ASSESSMENT OF MAXIMUM PV PENETRATION LEVELS IN LOW VOLTAGE NETWORKS USING MONTE CARLO APPROACH

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ABSTRACT

The paper analyses the influence of photovoltaic (PV) system on voltage profile and planning of low voltage (LV) networks. Further integration of PV should not be limited, despite their substantial impact on network performance. This is the reason the network planning methods should be upgraded taking into account the stochastic nature of LV networks and uncertainties regarding future location of PV in the network. Using Monte Carlo method the voltage situation in the future can be assessed and thus results of different voltage management strategies compared.

INTRODUCTION

Distribution power systems should be economically efficient, they should provide reliable energy supply, meet electricity peak demand and should have as little as possible impact on the environment [1]. The analysis usually consists of studying each of the feeders, using estimated peak values for loads and empirically defined simultaneity factors [2]. Since the only available data is the number of consumers and their requested peak power, the planning is based on some empirically defined rules [3]. Often, little attention is dedicated to the LV networks and the software tools used for LV network planning are relatively straightforward. Many times the weakness of LV feeders is the main reason of causing the voltage quality non-compliance. As a result of such approach, many times the networks are oversized. However, it has to be noted that this type of an empirical approach has served distribution companies well for many years and the method, presented in this paper, only upgrades this current practice to be more suitable for the needs of future smart grids.

Due to the stochastic nature of the LV networks, statistical approach seems adequate [4], [5], [6]. The result of current practice is only a single number, providing no insight in the probabilities of occurrences. By enriching the results using statistical approach, information on the probabilities of attributes such as voltage limits or power losses can be provided [7]. With sufficient large number of experiments, the probabilities of future voltage conditions can be evaluated and thus the maximum PV penetration limits can be assessed. By obtaining these results the future network investments can be more accurately determined, based on acceptable risk.

To illustrate some practical implications of the proposed planning method, its usage is presented on an actual LV distribution network in Slovenia.

PROBLEM FORMULATION

The world has seen an increasing growth of PV in the recent years which present several challenges and also business opportunities for network utilities. Their growth is still increasing rapidly. Their main concern is to maintain network voltage between tight limits, which is essential for correct operation of customer loads [8]. One of the main challenges is to determine the future voltage conditions due to connection of PV in the network, and because their location is usually unknown, only statistical estimate can be obtained. It could happen that the majority of the power plants will be installed only on one LV feeder, where there is a newer settlement, maybe at the end of feeders, where voltage deviations are more frequent, or maybe at the beginning of the feeders where the grid is stronger and they will not cause any voltage rise problems. This is the main reason of using Monte Carlo approach. The idea is that the expected number of power plants is situated randomly into the network and then the load-flow conducted. This procedure is repeated several times and in the end, statistical data is obtained, expressing in what percentage of the experiments the voltage levels (or any other criteria) were unsuitable, which can be, in simple form, written as:

$$P_N = \frac{M}{N} \tag{1}$$

where P_N is the non-compliance probability expressed in percentage, M is the number of times when voltage constraints are violated and N is the number of the experiments. Logically follows that larger is the number N, more accurately the result is calculated. If this procedure is conducted for different amounts of installed PV capacity, a curve which provides the cumulative density function with respect to installed capacity of PV can be obtained [9].

METHODOLOGY

Monte Carlo method

Monte Carlo method relates to a process that is completely random in all respects. It is used in all branches of science to study systems in which analytical solution cannot be obtained. The method is named after the city in Monaco, where the primary attractions are casinos. In distribution networks when investigating new smart grid technologies, reliability, cost estimation, loading capability, peak loads occurrences etc. Monte Carlo method is widely used [1], [10], [11]. In each case authors make a large number of simulations to analyze all possible operation scenarios.

Sampling without replacement with unequal probabilities

New smart grid technologies will enable to gather much more data of the customers which can be used to upgrade current network control and to improve the network planning methods, meaning that the network can be planned more precisely i.e. closer to the operating limits. One of important pieces of input data for the presented network planning is the likelihood of building a PV on the facilities and it can be given as a weight when randomly selecting the sites. There is a term for this selection process in mathematics which is in full length called »balanced sampling without replacement with unequal probabilities from a finite population«. The use of unequal probabilities in sampling was first suggested in [12], [13]. These weights can vary for each facility based on their type, age, connection power etc. Still the weights can be "1" for all of the facilities if there is no available data to be analysed.

Load-flow based algorithm

The planning algorithm can be presented in few steps, which are the following:

1) Firstly, model a distribution network in a load-flow program.
2) Determine the expected DG penetration and consumption.
3) Given the average size of DG in the network, determine their expected number
4) On the basis of data analysis determine the probability weights for each object separately.
5) Determine the number of Monte Carlo experiments.
6) Carry out the sampling with unequal probabilities and place DG randomly into the network.
7) Import the load/generation diagrams, attribute the selected diagrams randomly to the loads.
8) Scale the load diagrams properly according to the connection power of each household.
9) Calculate the load-flow (for different days and seasons if wished).
10) Save the data for later analysis.
11) Return to step 6) and repeated it for *N*-times.

Obtaining the results, statistical probability can be expressed, using (1). For a certain amount of PV in the network the probability of inadequate voltages (or any other observed criteria) is expressed. However, the whole algorithm can be repeated for different amounts of PVs in the network. The results can be in this case the cumulative curves which provide the information on the probabilities with respect to installed PV capacity.

CASE STUDY

Defining the input parameters

To carry out the simulations, some necessary input data have to be predefined.
For an average size of PV for the simulations 10 kW is presumed. However, this number can vary depending on the type of the settlement (village, suburb, city etc.).
To consider a stochastic nature of loads and PVs when running the simulations realistic load quarterly averaged profiles were taken into account.
As explained in previous chapter, the simulations are carried out by using unequal sampling. To show this effect, it is assumed that the houses connected to the feeder 4 (see Fig. 1) are older buildings. These objects are given a weight »0.2« and others obtain the weight »1«.
To reduce the necessary number of load-flows, not only a confidence interval is applied, but simulations are done for the most interesting operation conditions, which is noon peak hour. The simulations are also carried for each of the four yearly seasons.
One very important input parameter is also the feeding voltage at the primary side of the MV/LV distribution transformer. This voltage strongly depends upon the type of HV/MV OLTC transformer control and of the location in the MV network. This highlights the fact that when analyzing the LV networks, also the MV network behavior has to be considered. In the presented case the MV during the noon peak is above the nominal, which is 1.02 p.u.

Simulated network description

The presented planning method is verified in a real Slovenian LV distribution network. The network operates radially and is fed by 160 kVA 20/0.4 kV transformer. The maximum operating power ever measured through the transformer is 120 kVA and the maximal voltage drop is cca. 0.08 p.u. There are three main feeders with cables cross section of 70 mm^2; more distant lines consist of 35 and 16 mm^2 cables. There are 84 consumers in the network (see Fig. 1).
The loads reflect voltage dependent characteristics. They consist of 60 % of constant impedance and 40 % of constant power. All of the loads also have a power factor of 0.95.
For carrying out the load-flow calculation the network was modelled in Matpower 4.1 [14].
The Monte Carlo algorithm and all of the calculations were written in MATLAB.

Simulation results

In the simulations only the probability of voltage violations in the network as a function of installed PV was considered. The presented method enables to evaluate possible solutions to minimize future problems in the network. Few of the possible actions are:

- network reinforcement,
- use of static $Q(U)$ characteristic,
- installation of the MV/LV OLTC transformer,
- coordinated control,
- demand-side management etc.

Firstly, the simulations were carried out using classical (conservative) approach, which assumes two extreme operating conditions:

- maximum load and no PV generation and
- minimum load and maximum PV generation.

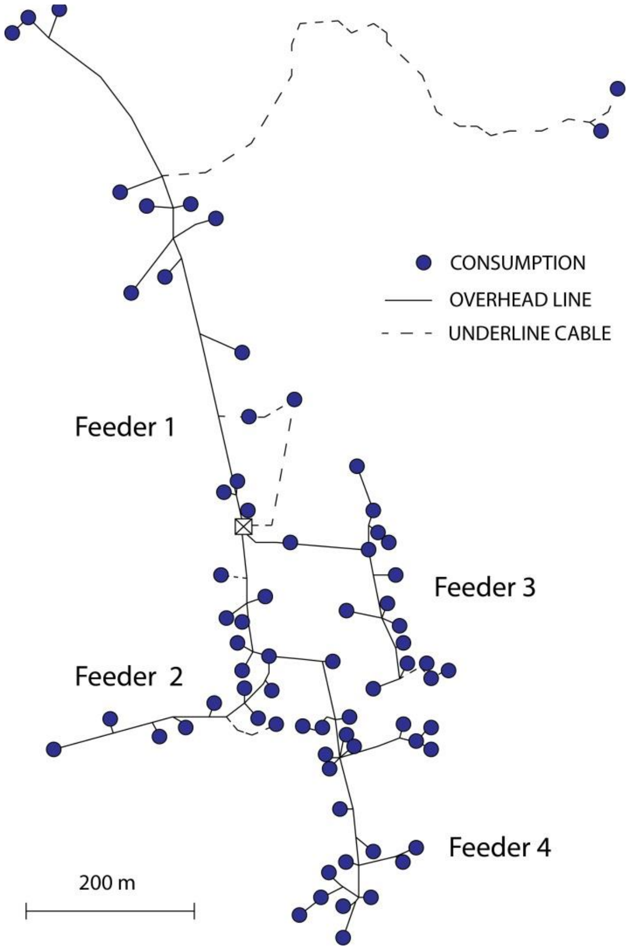

Fig. 1. Analyzed LV distribution network.

Fig. 2 presents comparison between classical (conservative) network planning using estimated peak loads and simultaneously factors and variable load profiles. In each case the PV operated with cosφ = 1. If it is assumed that 5 % acceptable risk is acceptable, the hosting capacity amounts to 170 kW. It can be seen that by only using time-varying load profiles, the network planning can be improved.

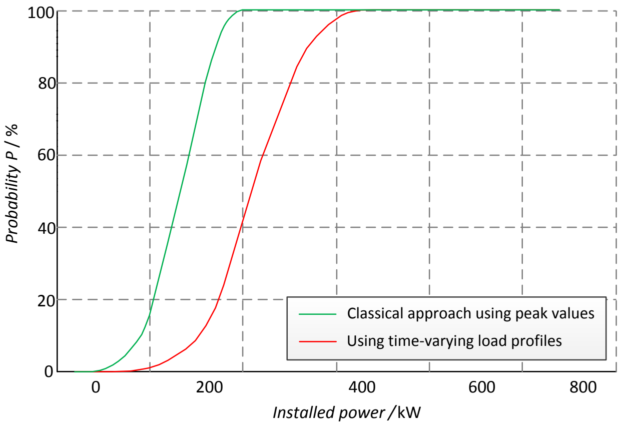

Fig. 2. Comparison of classical network planning vs. planning using time-varying load profiles. PV operate with cosφ = 1.

In Slovenia there are static $Q(U)$ characteristics prescribed which demand that PV participate in the voltage control using spare reactive power capabilities [15]. Different countries all around the world also have their specific grid codes which prescribe these characteristics which slightly vary from country to country. Using these characteristics and allowing 5 % acceptable risk, the hosting capacity rises up to 205 kW, which is a 35 kW improvement (see Fig. 3). However, the transformer which is rated 160 kVA is not overloaded. Due to consumption in the network the average power flowing through the transformer at 5 % probability is around 90-115 kVA; this mostly varies due to different possible solar radiation.

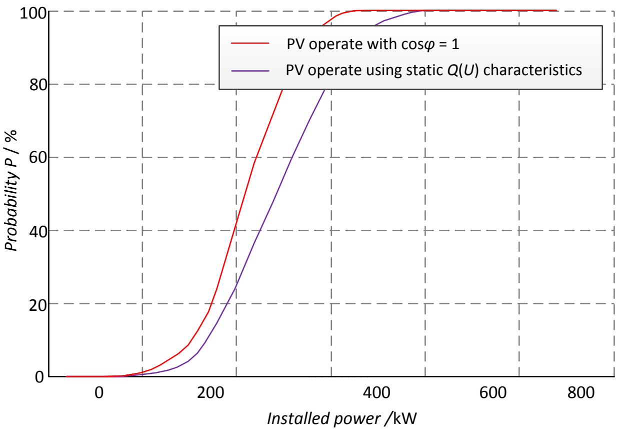

Fig. 3. Comparison of probability curves in the case of cosφ =1 operation and static $Q(U)$ operation.

The transformer presents the biggest impedance in the network. If this transformer could be replaced with a bigger one, this impedance could be lowered and grid reinforced. The next bigger standard transformer has a rated power of 250 kVA. If this is the case, the hosting capacity increases for about 80 kW and amounts to 250 kW (see Fig. 4). The average power flowing through the transformer is in this case 105-140 kVA.

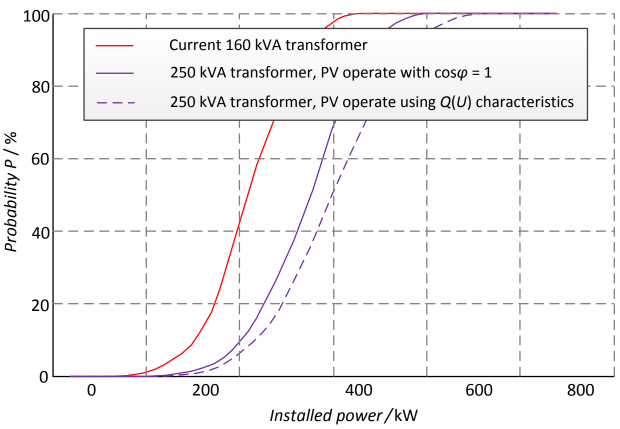

Fig. 4. Installation of a bigger distribution MV/LV transformer.

The method enables also to analyze installation of new smart grids technologies and concepts such as MV/LV OLTC transformer etc. The results are gathered in the Table I which shows the maximal PV installed capacity when there is a 5 % probability that the voltage limits are exceeded at least once a year. However, these criteria can be changed at will. Even 0 % probability can be chosen at which case parallels with classical network planning using estimated peak values can be drawn.

TABLE I
COMPARISON OF INVESTMENTS BASED ON 5 % ACCEPTABLE RISK

Action, operation mode	Max. amount of installed DG capacity in the network / kW
Classic network planning (PV → max., $P_{LOAD} = 0$)	115
New probabilistic network planning, PV operate with $\cos\varphi = 1$	170
New probabilistic network planning, PV operate by using $Q(U)$ characteristics	205
Installation of 250 kVA transformer	250
Installation of 160 kVA MV/LV OLTC transformer	360*
Installation of 250 kVA MV/LV OLTC transformer	400
Installation of 160 kVA MV/LV OLTC transformer, sampling with equal probabilities	438*

*Only voltage limit violations criteria is considered

The chosen solution is a compromise between the amount of increased hosting capacity and the necessary investment. At this point the best solution cannot be strictly defined as it can vary upon many input data which are different for each of the network, country, equipment supplier, costs of installation, ICT equipment already installed in the network etc. According to the analyzed possible solutions, installation of an MV/LV OLTC transformer with multiple voltage measurement points is technically the most effective, however, also very costly.

CONCLUSION

Current planning practice of LV networks is relatively straightforward. Such an approach many times results in oversized networks. The presented solution is based on a statistical planning using Monte Carlo method, which allows determining technical and economical optimal solutions to allow further integration of PV. By ennobling the results with statistical probability the decisions can be easier to make as it can be based on acceptable risk the utilities are willing to take. Monte Carlo approach is taken due to the fact that the location of future PV in the network is uncertain. The results provide a good insight of what is the most likely situation in the future network.

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