled as a harmonic current source. Since the harmonic current data of the loads from the studied network are unknown, the data of the 5th and 7th harmonic current emissions as a percentage of the base current of a residential customer configuration in Germany, [21] is used (Figure 3). The values in the time interval between 11 am and 3 pm are taken into consideration when PVs are active (values range in Table 3).

4.3.3 Harmonic emissions from PVs

The PVs-emitted harmonics are due to inverters using non-linear electronic components. The aim of the paper is to analyze the magnitude of their impact on the voltage HD level. In DIgSILENT, they are modelled as harmonic current sources. The used data are taken from [22] where the magnitudes of the harmonic currents emitted by six different PV inverters of different manufacturers are presented (Figure 4). The average value of four harmonic currents (three-phase inverters) is set as a value of PVs current sources since the frequency of using these four different inverters in Bosnia and Herzegovina is not known. In the analyzed network, there are three PVs and harmonic currents are the same for all of them. Their values are converted from amperes to a percentage of the base current (Table 4). I_h is the harmonic current in amperes, I_f is the base current and $I_\%$ is the harmonic current in percents. The values of harmonic sources are presented in Table 3.

Table 3. Values of the harmonic sources in the analyzed network in % of base values.

Source	**Harmonic Sources**			
	Harmonic current		***Harmonic voltage***	
	5th	7th	5th	7th
External grid			0.012133	0.015767
PVs	0.818	1.064		
Load 1 – 32	5.64 - 8.81	1.39 - 3.3		

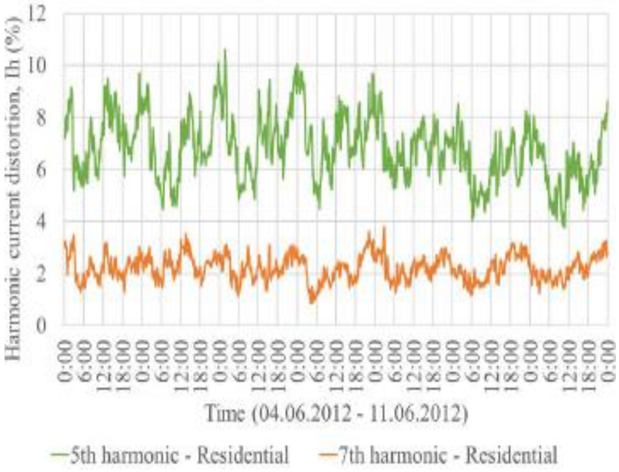

Figure 3. 5th and 7th harmonic current emissions as a percentage of the base current of a residential customer configuration in Germany [21].

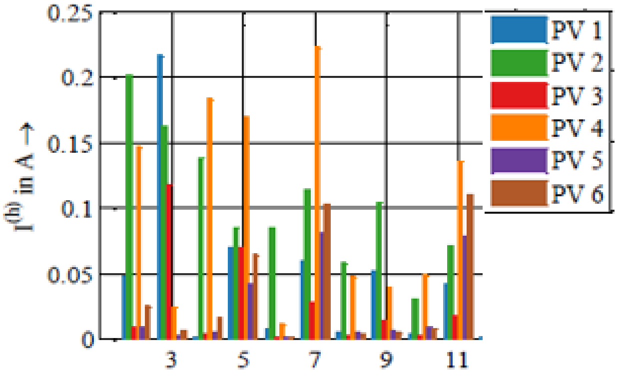

Figure 4. Magnitudes of the harmonic currents of six different PV inverters [22].

Table 4. Conversion of the unit of the PV harmonic currents from amperes to % of the base current.

5th harmonic				
	PV3	**PV4**	**PV5**	**PV6**
I_h	0.07	0.17	0.045	0.065
I_f	14.49	10.867	5.797	14.493
$I_\%$	**0.483**	**1.564**	**0.776**	**0.4485**
7th harmonic				
	PV3	**PV4**	**PV5**	**PV6**
I_h	0.03	0.22	0.08	0.1
I_f	14.49	10.867	5.797	14.493
$I_\%$	**0.207**	**2.01**	**1.38**	**0.69**

5 RESULTS

5.1 *Short-circuit analysis*

The IEC 60909-0:2001 standard is used to calculate the short-circuit currents. The short-circuit fault is analysed on the network with the DG facilities disconnected. PVs (3x570 kVA) are connected and the short-circuit analysis is resumed. PVs are disconnected and three SHPPs of the same power (2x570 kVA + 570 kVA) are connected. The results of the short-circuit currents of the three scenarios are compared. This is done for all types of the short-circuit faults (see Figures 5-9). The vertical line (y label) denotes the short-circuit currents and the horizontal line (x label) the loads (29 loads used for a comparison). All current values are in kA.

5.1.1 *Three-phase faults*

The analysis results of the three-phase short-circuit currents are shown graphically in Figure 5 for each of the three scenarios. As seen, the three-phase short-circuit currents, without DGs and with PVs connected, are the same. So, PVs do not affect the short-circuit level.

On the other side, when SHPPs of the same power are connected to the network, short-circuit currents increase (green color) because SHPPs feed the network at a fault occurrence.

5.1.2 *Line-t-line fault*

Figure 6 presents results of currents of a two-phase fault. The currents on faulty phases have the same magnitude but an opposite direction. The current on phase A is zero. PVs do not affect this type of the fault and SHPPs feed the network.

5.1.3 *Double-line-to-ground fault*

Currents of this kind of the fault are different in phases of the fault occurrence. Phase B short-circuit currents are presented in Figure 7 and phase C short-circuit currents are presented in Figure 8. Again, there is no significant impact of PVs.

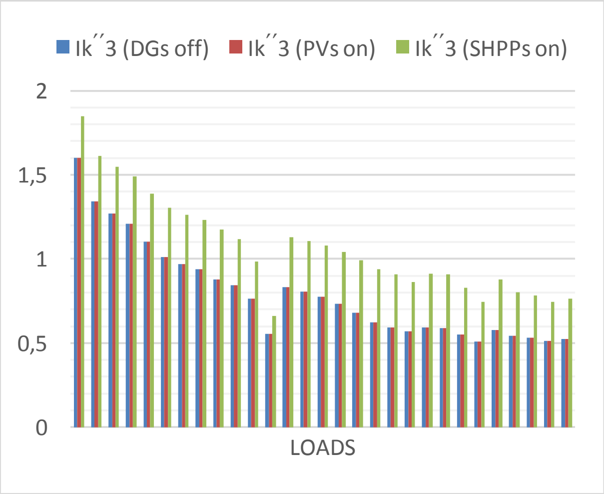

Figure 5 Comparison of three phase short circuit currents

5.1.4 *Single-line-to-ground fault*

Currents of this kind of the fault are very small. They are shown in Figure 9. The reason why the single-line-to-ground short-circuit currents are very small and differ fom the others, is that this is an isolated system. In such system, there is no intentional connection to earth. It is coupled to the ground through a distributed capacitance of lines and cables. The current circuit has to be closed. In this case, there is no circuit through which the current would circulate, except through the line and cable capacitance. Neglecting the longitudinal impedances, the current at the fault point depends only on the capacitive current of the network and the fault resistance.

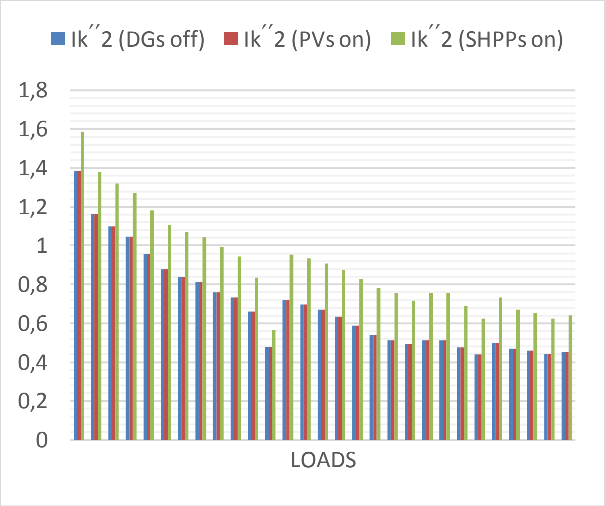

Figure 6. Comparison of the line-to-line short-circuit currents.

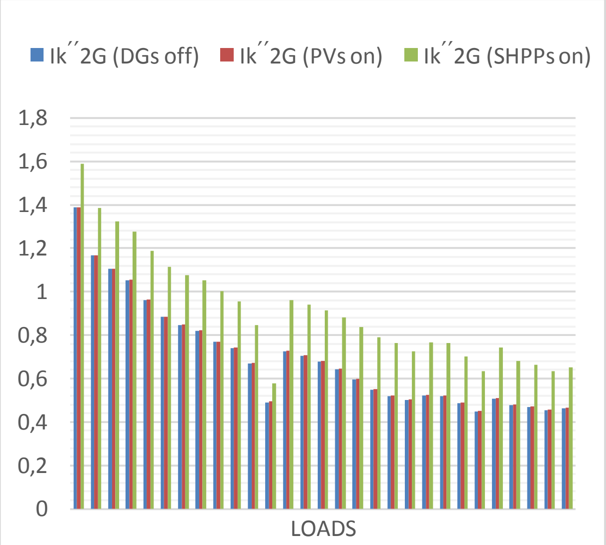

Figure 7. Comparison of the double-line-to-ground short-circuit currents (phase B).

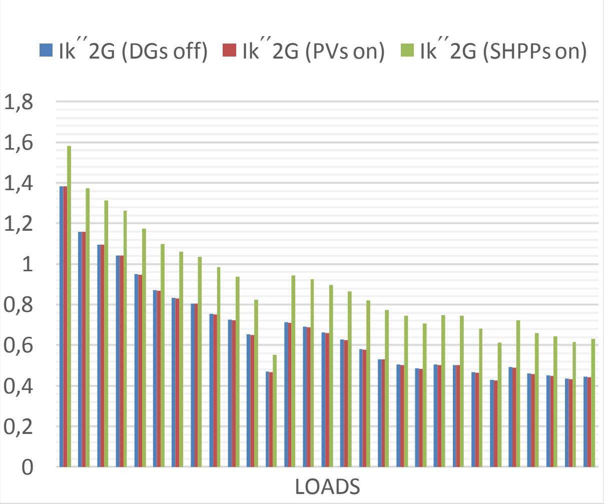

Figure 8. Comparison of the double-line-to-ground short-circuit currents (phase C).

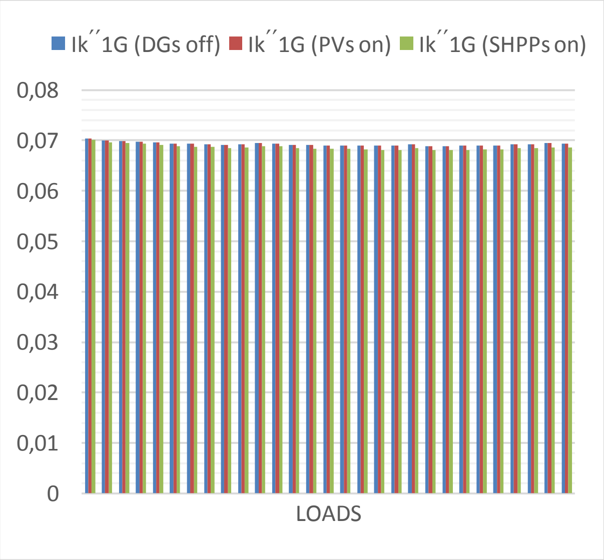

Figure 9. Comparison of the single-line-to-ground short-circuit currents.

Therefore, these capacitive currents are very small and there is no DG technology that would increase them. This kind of faults are called earth faults in an isolated neutral system. The DG impact is almost the same and insignificant because of the above reasons.

5.2 *Harmonic analysis*

A harmonic load flow is performed and results are compared with measurements performed on the same network by Elektroprivreda. The harmonic analysis is also done for (i) SHPPs and PVs disconnected, (ii) SHPPs disconnected, PVs connected and (iii) SHPPs connected, PVs disconnected.

The resultant harmonic voltage distortion levels in %, obtained on the bus of interest after performing a harmonic load flow, are presented in Table 5 and Figure 10. In Table 6 results of the Elektroprivreda measurements of harmonic voltage distortion levels on a real network are presented for two scenarios. Since PVs are modelled to analyze their impact, they are not connected to a real network. Figure 11 presents a comparison of the results obtained from this analysis and those measured by Elektroprivreda.

Table 5. Harmonic voltage distortion for three scenarios.

Scenarios	**Harmonic Voltage Distortion [%]**	
	5^{th} harmonic	***7^{th} harmonic***
Disconnected generation	1.849795	3.835216
PVs connected	1.892494	3.976288
SHPPS connected	1.363889	2.747793

Table 6. Harmonic voltage distortion for two scenarios measured by Elektroprivreda.

Scenarios	**Harmonic Voltage Distortion [%]**	
	5^{th} harmonic	***7^{th} harmonic***
Disconnected generation	1.813	3.200
SHPPS connected	1.343	2.164

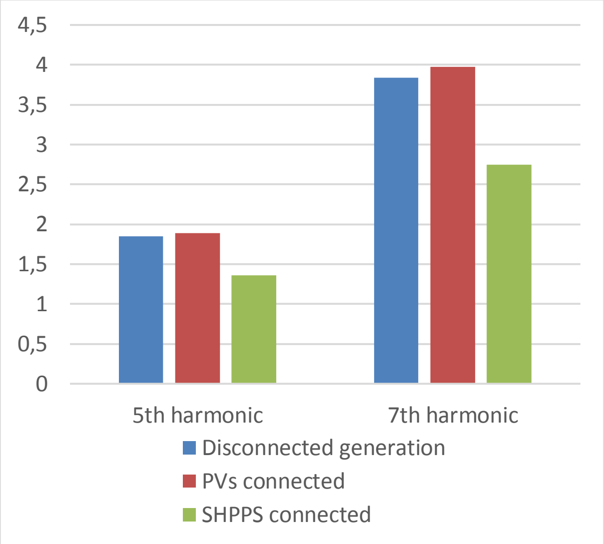

Figure 10. Graphical representation of harmonic voltage distortion for three scenarios.

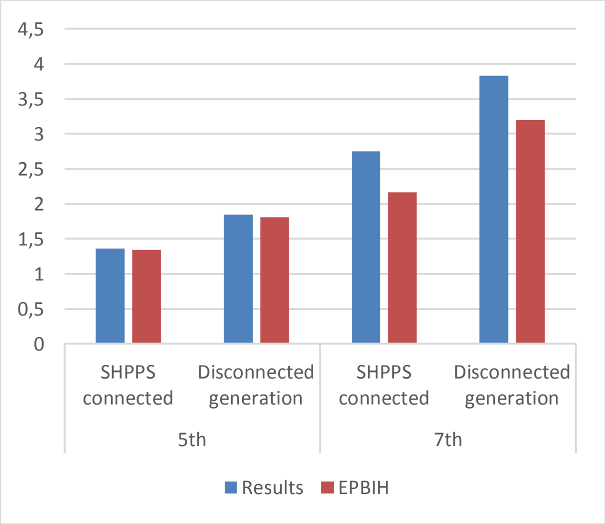

Figure 11. Results of a comparison with the Elektroprovreda measurements.

Figure 11 shows that the results are almost the same as those of the Elektroprivreda when it comes to the 5th harmonic for the SHPPs connected and disconnected. For the 7th harmonic, the results are not the same but the difference is very small.

6 CONCLUSION

The aim of the paper is to analyze the impact of different DG technologies at short-circuit currents and harmonic voltage distortion level in the 46-bus part of the Goražde MV power distribution system.

Though the power set to these two types of the DG technology (SHPP and PV) is of the same amount, there is a big difference in the obtained results and the way they act at a fault occurrence and HD level. To calculate short-circuit currents, the IEC 60909-0:2001 standard is used.

The results show that SHPPs affect the short circuit currents in the network by increasing them, which means that the generator is feeding the network at the time of the fault occurrence. In the first three cases, the current increases for about 0.2 kA, while in the case of a single-line-to-ground fault there is no significant impact because the system is isolated and an earth fault occurs. Besides strengthening the network by increasing the short circuit power, SHPPs also improve the network power quality by decreasing the harmonic distortion level (Table 5).

On the other side, PVs do not affect the short-circuit currents of any type of the fault. When PVs are connected, the harmonic voltage distortion increases, but does not violate the permissible limits. There is no big difference between HD when there is no generation connected to the system and when PVs are connected, especially for the 5th harmonic.

As mentioned above, the reason for the PV-caused harmonics are the inverters. Due to the advancement in the technology, the novel inverters are no longer expected to cause so much harm in the network. However, different results can be expected in other networks, especially those with a low short-circuit power.

Figure 11 shows a comparison between the results of the study and of the Elektroprivreda for a power network. For the 5th harmonic, the results are almost the same, proving a very good match between the model and the measurements. For the 7th harmonic, the results are very similar. In the case of a disconnected generation, the difference is 0.64%, and in the case of SHPPs connected, the difference is 0.58%. These results are still quite good. The difference can be justified by the fact that the harmonic current data of loads is used from another country. The HD level is higher with those values because Germany is a more developed country than Bosnia and Herzegovina. Consumers in Germany use devices which include more electronics and thus cause a greater harmonic distortion.

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