Photovoltaic systems and yearly net self-sufficient electricity supply in distribution networks

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Abstract. The paper deals with distributed photovoltaic (PV) systems capable of accepting reference values for the reactive power generation and active power curtailment. The aim of the performed research is to analyze to what extent can the use of controllable PV systems increase the total share of PV systems in electric grids and to what extent can controlled PV systems increase the yearly net self-sufficient electricity supply. In the case study the analysis is performed from the viewpoint of the distribution grid, considering the voltage profile, conductor loading and grid losses. Problems related to the power system stability are not discussed.

Key words: distribution network, controllable PV systems, yearly net self-sufficient electricity supply, voltage profile, network losses.

1. Introduction

Solely the evaluation of solar and photovoltaic potential [1,2] is insufficient for installation of a PV system. At least the environmental impacts, the electric grid configuration and load profiles should be evaluated and considered together with the economic assessment [3-7]. This paper deals with distributed photovoltaic (PV) systems equipped with inverters, capable of accepting reference values for the reactive power generation and active power curtailment. In this way, the PV systems become controllable sources, which could help the electricity networks to accept a higher share of PV systems without required network reinforcements. Such a functionality is important also from the viewpoint of

yearly net self-sufficient energy supply of households and other smaller users introduced in some countries [8], which should be performed without additional investments in electricity network infrastructure. Some aspects of PV systems based yearly net self-sufficient energy supply are treated in [9-11] for Slovenia and worldwide in [12-16].

This paper analyses an extreme case where 100% yearly net self-sufficiency in electricity supply should be achieved by controllable PV systems. Four existing medium voltage distribution networks are involved in the analysis. Considered are the actual network configurations, the measured load profiles for the active and reactive power, the measured power generation profiles of existing PV systems, and the efficiency characteristic of PV system inverters that depend on the generated active and reactive power. The network voltage profiles, line loading and network losses are determined by Backward-Forward-Sweep (BFS) [17] load flow method. The reference values for the reactive power generation and active power curtailment of individual PV systems are determined in a Differential Evolution (DE) based procedure [18-20].

The content of this paper is as follows. The electricity networks involved in the analysis are described in section 2 together with applied load and generation profiles. The performed analysis, applied objective functions and case studies are described in section 3. The results are presented in section 4, whilst final conclusions are drawn in section 5.

2. Descriptions of networks, load and generation profiles

This section gives brief descriptions of four medium voltage networks involved in the analysis. It is followed by the descriptions of applied load and generation profiles.

A. Network descriptions

The 31.5 MVA transformers 110/20 kV, equipped with on load tap changers, are installed in the transformer substations (TS) “Breg” and “Rogaška Slatina”. The TS “Breg” supplies the feeders “Breg” and “Majšperk” whilst the TS “Rogaška Slatina” supplies the feeders “Podčetrtek” and “Zibika”. All aforementioned feeders are described in this subsection. They are shown in Fig. 1 in the form of single-line diagrams.

Transformer substation “Breg” - feeder “Breg”

The feeder “Breg” consists mostly of the overhead lines with bare Al/Fe conductors. Their cross sections are 70 mm², 35 mm² and 25 mm². The total length of the feeder is 29.85 km. It supplies 27 transformers 20/0.4 kV. The measured peak load is 2.26 MVA. Eleven PV systems, operating in a 0.4 kV network, with the total power of 1.23 MWp, are connected to the feeder “Breg” in 6 nodes through the transformers 20/0.4 kV.

Transformer substation “Breg” - feeder “Majšperk”

The 20 kV feeder “Majšperk” supplies 3114 customers located in the western part of the countryside region Haloze. Its total length is 58.8 km. It consists mostly of the overhead lines with bare Al/Fe conductors the cross sections of which are 70 mm², 35 mm² and 25 mm². It contains 61 transformers 20/0.4 kV, one transformer 20/1/0.4 kV. The measured peak load is 3.8 MVA, whilst the total installed power of 25 PV systems and 3 gas co-generations is 3.82 MW, which exceed the peak load. The power generation systems are connected to 14 system nodes.

Transformer substation “Rogaška Slatina” - feeder “Podčetrtek”

The 20 kV radial feeder “Podčetrtek” is connected to the transformer substation “Rogaška Slatina” and supplies 52 transformers 20/0.4 kV. It consists partly of the overhead lines with bare Al/Fe conductors, with cross sections 70 mm², 35 mm² and 25 mm², and partly of XHE49A cables, with cross sections 150 mm² and 70 mm². A 27 PV system with a total installed power of 1.97 MW is connected to the feeder, with a total length of 59.72 km. The PV systems are connected to the feeder in 18 nodes.

Transformer substation “Rogaška Slatina” - feeder “Zibika”

Similar as in the previous case, the 20 kV radial feeder “Zibika”, with the total length of 52 km, supplies 48 transformers 20/0.4 kV. It consists of the same overhead

Fig. 1 Single-line diagrams of the 20 kV feeders “Breg” and “Majšperk” in the transformer substation “Breg” and “Podčetrtek” and “Zibika” in the transformer substation “Rogaška Slatina”

lines and cables as in the previous case. The total installed power of 11 PV systems, connected to the feeder in 7 nodes, is 0.84 MW.

B. Load and generation profiles

Load profiles were determined based on average hourly measurements performed in the transformer substations “Breg” and “Rogaška Slatina”, as well as measurements performed on individual transformers 20/0.4 kV. After their normalization with respect to the nominal power of

individual transformers and after the analysis of maximal, minimal and average hourly values, it became evident, that the difference among individual profiles is small even when it is observed seasonally. Therefore, in order to keep a reasonably low number of required load flow calculations, the approximations of normalized minimal, maximal and average hourly load profiles were calculated for the Summer and Winter season, considering separately the active and the reactive power. The obtained results are shown in Fig. 2.

Fig. 2 Approximations for the hourly minimal, maximal and average load profiles in the form of active P and reactive power Q for the Summer (May to October) and Winter (November to April) season.

Based on measurements, performed on PV systems connected to the discussed distribution networks, a normalized hourly electricity production characteristic of PV systems for individual months has been determined. It has been determined as an average monthly production of individual PV system in the given hour normalized by PV system's nominal power and averaged with respect to all PV systems involved in the analysis. It is shown in Fig. 3.

Fig. 3 Normalized hourly output power characteristic of PV systems P_{PV} (p.u.) given for individual months.

In the analysis, the normalized load and generation characteristics are multiplied by the nominal power of the discussed element before they are used in the load flow calculations. Additionally, a measured efficiency characteristic of a micro inverter prototype is applied in order to account for the impact of reactive power generation on the reduction of active power generation. The applied efficiency characteristic is shown in Fig. 4.

Fig. 4 Efficiency characteristic of an inverter given as a function of generated active P and reactive power Q .

3. Analysis, applied objective functions and case studies

For the selected network from the set of networks shown in Figure 1, and for the given time interval, the loads and power generation of PV systems are determined by multiplying characteristics shown in Figures 2 and 3 with the nominal power of individual elements. Due to the radial structure of the discussed networks, the Backward/Forwards Sweep (BFS) method [6] is applied for load flow calculations. The transformer substation is considered as a reference (slack) bus. The violation of

voltage profile and line current overloads are prevented by three different optimization approaches:

- by the reactive power generation in PV systems;
- by the active power curtailment of PV systems;
- by the combination reactive power generation and active power curtailment.

A stochastic direct search algorithm, capable of finding global minima of nonlinear and constraints optimization problems, called Differential Evolution (DE) [7,8], is applied as the optimization tool. It is used to determine the required level of reactive power generation, active power curtailment or optimal combination of both of them, considering that the proper voltage profile is provided in all nodes and none of the lines is current overloaded. The relative share of reactive power generation, active power curtailment or both, is equal for all PV systems in the discussed network. DE actually mimics evolution in nature, which includes crossover, mutation and selection. In order to perform an appropriate selection process, properly defined objective functions are required.

In this work three different objective functions are applied in respect to the given optimization goal. The main goal of all optimizations performed is provision of the proper voltage profile in all nodes and prevention of line current overloads. The fulfilment of these conditions is given in the form of optimization constraints. In the first case of optimization this goal is achieved by the reactive power generation in all PV systems. Since the reactive power generation causes decreased efficiency of the inverter (see Figure 4), the optimization is performed by the maximization of the total generated active power of PV systems. This is done by the objective function q_1 (1), where $W_{gen_post_opt}(i)$ [kWh] is the energy generated in the PV system i after optimization in the given time interval (one hour), whilst n is the total number of PV systems.

$$q_1 = \sqrt{\frac{1}{\sum_{i=q}^n W_{gen_post_opt}(i)}} \quad (1)$$

In the given case, the optimization is applied to determine the factor K_Q which represents the ratio between the generated reactive power Q and active power P and (2).

$$Q = K_Q P \quad (2)$$

The same objective function (1) can also be applied in the case when the proper voltage profile and the prevention of line current overload are achieved by the active power curtailment. In this case the factor K_P , representing a relative reduction of the active power P , is determined by DE. However, when an optimal combination of the reactive power generation and the active power curtailment is applied simultaneously, in order to provide a proper voltage profile and to prevent line current overloading, both K_Q and K_P have to be determined in the optimization process. This approach requires a newly defined objective function q_2 (3):

$$q_2 = \frac{W_{loss_post_opt} + \sum_{i=q}^n W_{gen_post_opt}(i)}{W_{loss_pre_opt} + \sum_{i=q}^n W_{gen_pre_opt}(i)} \quad (3)$$

where W denotes the energy in the given time interval, the network losses are denoted with the index *loss*, the active power generation in a PV system is denoted with the index *gen*, *pre_opt* means before optimization, *post_opt* means after optimization whilst the meaning of the symbols i and n is unchanged.

In the case when the objective function q_2 is applied, the sum of increased network losses and reduced active power generation in PV system is minimized.

In order to check the ability of discussed networks to accept an increased share of PV systems, required to provide yearly net self-sufficiency. This is achieved by the installation of additional PV systems distributed in the network. Their power is proportional to individual loads, whilst their total installed power is selected to generate enough electric energy to cover the yearly load demand. The three case studies are defined:

1. In the case A, the average load and PV system power profiles are used. The optimization based on the objective function (3) determines the reactive power generation and the active power curtailment in PV systems in order to prevent the violation of voltage profile and normal line current loading. It is activated when the voltage exceeds 110 % of nominal load U_n in at least one node, or at least one line is current overloaded.
2. In the case B, the minimal yearly load and the maximal yearly PV system power values are used. This case is used to evaluate the proposed approach in only one extreme point, whilst the case A is used to check the average operation conditions over the entire year. Identical optimization procedures are applied in the cases A and B.
3. The case C is used to evaluate to what extent can the reactive power generation in PV systems reduce the power system losses when the average load and PV system power profiles are used. The optimal reactive power generation is determined in the optimization procedure based on the objective function (1). It is applied when the active power of PV systems exceeds 5 % of the nominal power.

4. Results

In order to perform the analysis additional PV systems were introduced in the discussed networks. Considering the PV system active power generation profile shown in Fig. 3, additional PV systems are introduced at the load locations in such a way to provide yearly net self-sufficient electricity supply. This means that all installed PV systems yearly generate the same amount of energy as it is consumed by the loads in a year.

A. Average load and generation profiles

The calculations were performed for the average load and generation profiles shown in Fig. 2. The results obtained

for the case A (see end of the section 3) show that the proper voltage profile can be provided by a proper reactive power generation in PV systems.

B. Minimal load and maximal generation

In the extreme case, when the maximal active power generation of PV systems in the year was considered together with the minimal load in the year, which represents the case B described at the end of section 3, only reactive power generation of PV system was insufficient to provide a proper voltage profile. In the given case, the PV systems' active power curtailment up to 40% was required.

C. Reactive power generation and network losses

In the cases when the reactive power generation of PV systems is not required to provide proper voltage profile, it can be applied to reduce network losses, which is the case C described at the end of section 3. The results of performed analysis show that the network losses can be reduced in this way. However, this approach makes sense only in the cases when the reduction of network losses exceeds the decrease in energy production of PV systems caused by decreased inverter efficiency due to reactive power generation (Fig. 4).

5. Conclusion

The results of the analysis performed in the paper clearly show that the share of distributed PV systems in electricity networks can be increased substantially if active controllable PV systems are applied. Moreover, the proposed approach based on controllable distributed PV systems, can lead to yearly net self-sufficient energy supply in distribution networks without network reinforcements, however, on the cost of up to 50 % increased network losses. The primary goal of the controllable PV systems is to provide a proper voltage profile and to prevent line current overloading by a proper reactive power generation and active power curtailment. The active power curtailment should be used only in the cases when the reactive power generation is insufficient to provide a proper voltage profile and to prevent lines from current overloads.

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