PHOTOVOLTAIC POWER PLANTS AS ACTIVE ELEMENTS OF DISTRIBUTION NETWORKS

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Abstract: According to the Grid Codes in many countries, the photovoltaic (PV) power plants are obliged to generate reactive power and to curtail active power if this is required. In order to evaluate the impacts of reactive power generation and active power curtailment on yearly electricity production of PV power plants, the principle of micro-inverter operation and inverter's limits of operation are discussed in relation to the active and reactive power generation. Presented is the measured efficiency characteristic of a micro-inverter. In the case study, presented in the scope of the paper, the impacts of reactive power generation and active power curtailment on yearly electricity production of PV power plants and yearly energy losses in the distribution network (DN) are discussed. Additionally, the suitability of existing DN for the yearly net self-sufficient energy supply, introduced through the net metering, is evaluated. The analysis was performed on existing low and medium voltage parts of DN, using the series of time-discrete load flow calculations in combination with a stochastic search algorithm called differential evolution.

Keywords: PV power plant, distribution network, reactive power generation, active power curtailment, self-sufficient energy supply.

1 Introduction

Proliferation in numbers of distributed generation units, connected to the distribution networks (DN) is evolving the DN to an active part of electric power system. With proper incorporation of these units, numerous technical and economic benefits on DN operation are achieved [1],[2]. With active participation of photovoltaic (PV) power plants in DN operation, through reactive power generation and active power curtailment, that has already been introduced in some countries through Grid Codes [3],[4],[5], new opportunities for distribution network control rise.

In order to evaluate the impacts of reactive power generation and active power curtailment on the yearly electricity production of PV power plants, the principle of inverter (micro-inverter) operation and inverter's limits of operation are discussed in relation to the active and reactive power generation [6]. Presented is the measured efficiency characteristic of a micro-inverter. The measured efficiency characteristic is approximated by a surface, given as a function of generated active and reactive powers [7].

The paper analyzes the reactive power generation in PV power plants, connected to the DN, and benefits that can be achieved with its proper generation, optimized for considered operating states. Since electric energy losses represent a considerable share of energy transported from transmission network to final consumers, various implementation of PV power plants reactive power control are used as a mean to reduce these losses [8], [9]. The discussed medium and low voltage distribution networks were also checked regarding their suitability for the introduction of a yearly net self-sufficient energy supply. To do this, additional PV power plants are considered in the vicinity of each load. The performed analysis is based on active and reactive powers load profiles and active power generation profiles of PV power plants, all measured in discussed networks. These profiles are applied in order to determine the optimal reactive power generation and active power curtailment of PV power plants in each time interval. The aim of optimization is to provide proper voltage profiles in the discussed networks, and consequently, to analyze the impact of such operation on network losses and electric energy production of PV power plants. A stochastic search algorithm called Differential Evolution (DE) is applied as the optimization tool.

The presented paper is structured as follows. Section 2 presents the principle of inverter operation and its limits of operation in relation to the active and reactive power generation dependent efficiency characteristic. Section 3 presents the low voltage and medium voltage distribution networks with their time-dependent loading and generation profiles that are used in case studies of three different operating scenarios. The evaluation methodology is presented in Section 4. Results obtained are given in Section 5, which is followed by the Section 6, which concludes the paper.

2 Reactive power generation in PV systems

Inverters for PV systems have the ability to generate reactive power Q. Limits for the reactive power generation is shown in Figure 2.1 where P and Q are the actual inverter generated active and reactive power, respectively, whilst S_{max} is the rated apparent power of the inverter.

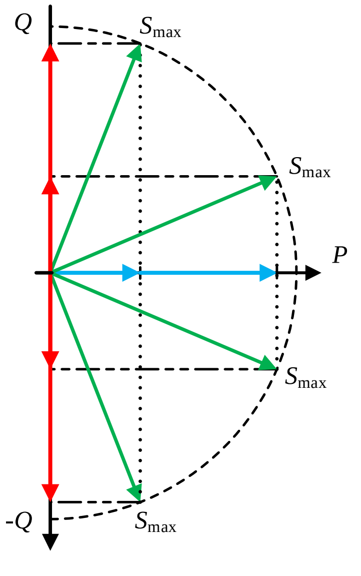

Figure 2.1: Capability PV inverter for reactive power generation

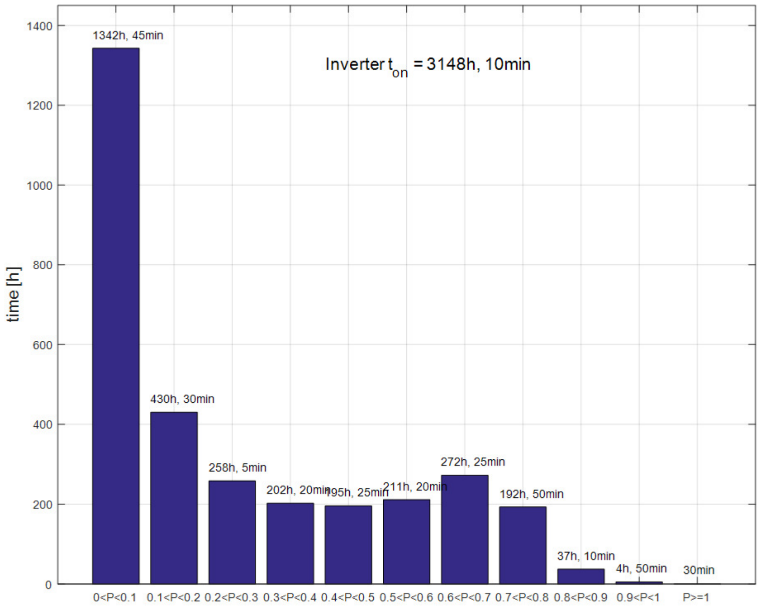

Figure 2.2: Average active power generation over a year

The increasing active power generation decreases the ability for generation of reactive power. In some countries, according to their “grid codes”, the inverters for PV systems must be capable to generate the reactive power, often in the range cos$\varphi \geq 0.8$. If the PV inverter rated power $S_{\max}$ equals the maximum active power of the PV system connected to it $P_{\max}$, the generated active power P must be sometimes curtailed to enable operation with cos$\varphi = 0.8$. Figure 2.2 shows the average annual time of operation within the specific output power range of a 7.5 kWp PV power plant operating since year 2004. According to Figure 2.2, around 42 hours per year the active power curtailment would be required to assure permanent operation of the PV power plant with cos$\varphi = 0.8$. Considering the rated power of the inverter $S_{\max}$ together with Figure 2.1 and Figure 2.2, the percentage of total operation time in which the PV power plant could operate with different values of cosφ is determined. It is shown in Figure 2.3.

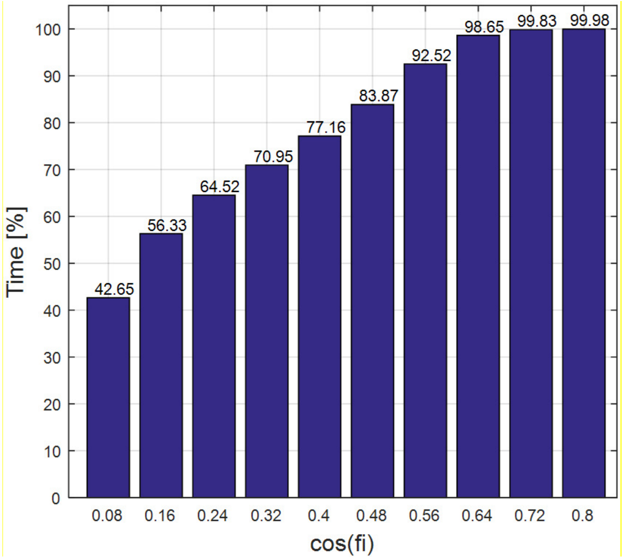

Figure 2.3: Percentage of operation time in a year where discussed PV power plant is capable to operate at different values of cosφ

The generation of reactive power in the inverter increases the current through the inverter elements which influences the efficiency characteristic of the inverter and through it also the annual energy generation of a PV power plant.

2.1 Efficiency characteristic of the inverter

In this work the characteristic of a 260 W micro-inverter prototype is determined experimentally using measured values. Schematic presentation of the micro-inverter is shown in Figure 2.4.

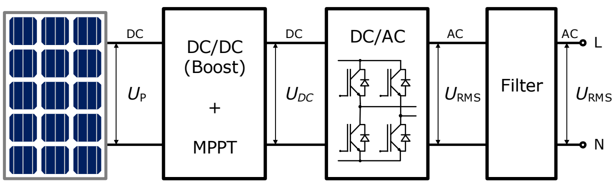

Figure 2.4: Schematic presentation of a PV module with micro-inverter

Normally, micro-inverters have lower efficiency than string and central inverters. However, because the micro-inverter is mounted directly to a single PV module, conditioning of the module and the maximum power point tracking should be better than in the cases of other inverters where several PV modules are connected in series and/or in parallel. According to (Yong Sin & Roland, 2014) the energy generated in the PV power plant equipped with micro-inverters should be higher than in the cases when other types of inverters are applied.

In the case of the experimental inverter, the efficiency values were measured for different values of generated active P and reactive Q powers at the output of the inverter. The obtained values were used to determine the active and reactive powers dependent approximation function of the inverter's efficiency shown in Figure 2.5.

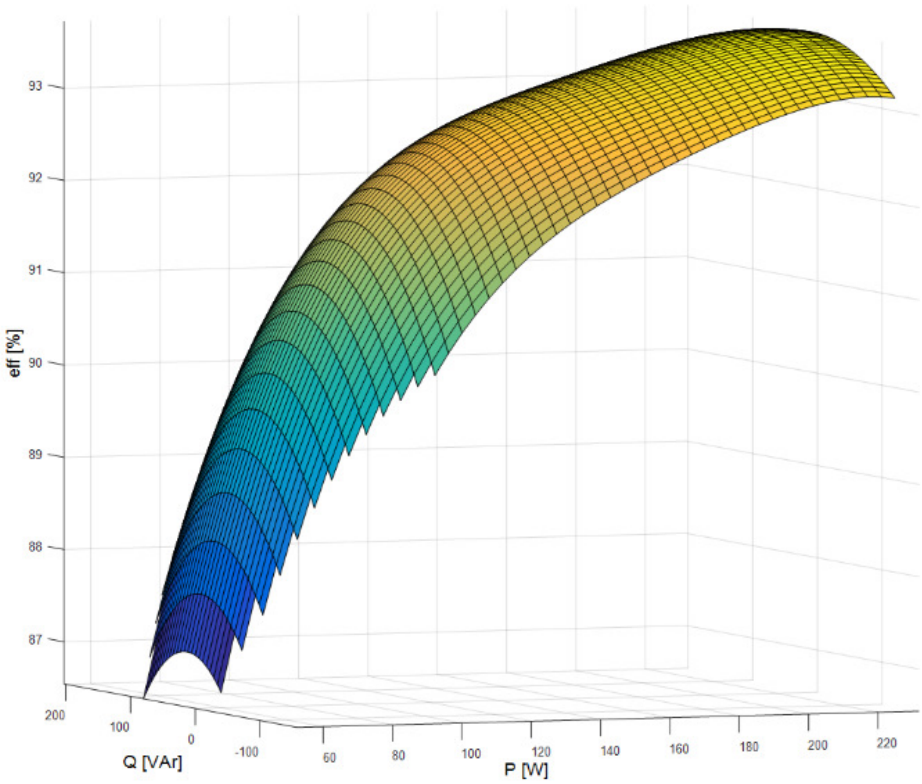

Figure 2.5: Efficiency characteristic of an inverter given as a function of active power P and reactive power Q.

The efficiency characteristic (Figure 2.5) is used to evaluate how the generated reactive and active power curtailment influence the annually generated energy of PV power plants.

3 Description of test sites

3.1 Distribution networks

The analysis of the impact of PV power plants, acting as active elements of the DN, on different aspects of network operation, have been performed on real, existing low voltage and medium voltage parts of a DN. The low voltage network contains two 50 kWp PV power plants and has a peak loading of 115 kW. The medium voltage network contains 27 PV power plants, connected in 18 nodes of the network, with a sum of rated powers 1.97 MWp, and has a peak loading of 2.5 MW. The schematic presentations of test sites are given in Figure 3.1.

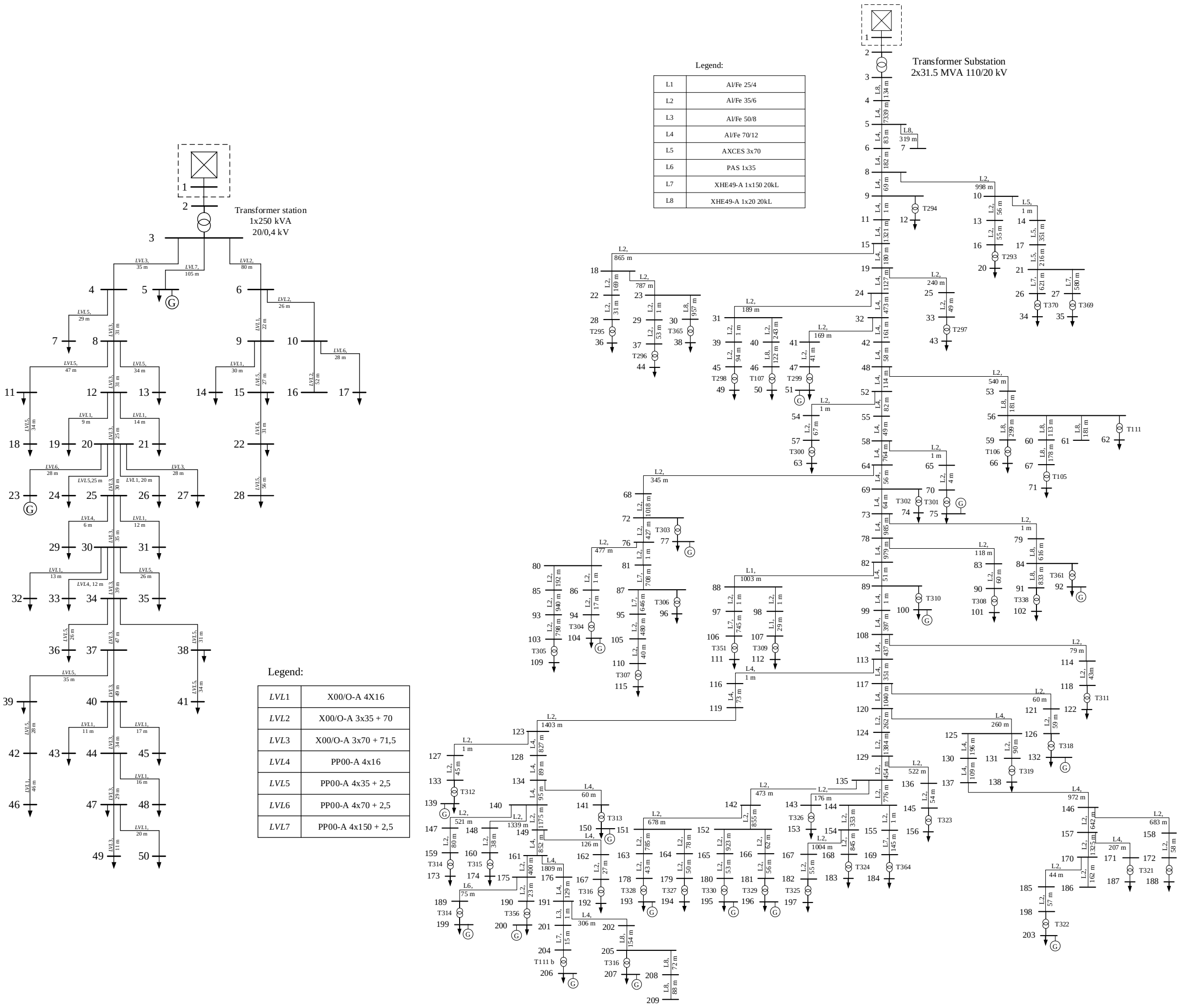

Figure 3.1: Schematic presentation of discussed low voltage (left) and medium voltage (right) distribution networks.

3.2 Power loading and generation profiles

For the purposes of performing a series of time-discrete load flow calculations, power loading and generation profiles were created, based on the long-term measurements of the power consumed and generated in multiple nodes of the network. Examples of the yearly measurements on a single distribution substation in a test medium voltage DN, of power consumed and power generated from connected PV power plants, are given in Figure 3.2.

From the set of measurements, similar to the ones presented in Figure *3.2*, maximal, minimal and average loading profiles, as well as average and maximal generation profiles, representing a characteristic day in every month have been determined, allowing a thorough analysis of different operating scenarios. Each set of profiles is represented with 12 curves given in 1 hour intervals. Figure 3.3 presents an example of average loading and PV generation profiles, given in per unit system.

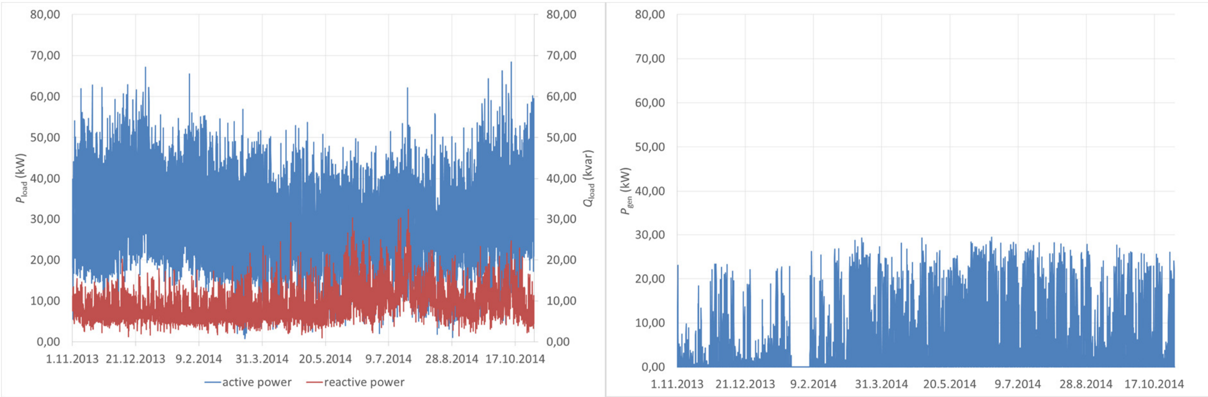

Figure 3.2: Annual measurements of active and reactive power consumed (left) and power generated (right) on a single 20/0.4 kV distribution substation.

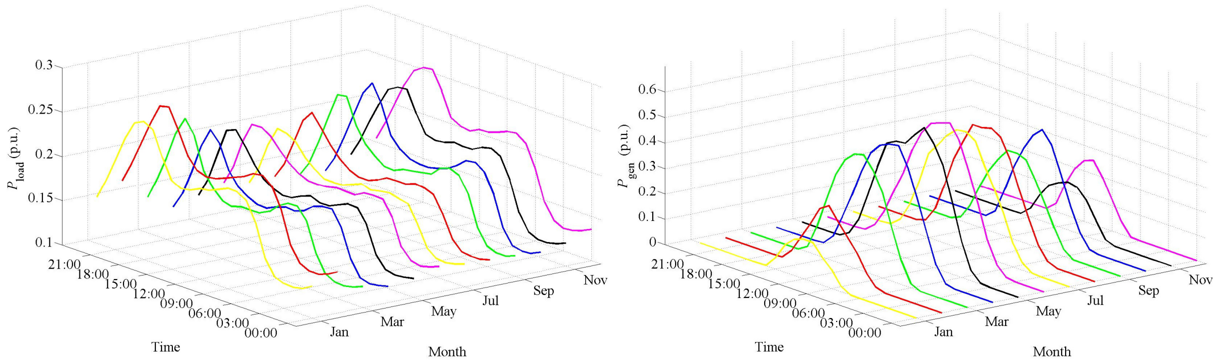

Figure 3.3: Average loading and generation profiles.

4 Evaluation methodology

The evaluation of the DN operation state has been performed using time-discrete load flow calculations, based on the “Backward – Forward Sweep” method [10]. Analyzed were scenarios of ensuring the proper voltage profiles with optimal reactive power generation, minimization of annual losses of electric energy with optimal reactive power generation and suitability of networks for the yearly net self-sufficient energy supply accompanied with optimal combination of reactive power generation and active power curtailment. A detailed description of these operating scenarios is given in Subsection 4.1.

Optimal values of reactive power generation and active power curtailment from PV power plants were determined using the optimization method called differential evolution (DE) [11]. DE is a parallel direct search method that mimics the processes of evolution, mutation and crossover. Its goal is to create a diverse population of possible search parameters and to find the results that satisfy the objective of the chosen fitness function q_{fun}. In all optimization scenarios, penalties p were applied to the value of the obtained fitness function, introducing different calculation restrictions, including voltage constraints (±10% of nominal voltage), as well as to guarantee currents under the prescribed limits in all line segments. The reactive power generation was constrained with $\cos\varphi \geq 0.8$.

4.1 Operating scenarios

4.1.1 Providing the appropriate voltage profiles

A voltage increase can occur in parts of the DN, where the power generation from PV plants is greater than the power consumed. In Slovenia, the voltage tolerance band is ±10% of the nominal voltage. The low and medium voltage DN, presented in Section 3, do not have enough generating units to create this problem. However, in order to analyze if the reactive power generation from existing PV plants would be sufficient to mitigate the possible problem of voltage rise, the tolerance band was narrowed to ±3%, meaning that the voltage in each node of the medium voltage network should be 20±0.6 kV, and 400±12 V for the low voltage network. Series of time-discrete load flow calculations were performed for every hour of every average day in a month, triggering the optimization process in any time point (n) where overvoltage occurred. Time-dependent profiles used in this scenario were minimal for the loading and maximal for the PV power generation, as this operating scenario is most likely to cause the problems with voltage rise. The fitness function for this operation state $\boldsymbol{q}_{\mathbf{fun}}$ is given with (1), stating that the reactive power generation should mitigate the problem of voltage rise, while minimizing the losses of PV power plants' energy production ($W_{\mathrm{gen_{OPT}},\mathrm{n}}$). The loss of energy production in PV power plants occurs due to efficiency characteristic of the inverter, which decreases with the increasing share of generated reactive power, as shown in Figure *2.5*.

$$\boldsymbol{q}_{\mathbf{fun}} = \sqrt{\frac{\mathbf{1}}{\sum_{1}^{n} \boldsymbol{W}_{\mathbf{gen_{OPT}},\mathbf{n}}}} + \boldsymbol{p} \qquad (1)$$

4.1.2 Annual electric energy loss minimization

Consumers in the DN are mostly of resistive – inductive nature, requiring the supply of reactive power in order to operate properly. This reactive power can be supplied through the distribution station and power lines, causing the increase of line currents and consequently the greater losses in the DN. Another way of reactive power supply is locally – from the existing PV power plants. Series of time-discrete load flow calculations were performed for every hour of a characteristic day in every month, determining annual losses of electrical energy in the test DN, with ($W_{\mathrm{loss\_OPT}}$) and without the optimal reactive power generation (W_{loss}), performed for every time point with sunlight available. Network losses are composed of line losses and losses in iron and copper of distribution substations. Average time-dependent loading and PV generation profiles were used in this scenario. The fitness function for optimal reactive power generation $\boldsymbol{q}_{\mathbf{fun}}$ that results in the minimization of network losses is given by (2).

$$\boldsymbol{q}_{\mathbf{fun}} = \frac{\boldsymbol{W}_{\mathbf{loss\_OPT}}}{\boldsymbol{W}_{\mathbf{loss}}} + \boldsymbol{p} \qquad (2)$$

The optimal generation of reactive power was performed in two ways:

- reactive power was equally distributed among the PV power plants, proportionally to their rated powers;
- reactive power was determined for every PV power plant individually, in a way that suits the DN operation the most.

4.1.3 Net self-sufficient energy supply

The discussed distribution networks were checked for the possibility of a yearly net self-sufficient energy supply, through the PV power plants solely, without additional investments in the network infrastructure. In order to achieve the yearly net self-sufficient energy supply, energy generated in PV power plants inside networks should match the energy consumed within the network on an annual level ($\boldsymbol{W}_{\mathbf{load\_annual}}$). Table 4.1 gives the values of the sum of rated powers of the PV power plants ($\boldsymbol{P}_{\mathbf{PV}}$) with the number of operating hours of PV systems. The determined rated power of PV power plants was distributed in the network, proportionally to the loads in each node, resulting in power generation that matches the power consumed in a year. The operating hours are determined considering generation profiles of existing PV power plants in the discussed DN.

Table 4.1. Annual power consumed and required sum of rated powers of the PV systems with operating hours.

DN	$\boldsymbol{W}_{\mathbf{load\_annual}}$	$\boldsymbol{P}_{\mathbf{PV}}$	Operating hours
Test LV DN	204,97 MWh	252,58 kWp	812 h
Test MV DN	9,80 GWh	11.40 MWh	860 h

The optimization of reactive power generation (Q_{OPT}) and optimal combination of reactive power generation and active power curtailment (PQ_{OPT}), is performed for two different operating scenarios A and B, investigating the possibility of a net self-sufficient energy supply in low (LV DN) and medium voltage (MV DN) test networks. A short description of these scenarios is given in Table 4.2.

Table 4.2. Description of different analyzed scenarios for investigating net self-sufficient energy supply.

Scenario	Loading	PV generation	Condition that triggers the optimization	Optimization type
A	Point of minimal loading	Point of maximal generation	Voltage increase >10%	PQ_{OPT}
B	Average profile	Average profile	Sunlight available	Q_{OPT}

The fitness function for scenario A is given in (3). It results in mitigation of voltage rises with generation of reactive power, and if this isn't sufficient – with active power curtailment. Values $\boldsymbol{W}_{\mathbf{loss}}, \boldsymbol{W}_{\mathbf{gen,n}}$ represent the DN energy losses and energy production of PV power plants before, and $\boldsymbol{W}_{\mathbf{loss\_}\mathrm{OPT}}, \boldsymbol{W}_{\mathbf{gen\_}\mathrm{OPT},\mathbf{n}}$ values after the optimization.

$$\boldsymbol{q}_{\mathbf{fun}} = \frac{\boldsymbol{W}_{\mathbf{loss\_OPT}} + \sum_{1}^{n}(\boldsymbol{W}_{\mathbf{gen,n}} - \boldsymbol{W}_{\mathbf{gen\_OPT,n}})}{\boldsymbol{W}_{\mathbf{loss}} + \sum_{1}^{n}\boldsymbol{W}_{\mathbf{gen,n}}} + \boldsymbol{p} \qquad (3)$$

The fitness function for scenario B is the same as in (2), causing the minimization of annual losses with optimal reactive power generation.

5 Results

The described efficiency characteristic of the inverter, monthly load profiles for active and reactive powers as well as monthly profiles for active power generation of PV power plants, are applied to evaluate the impacts of reactive power generation in PV power plants on the yearly electrical energy production of PV power plants and the yearly energy transmission losses in existing low voltage and medium voltage distribution networks. The results obtained are presented in the following subsections.

5.1 Providing the appropriate voltage profiles

The generation of reactive power with inductive nature lowers the voltage profiles at the cost of an increase in energy losses in the network. Table 5.1 presents the results of the change in annual network losses (ΔW_{loss}) and PV power plant generated energy (ΔW_{gen}), before and after the optimization.

Table 5.1: Change in annual network losses and PV power plants generated energy due to optimal reactive power generation for ensuring the appropriate voltage profiles.

DN	$\Delta \boldsymbol{W}_{\mathbf{loss}}$ $(\mathbf{kWh})$	$\Delta \boldsymbol{W}_{\mathbf{gen}}(\mathbf{kWh})$
Test LV DN	7.23	-2.02
Test MV DN	81.25	-0.32

The active power generation from PV systems was somewhat decreased, due to the fact that reactive power generation decreases the efficiency of an inverter. It was determined that in the low voltage test site, voltages exceeded the ±3% tolerance band in 320h (of 8760h in a year), while in the medium voltage test site 127h (out of 8760h). In all cases, the optimal reactive power generation was sufficient to decrease voltages back to the permitted tolerance band.

5.2 Annual electric energy loss minimization

The aim of this operating scenario was to investigate what benefits to the network operation, in context of energy loss minimization, can be achieved with optimal reactive power generation, while other parameters (voltages and line currents) are kept within the prescribed limits. Contrary to the case in Subsection 5.1, reactive power generated in this scenario had a capacitive nature, causing an increase in voltage profiles but decreasing the energy loss in the distribution network. Penalties ensured that voltage profiles were kept within the tolerance band.

Table 5.2: Change in annual network losses and PV power plants generated energy due to optimal reactive power generation for annual electric energy loss minimization.

DN	Reactive power generation distribution	$\Delta \boldsymbol{W}_{\mathbf{loss}}$ $(\mathbf{kWh})$	$\Delta \boldsymbol{W}_{\mathbf{gen}}(\mathbf{kWh})$
Test LV DN	equal	-44.98	-76.58
	unequal	-49.76	-63.86
Test MV DN	equal	-5925.70	-3552.50
	unequal	-6200.10	-4752.50

The results presented in Table 5.2 indicate that generation of reactive power, unequally distributed among the PV power plants, results in greater benefits to the DN operation, since reactive power can be locally adjusted to fit the needs of individual parts of the network and the minimization of losses achieved is greater. However, this operation regime results in greater losses of PV power plant generated energy, and therefore, greater financial losses for the owners of the power plants.

5.3 Yearly net self-sufficient energy supply

The discussed medium and low voltage distribution networks were also checked regarding their suitability for the introduction of a yearly net self-sufficient energy supply. To do this additional PV power plants are installed in the vicinity of each load. The results obtained for two different operating scenarios are presented in Table 5.3.

Table 5.3: Change in l network losses for different operating scenarios of yearly net self- sufficient energy supply: scenario A – the results are given for the worst hour; scenario B – the results are given annually

DN	Scenario	$\Delta \boldsymbol{W}_{\mathbf{loss}}$ $(\mathbf{kWh})$	$\Delta \boldsymbol{W}_{\mathbf{gen}}(\mathbf{kWh})$
Test LV DN	A	-1.29	-12.98
	B	-92.90	-72.10
Test MV DN	A	-0.194	-1.276
	B	-9.981	-4.056

The optimization of the DN operating states with reactive power generation and active power curtailment in scenario A, was performed for an extreme operating point with maximum PV generation and minimal loading considered. It has been shown, that this kind of optimization is sufficient to mitigate the problem of overvoltage that occurs, yet at the cost of bigger losses of PV power plants generated energy in the discussed hour of extreme operation conditions.

When considering the average time-dependent loading and generation profiles, voltage profiles did not rise above the permitted limits in any point of the calculation. Therefore, scenario B was performed in every point where sunlight was available and it reduced the annual losses of electrical energy with optimal reactive power generation. Even though the optimization was performed for reactive power, PV power plants generated energy decreased as well, due to the considered inverter efficiency characteristic shown in Figure *2.5*.

The results presented in all three subsections depend on the operating states of the network. Thus, different results of change in network losses and losses of PV power plants generated energy could be achieved for different profiles of power loading and generation.

6 Conclusion

The aim of the paper was to investigate the possibility of active participation of PV power plants in DN operation through reactive power generation and active power curtailment. The impact of this participation on energy production in PV power plants and DN losses were analyzed.

Inverter sizing: Based on monitoring system data of an existing PV power plant, it is shown that even in the cases when the inverter is chosen in such a way, that its maximal apparent power equals the maximal active power of the PV system, only around 42 hours per year the active power curtailment would be required to operate all the time with cosφ = 0.8.

Voltage profiles and energy losses: The results presented in the paper clearly show that the reactive power generation in PV power plants can be used to control the voltage profile in the distribution network. The reactive power generation in PV power plants can be used also for reduction of losses in the distribution network, however on the costs of reduced energy production in PV power plants. The reduction of losses and the reduction of energy production in PV power plants highly depend on the level of network loading.

NET self-sufficient energy supply: The results obtained clearly show that the discussed distribution networks are already suitable for the yearly net self-sufficient energy supply, but only in cases when the average load and generation profiles are considered. In the extreme case of maximal PV generation and minimal loading, the reactive power generation and active power curtailment in PV power plants are indispensable to provide proper voltage profile.

Acknowledgement

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7 References

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