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Assessment of maximum distributed generation penetration levels in low voltage networks using a probabilistic approach

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ABSTRACT

The main objective of network planning is to determine the technically and economically optimal solution that will ensure continuity of supply and adequate power quality as well as allow further integration of distributed generation (DG), despite its substantial impact on the network performance. The maximum DG penetration level also has to be planned or at least assessed, and is heavily dependent on the DG location and size and on the voltage control method. The paper presents a probabilistic approach to network planning, which has many advantages compared to the traditional approaches using estimated peak values and empirically defined simultaneity factors. The method enables the evaluation of the future voltage conditions and therefore the comparison of different network development scenarios, taking into account the stochastic natures of future DG location and loads consumption. By analyzing different solutions, it is possible to minimize the necessary investments in the network. The planning method is presented on an actual low-voltage (LV) distribution network, but it can be used also in medium-voltage (MV) network planning as well.

Introduction

Background

Network utilities should always provide sufficient network capacity to meet electricity peak demand [1]; therefore network planning is based on projections of consumption. The analysis usually consists of studying a feeder at a time, using estimated peak values for loads and empirically defined simultaneity factors, as not all the loads operate at their nominal power all the time. Since the only available data is the number of consumers and their requested peak power, the planning is based on some empirically defined rules [2]. Often, little attention is dedicated to the LV networks. The main and usually the only planning criteria in the LV distribution networks is the required voltage-drop compliance with standards. The software tools used for LV network planning are relatively straightforward. Such an approach results in low utilization factors many times [2]. Nevertheless, this type of an empirical approach has served distribution companies well for many years.

For better utilization of the current infrastructure and for increasing DG penetration limits at the lowest possible costs, planning could be upgraded to the next level. Due to the stochastic nature of the LV networks, statistical approach seems adequate [3,4]. The initial idea of statistical approach of network planning is that planning with the assumption of the worst possible condition in the network is too pessimistic. Requested capacity is only a single number, providing no insight in the probabilities of occurrences [1]. To form the basis of planning decisions, different from the worst case scenario analysis, an approach which provides information on the probabilities of attributes such as voltage limits or power losses should be used [5].

The paper describes LV network planning based on the statistical Monte Carlo approach, taking into account the stochastic nature of future DG location and stochastic consumption. With random patterns and repetition of experiments, the probabilities of future voltage levels can be calculated and thus the maximum DG penetration limits can be assessed.

Problem formulation

In recent years, a huge amount of DG is connecting to the network and their growth is still increasing rapidly. Because of this, the network operator's task is more difficult when planning the LV networks, as he must not only predict the consumption, but also

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the generation from DG. Even if he uses the most advanced methods to determine the amount of newly installed DG, their location usually cannot be determined. To solve this problem, the statistical Monte Carlo method should be used.

Since the similar topic is discussed also in [7,8], it has to be noted that the presented method takes into account new options which have not been discussed yet, for example sampling with unequal probabilities, which is presented in Section 'Solutions for increasing network hosting capacity'. Secondly, when dealing with the necessary number of the Monte Carlo experiments, a confidence interval was set, and this allowed varying the number of experiments depending on the desired accuracy. This problem is not addressed in [7,8], and the number of experiments was fixed to 100. Furthermore, the problem of certain potentially influential variables (e.g. DG size) on the hosting capacity is presented in the paper and discussed. On the basis of the results, obtained by this method, the optimal technical and economical solution for network development can be selected. The advantages of the proposed method are presented on an actual LV distribution network case. However, the method can be used also for MV network planning.

The structure of the paper is as follows: the methodology of the proposed network planning approach is presented in Section 'Methodology', possible solutions for increasing network hosting capacity are discussed in Section 'Solutions for increasing network hosting capacity', the proposed method is validated by a case study in Section 'Case study' and, finally, conclusions are given in Section 'Conclusion'. During the review of this paper some interesting researches which confirm the suitability of this approach have also been published and are cited in the last Section 'Appendix'.

Methodology

Statistical Monte Carlo method

The Monte Carlo method is used in all branches of science to study systems in which analytical solution cannot be or is hard to be obtained [9]. A specificity of the method is the usage of random section techniques, which provides the approximate solution. When investigating the loading capability of a distribution network, the statistical Monte Carlo method was used in [6]. In [10], it was used when investigating DG systems performance. In [11], the authors presented a method for the selection of the optimal size of a photovoltaic (PV) system, based on the hourly solar radiation. In [1], the Monte Carlo simulation method is applied in dealing with probabilities of occurrences of peak loads and in [12], Monte Carlo is used for evaluating the power system reliability indices.

As said already in the introduction, the formulated problem is solved by Monte Carlo method. For example, the operator can predict that in a few years from now in some LV network around 1 MW of PV is to be installed. Two questions arise: how many PV present a total installed capacity of 1 MW and where will they be located. The first question can be fairly easy to answer; an average DG unit has to be considered and the power divided. The location, however, remains unknown in most cases. To solve this problem, the statistical Monte Carlo method with a large number of repetitions can be used. The idea is that the expected number of PV is situated randomly into the network and then the load-flow conducted. This procedure is repeated many times (N 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 load-flow calculations (experiments). The larger the number N, more accurately the probability can be defined. If this procedure is conducted for different amounts of installed DG capacity, a curve which provides the probability density function or cumulative density function of relevant variables [6] with respect to installed capacity of DG can be obtained.

Sampling without replacement with unequal probabilities

One of the important pieces of input data used in the proposed method is based on the analysis of the facilities in the network facing the load growth in the medium and long-term. The likelihood of installing a PV on the facility is given as a weight when randomly selecting the sites. There is a term for this selection process in mathematics which is called "balanced sampling without replacement with unequal probabilities from a finite population". The concept of sampling with unequal probabilities is of recent origin [13]. The use of unequal probabilities in sampling was first suggested in [14] (1943). Some years later the use of symmetric sampling with unequal probabilities was presented [15]. Since then many papers were published dealing with this topic, and many of them are summarized in [13]. This is a well-known problem in mathematics and appears in all branches of science, especially when solving mathematical problems [16–19]. The usage of this method is proposed in this paper as it avoids the possibility of samples i.e. buildings being selected more than once and takes into account that the probabilities of installing a PV on the facility can vary based on their type, age, connection power, etc. It is important that the network operator makes analysis of the available data and determines whether there are any correlations to be taken into account in the further analysis of their networks.

Sampling with unequal probabilities can be expressed analytically. For three numbers, i.e. objects A, B and C, when selecting two of them, the probabilities of occurrence P_a, P_b and P_c can be derived from likelihood three, expressed as:

$$\begin{bmatrix} P_a \\ P_b \\ P_c \end{bmatrix} = \begin{bmatrix} 1 & \frac{w_a}{E-w_b} & \frac{w_a}{E-w_c} \\ \frac{w_b}{E-w_a} & 1 & \frac{w_b}{E-w_c} \\ \frac{w_c}{E-w_a} & \frac{w_c}{E-w_b} & 1 \end{bmatrix} \begin{bmatrix} w_a \\ w_b \\ w_c \end{bmatrix} \tag{2}$$

where w_a, w_b and w_c are weights for each object and E is the sum of the weights. Eq. (2) can be generalized for any number of variables.

The satisfactory number of Monte Carlo load-flow experiments

As the results of repeating the experiments N times, the vector v of length N is obtained. It contains only two different numbers:

- 1 – indicating that in the selected simulation the voltages are inadequate and
- 0 – indicating that in the selected simulation the voltages are within the limits.

This can be written as:

$$v(1 \ldots N) \in \{0, 1\} \tag{3}$$

where v presents the results vector with a Bernoulli distribution. The voltage limits are defined by SIST EN 50160 standard used by Slovenian utilities [20], which states that under normal operating conditions excluding the periods with interruptions, supply voltage variations should not exceed ±10% of the nominal voltage.

In the limit case when the number N goes to the infinity, the probability P_∞, using (1), can be written as