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SOME ASPECTS OF IMPLEMENTING GRID-CONNECTED PV SYSTEMS

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Abstract: *Generation of electric energy from renewable energy sources is a challenge that has to be carefully envisaged since it represents not only a potentially profitable enterprise but also a source of problems for the complex operation of large electric power systems. The paper presents some aspects of grid-connected photovoltaic (PV) systems, especially the determination of solar potential, selection of PV technology and PV system protection. Finally, some aspects of the impacts due to parallel operation of low voltage distribution network and PV system are presented. Research results demonstrate major indicators of PV system impact on the low voltage distribution network. The influence of PV system operation upon voltage profiles, both for the closed and open loop form of low voltage network operation has been analyzed. Briefly, the fault current contribution impact of PV systems has also been investigated.*

Keywords: – renewable energy sources
– photovoltaic systems
– grid-connected PV systems
– voltage profile impact
– fault current contribution

1. INTRODUCTION

The use of solar energy as an inexhaustible energy source has been present for thousands of years. Nevertheless, the photovoltaic (PV) effect was not discovered until1839. The discovery was made by Edmond Becquerel who was able to generate voltage (current) in a material subjected to solar radiation. In his time, the photovoltaic discovery did not get much attention. However, more than 40 years after Becquerel's discovery, Charles Fitts constructed the first functional solar cell [1]. In the year 1954, the first PV cell that generated a usable amount of electric energy was presented by Bell Labs in the USA. By the year 1958, PV cells were installed in commercial applications, especially in spacecraft applications. Even though the photovoltaic effect is closely linked to the photoelectric effect, the two phenomena are different and need to be distinguished. In fact, in the photoelectric effect, the electrons are released from the surface material after exposure to radiation of sufficient energy. Unlike the process of the photoelectric effect, the process of the photovoltaic effect is characterized only with the change in electron energy levels (i.e. the transition from valence band to the conduction band) inside the material, which in turn results in voltage build-up on the electrodes. The photoelectric effect was first discovered by Heinrich Hertz in 1887. However, it was only in 1905 that Albert Einstein explained the photoelectric phenomenon, introducing the concept of photon quanta and setting the foundation of quantum physics. The aforementioned discovery brought Einstein the Nobel prize in physics in the year 1921.

Correspondingly, the Republic of Croatia has adopted several legal acts that stimulate electric energy production from renewable energy sources (RES) and highly efficient energy conversions, such as cogeneration. These legal acts have resulted in the institutional framework for future RES projects, in particular designating RES as preferred producers of electric energy, with guaranteed infeed tariff [2].

As PV systems are characterized by high initial capital investments, they are to be largely stimulated by the state, i.e. for the smallest PV systems (up to 10 kWp), the feed in tariff is as high as 0, 46 €/kWh. In the paper some aspects of grid-connected PV systems will be presented. These systems are intended only for parallel operation with the electric power system.

In the first part of the paper, a suitable methodology for solar potential determination has been presented as the most important parameter for the analysis of cost effectiveness of the PV system. Hence, a short review of suitable PV cell technologies and inverter concepts interfacing the low voltage distribution network (LVDN) will be elaborated.
In the last part of the paper some aspects of PV systems protection are briefly discussed. Also, by modeling a real LVDN some consequences of a PV production plant are analyzed and the results are presented.

2. SOLAR POTENTIAL DETERMINATION

The most important parameter indispensable to perform the feasibility study of the planned PV system, is the amount of solar potential at the location where PV panels are to be installed. Actually determination of solar potential can be done in one of the following methods:

1) direct measurement of the solar radiation, using appropriate measuring instruments – pyranometers, at site location,
2) assumption of solar radiation data given in literature [1] for the location closest to the location under consideration, or meteorological data ordered from the Meteorological and hydrological service,
3) plotting GPS coordinates of the location under consideration and free computer application PVGIS found on the web pages of the European Commission,
4) using professional software for PV systems planning and analysis (e.g. PV*Sol), Figure 1.

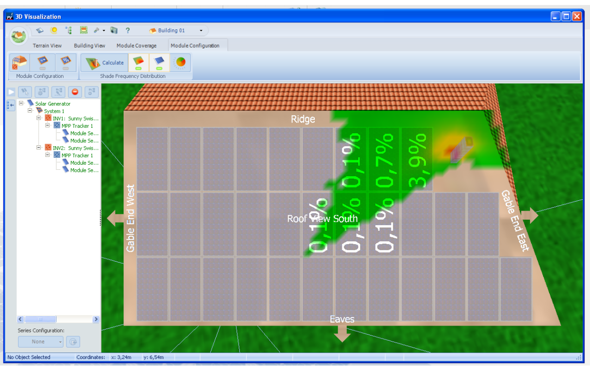

*Figure 1. Computer application PV*Sol, [3]*

Each of the mentioned methods is characterized by certain advantages and shortcomings, thus the methods 1), 2) and 4) require certain financial assets, while the method 3 does not require any. However, only the methods 1) and 4) give insight into actual irradiation at the location site, taking into consideration the effects of shadowing due to neighbouring buildings, trees and/or other objects, Figure 2.

Figure 2. Pyranometer – solar radiation measurement instrument

The knowledge of yearly solar irradiation/electric energy production is directly linked to the yearly income due to electric energy infeed in the distribution network, Figure 3.

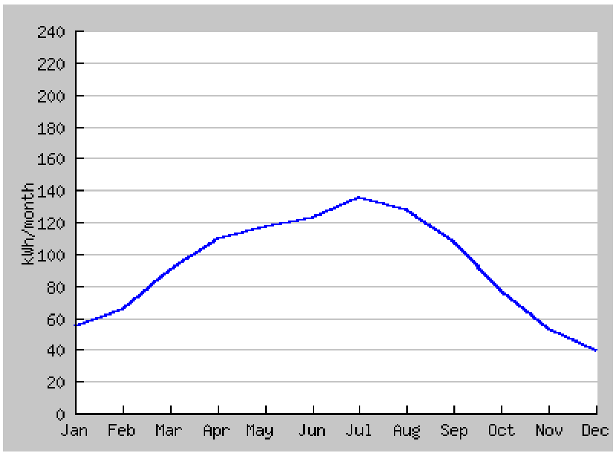

Figure 3. Estimation of PV system electric energy monthly production – PVGIS, [4]

Furthermore, knowledge of monthly and daily irradiation/energy production profiles provides valuable information to distribution network operators, who can therefore plan and operate distribution networks in an increasingly safe and reliable manner. Additionally, the fact is that PV system unload distribution network feeders are also well known, i.e. active power flows are partially compensated due to PV system feeding neighbouring loads [5].
Given the particular sensitivity to the overall techno-economic investment analysis of cost-effective PV

system project, the aspect of solar potential has to be assessed with great care, since erroneous initial assumptions cannot be corrected easily once the PV system has been installed.

3. SELECTION OF PV TECHNOLOGY AND PV SYSTEM CONCEPT

While the selection of the appropriate inverter concept is limited to a modest number of manufacturers and models, the choice of PV modules is considerably large.

In fact, a very large number of different PV technological solutions exist today on the market. The solutions are suitable for a variety of applications – from standalone systems, grid-connected systems, marine applications, spacecraft applications etc.

First, a decision must be made regarding PV cell material (monocrystalline silicon, polycrystalline silicon, amorphous silicon, gallium-arsenide multijunctions, cadmium-telluride, copper-indium selenide, organic/polymer cells) hence cell type. In general, PV cells are divided into 4 main groups [6]:

1) silicon crystalline cells,
2) thin-film cells,
3) hybrid-type cells,
4) nanostructural cells.

Every PV solar cell is characterized by solar cell efficiency conversion of solar radiation into electric energy, dimensions, and by other less important but still significant technical parameters (temperature dependency, mechanical resistance, colour, transparency, etc.). The most important non-technical parameter is, of course, the panel price.

Another important aspect of PV systems is the way the PV cells are connected to forming PV panels. In fact, two PV cells can be connected together in only two basic ways:

1) serial and
2) parallel.

With serial connection of PV cells, one obtains a so called PV string, while with parallel connection of PV cells submodules are obtained. The total voltage of serially connected PV cells equals the sum of the voltages on each PV cell, while the overall current is equal for every PV cell in the string. When connecting PV cells in parallel, the voltage at each submodule is kept the same, while the overall current is equal to the sum of every submodule current.

PV cell shadowing is one of the most important problems related to PV system operation. Namely, if one of the PV cells in the PV string is shaded, a reverse polarity voltage is formed on the shaded cell. Voltage increase on the shaded cell can result in cell breakdown, which in turn transforms the shaded PV cell into a pure resistive element in the electric circuit of the PV string. Unshaded cells continue to produce electric current, thus forcing current through the shaded cell, thereby increasing cell temperature. The aforementioned mechanism can lead to cell burn-out and even fire. Today, cell shading problems have been successfully overcome by installing by-pass diodes which take over the current from the reverse polarized PV cells.

The next important aspect of the planned PV system is the concept of the inverter system. In fact, special attention must be dedicated to the following:

- monophase/triphase inverter,
- central inverter/multiple inverters,
- inverter efficiency,
- inverter price.

Today, several different concepts exist for interfacing the PV system with electric power system [6]:

1) systems with one central inverter,
2) systems with string inverters,
3) systems with MPP trackers,
4) systems with module inverters,
5) systems with DC busbar.

Due to limitation in space, only systems with one central inverter will be dealt with in details. Other systems have been well covered in literature [1,6].

Systems with one central inverter are usually suitable for PV systems with few parallel branches, composed of a relatively small number of PV panels serially connected, Figure 4. These systems tolerate well shading of individual cells, due to short length of PV strings. Since the strings are connected in parallel, the current entering the inverter equals the current sum of all strings, thus imposing the need for „richer" dimensioning of the DC distribution cabling. The output voltage for this type of solar generator is relatively low (U_{out}<120Vdc). These concepts are predominantly used for smaller applications, mainly integrated PV systems - roof mounted or facade integrated.

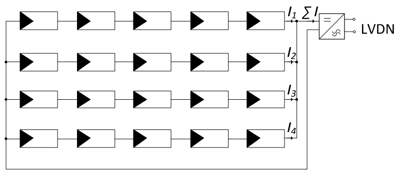

Figure 4. PV system with central inverter, U<120Vdc

The PV system concept where the input voltage to the inverter exceeds 120 Vdc is usually accomplished with several long PV strings connected in parallel, Figure 5.

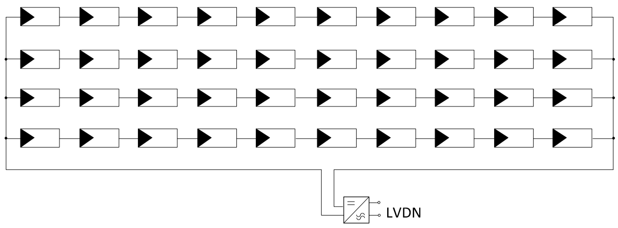

Figure 5. PV system with central inverter, U>120Vdc

The essential advantage of above mentioned system is the relatively low value of currents flowing through the DC distribution system; hence, DC distribution cables ampacities are also low. The principal shortcoming of central inverter type concept is the problem of cell shadowing, due to long PV cell strings.

Solutions of this type are mainly adopted for medium and large PV applications. The output voltage of the DC system is often as high as 1000 Vdc.

The selection and configuration of the inverter system strongly affects PV system reliability i.e. the production of electric energy. For example, in [7] a solution with adaptive input inverter voltage has been presented. This approach has overcome difficulties because of shadowing and variations in solar power. That means that PV energy can be transmitted to DN for different photo-voltages. In [8] the impact of inverter configuration on PV system reliability has been presented, along with a suitable PV system life-cycle analysis for quantification the effects due to inverter failure.

4. PV SYSTEM PROTECTION

4.1. Solar generator's DC side

PV cells subjected to solar radiation generate direct voltage and current, therefore DC side of the PV system necessitates the adequate protection. In addition to numerous other peculiarities of PV modules (shut-down of PV not possible without panel shadowing, short-circuit current value similar to the current at MPP) like the presence of DC voltage in the range of 300-600 Vdc, and even higher, a careful selection of protective and isolating devices must be undertaken. These devices have to stop the fault current from flowing and isolate the faulted section of the PV system. Figure 6 presents a possible concept for protection of DC side of the PV system.

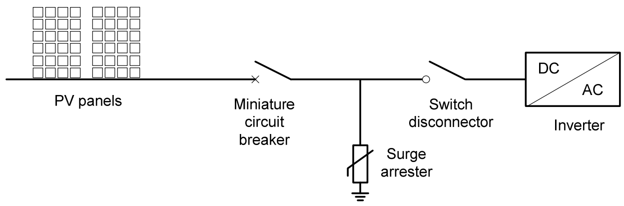

Figure 6. Possible concept of DC side protection of the PV system

According to Figure 6, subsequent protective/isolating elements downstream the inverter towards the PV generator (PV panels) are installed:

1) switch disconnector,
2) surge arresters,
3) miniature circuit breaker/fuse.

The switch disconnector is the element that separates PV panels – the energy source, in a visible and safe manner from the inverter in case of fault, or due to maintenance operations.

PV systems are usually located at locations high above the ground, and thus often exposed to the influences of atmospheric discharges. Consequently, installation of surge arresters at each pole of the DC system should not be neglected, since the basic insulation level (BIL) of PV panels is usually higher than that of the inverter. Accordingly, by protecting the inverter, we also protect PV panels, on condition that the distance between panels and inverter is less than 10 meters. It is advisable to install surge arresters on the PV generator side, i.e. before the switch disconnector, so as to provide protection to

PV panels at all times, regardless of the switch disconnector position.

Fuses are protective elements that are commonly used to protect PV strings. Unlike diodes, as a measure for protecting PV strings against reverse current, fuses are capable of interrupting electric circuits subjected to faults. Although fuses are cheap and simple to implement, some aspects must be observed:

1) fuse characteristic must be of gR-(PV) type, suitable for protection of semi-conductive components,
2) fuse current rating must be neither less than $1{,}25 \cdot I_s$ (1,25·string current), nor higher than the value indicated by the PV panel manufacturer,
3) fuses must be installed into appropriate fuse-disconnectors capable of dissipating heat in the worst operating conditions.

Miniature circuit breakers (MCB), with adequate thermo-magnetic operating characteristics, are also suitable for PV system component protection. Compared to fuses, MCBs are more advanced protective devices, more expensive and much more sensitive to voltage transients and thus susceptible to spurious operation. On the other hand, MCBs comprehend both protective functions and isolating functions in one device. In the next figure a fuse selection procedure for PV panel protection is presented.

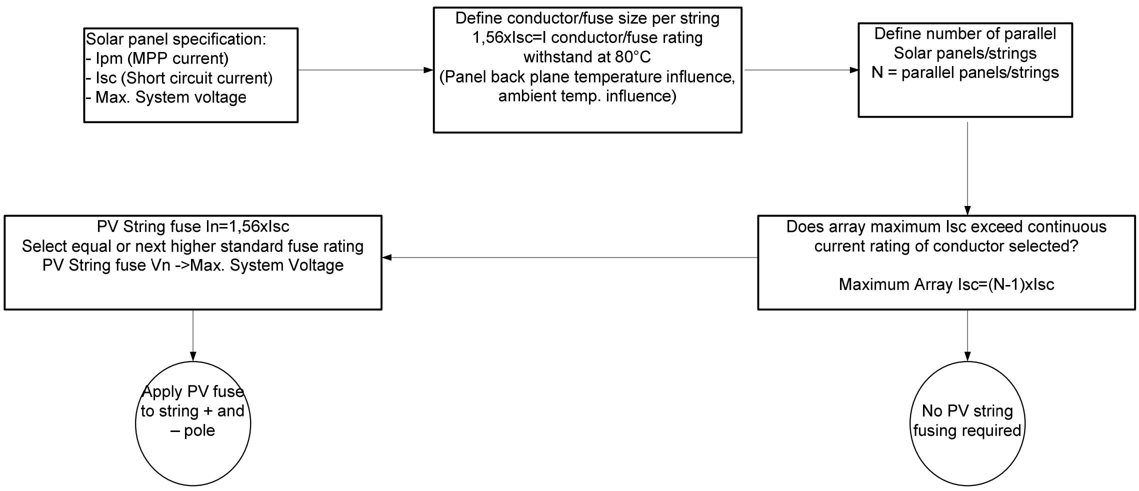

Figure 7. Fuse selection procedure

4.2. Solar AC side generator

The AC side of a PV system is composed of several protective and switching elements, but their function and position within the installation is habitual for LV distribution installations. Figure 8 depicts a possible concept of the AC side protection of the PV system. The switch disconnector downstream the inverter has the same function as the one installed on the DC side. Afterwards, a surge arrester is installed, which protects the inverter from surges coming from the LVDN. The automatic circuit breaker and residual current device are devices that are commonly used in LV distribution, to provide protection for persons and property against overcurrents and indirect touch potentials during faults.

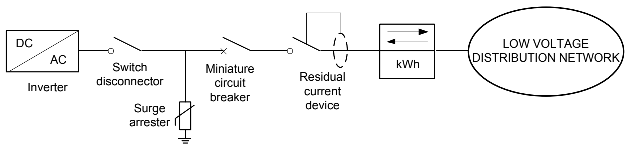

Figure 8. Possible concept of PV system's AC side protection

Measuring devices, at the interface with the LVDN, are the last element of the AC side of a PV system. Their accuracy guarantees obtaining proper financial assets for the electrical energy fed into the LVDN.

5. IMPACT OF PV SYSTEM OPERATION ON LOW VOLTAGE DISTRIBUTION NETWORKS

It is well known that after introducing generation into the LVDN, the conditions in the network radically change. In fact, LVDN have traditionally been conceived, designed, constructed and developed as radial networks with clearly defined active power flows – from higher voltage networks to lower voltage networks. Control and protection of such networks are simple and efficient with known problems and locations of “bottlenecks”. The injection of active power with the PV system into LVDN changes the habitual power flow direction, so that the active power flows from the low voltage level towards higher voltage level, i.e. towards secondary distribution substations (MV/LV). In practice, it rarely happens that the energy generated at LV will exceed distribution transformers headed towards MV network. It is more probable that all energy generated by the PV system will be consumed locally at LV loads. The aforestated is viable holds as long as the PV penetration level in LV networks is low. As opposed to small PV systems, medium and large PV grid connected systems are usually realized with dedicated transformer substations whereas all produced energy is fed into the distribution network or even sub-transmission network.

Alteration of power flows in LVDN the usual voltage profile change, and, in most cases, unloading of LV circuits occurs, since PV systems maximum generation normally coincides with periods of LVDN high loading.

The other aspect, commonly ignored, is the impact of PV systems fault contribution due to inverter’s current injection during fault conditions in LVDN. Furthermore, the impact on protection coordination in distribution networks with distributed generation has to be envisaged [9].

The aspects, stated before, have been analyzed with the help of Digsilent-Power factory software. A real LVDN that serves a business-residential area through a distribution transformer substation (DTS) 10(20)/0,4 kV, Figure 9 has been modeled.

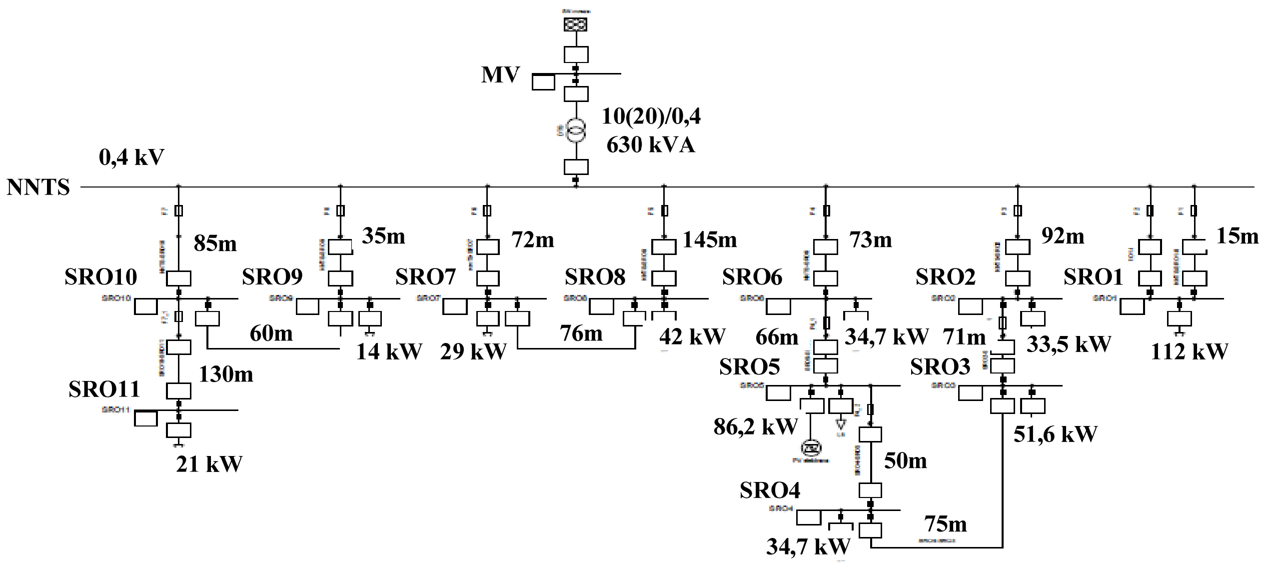

Figure 9. Power factory model of a real low voltage distribution network – PV system connected at node SRO5

The LVDN is composed of a distribution transformer substation 10(20)/0,4 kV with one distribution transformer of rated power S_n=630 kVA and 8 low voltage circuits. Low voltage circuits are of underground cable type. The main circuits are realized by 1kV XP00-A 4x185 type cables, while the branches are realized with 1kV XP00-A 4x95 mm^2 type cables. The location in the LVDN at which the PV generator shall be installed is denoted by SRO 5, Figure 9.

Figures 10 - 12 demonstrate voltage profiles for different operating conditions on the LVDN – maximum loading, 50% loading and no-load conditions for different levels of PV generation. Fifteen different scenarios have been simulated (P_L-LVDN loading, P_{PV}-PV generation level):

- S-1 – P_L=100%, P_{PV}=0%
- S-2 – P_L =50%, P_{PV} =0%
- S-3 – P_L =0%, P_{PV} =0%

- S-4 – P_L =100%, P_{PV} =100%
- S-5 – P_L =50%, P_{PV} =100%
- S-6 – P_L =0%, P_{PV} =100%
- S-7 – P_L =100%, P_{PV} =75%
- S-8 – P_L =50%, P_{PV} =75%
- S-9 – P_L =0%, P_{PV} =75%
- S-10 – P_L =100%, P_{PV} =50%
- S-11 – P_L =50%, P_{PV} =50%
- S-12 – P_L =0%, P_{PV} =50%
- S-13 – P_L =100%, P_{PV} =25%
- S-14 – P_L =50%, P_{PV} =25%
- S-15 – P_L =0%, P_{PV} =25%

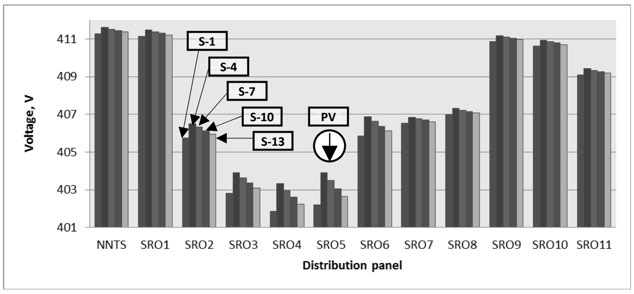

Figure 10. Voltage profiles at maximum LVDN loading

By inspection of voltage profiles given in Figures 10 – 12 it can be noted that the profiles lack resemblance to typical voltage profiles inherent to radial distribution networks. This is so due to LVDN operation in closed loop form.

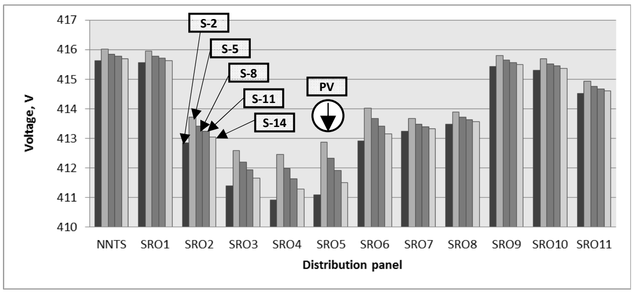

Figure 11. Voltage profiles at 50% LVDN loading

A voltage increase at nodes electrically close to PV generator's connection point is evident (SRO3, SRO4, SRO5 and SRO6).

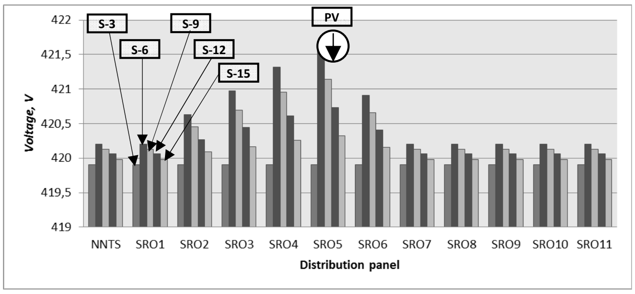

Figure 12. Voltage profiles at LVDN no-load conditions

A considerable distinction in the voltage profile presented in Figure 12 is evident, which is due to no-load operation of the LVDN.

The influence of PV generator connection point has also been analyzed and the results are presented in Figures 13 - 14. Namely, by performing power flow calculations for the LVDN operated both in closed loop and open loop form, voltage profiles for all network nodes were obtained and compared to the values obtained for LVDN operation without PV generation. Figure 13 demonstrates the overall relative voltage increase for all network nodes due to PV system current injection into LVDN operated in closed loop form, while Figure 14 demonstrates the same values quantities for LVDN operated in open loop form.

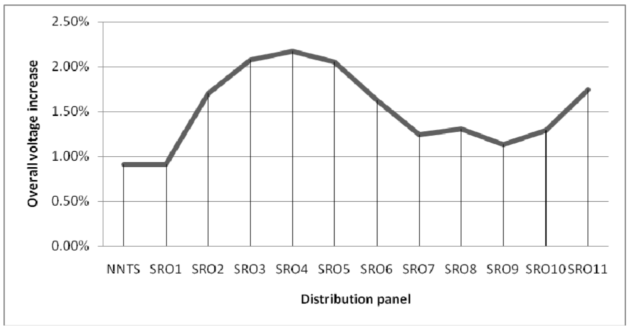

Figure 13. PV generator operation impact on LVDN voltage increase – closed loop form operation

By inspection of Figures 13 and 14 a maximum voltage profile increase can be perceived at node denoted by SRO4, which suggests that connecting the PV generator at node SRO4 a maximum voltage increase at all nodes of the network can be expected. Higher voltage increase in the LVDN, operated in open loop form, can also be noted.

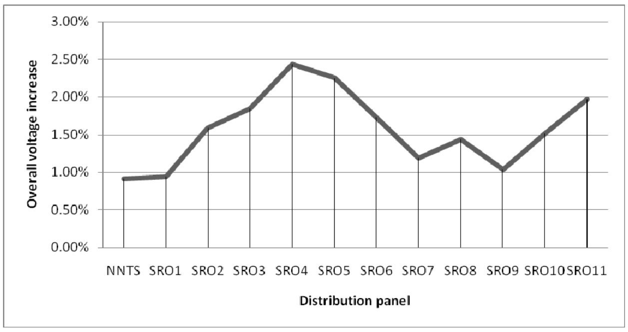

Figure 14. PV generator operation impact on LVDN voltage increase – open loop form operation

Hereafter, the impact of grid-connected PV system fault current contribution will be briefly analyzed. The mentioned impact, as the economic impact of PV fault current contribution has been elaborated for some cases [10-12].

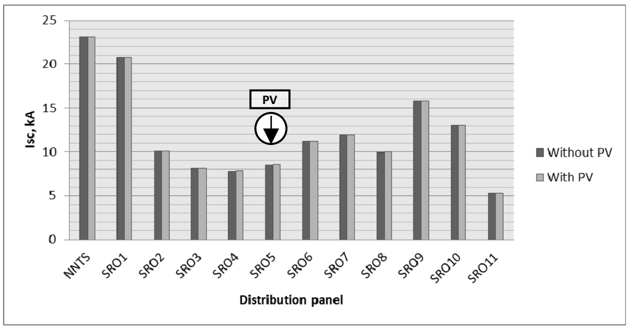

Figure 15. LVDN triphase fault currents – closed loop form operation

The relative increase in fault current due to PV system contribution is presented in Figures 16 and 18.

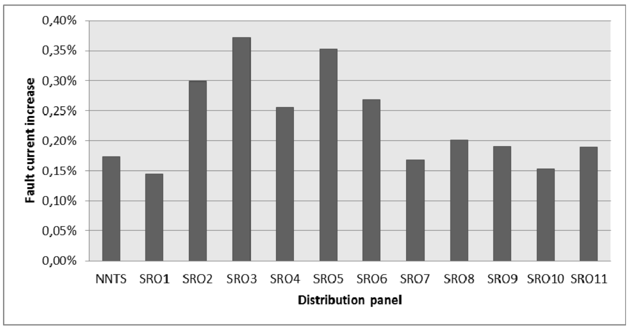

Figure 16. Fault current relative increase due to PV system operation – closed loop form

The highest relative increase of fault current can be observed for nodes denoted by SRO3 and SRO5, form LVDN closed loop form operation. The highest relative increase of the fault current at node SRO5 is as expected, since this node is the node to which the PV generator is connected. The high relative fault current increase at node SRO3 is due to electrcal proximity to node SRO5 and double-ended supply.

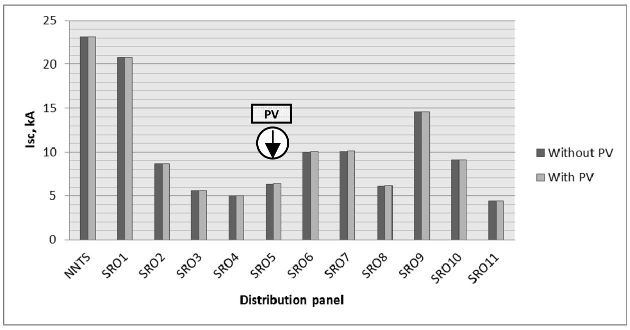

Figure 17. LVDN triphase fault currents – open loop form operation

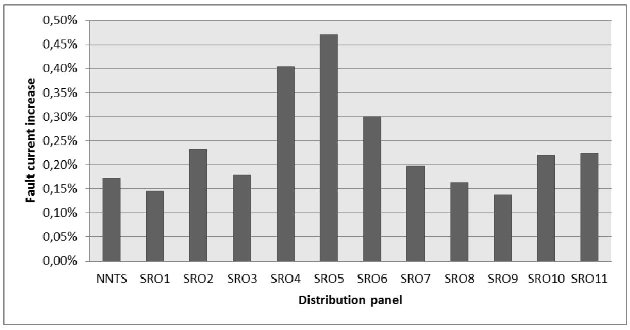

Figure 18. Fault current relative increase due to PV system operation – open loop form

The relative increase of fault currents presented in Figure 18 is as expected, with regard to LVDN closed loop form operation and the addition of a new source of fault current at the node denoted by SRO5.

6. CONCLUSION

Generation of electric energy by renewable energy sources is a challenge that has to be carefully envisaged since presents both a potentially profitable enterprise, and a source of problems to the complex operation of large electric power systems in the near future [13].

The paper presents some aspects of grid-connected PV systems, especially determination of solar potential, selection of PV technology, PV system protection and finally some aspects of the impacts due to LVDN and PV system parallel operation. Research results, presented in figures, demonstrate major indicators of PV system impact on LVDN. The influence of PV system operation upon voltage profiles, both for closed loop and open loop form of LVDN operation, has been analyzed. Briefly, the fault current contribution impact of PV systems has also been investigated.

Future research will be focused on truthful PV system and components modeling. In so doing, detail models of PV components (PV cells, MPP tracker, inverter) will be developed, hence a dynamic simulation of parallel operation of PV systems and distribution network will be possible. Accordingly, the impact on PV system dynamic characteristics due to solar radiation fluctuation, temperature and wind variation will be subject to analysis.

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