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Efficient integration of (n – 1)-security into probabilistic network expansion planning

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ABSTRACT

This paper presents a new efficient way to integrate the (n – 1)-security into modern probabilistic network expansion planning. Therefore, a method is presented for an (n – 1)-secure probabilistic load flow based on AC distribution factors. For the simulation of multiple segment outages, a new mathematical description is presented. The presented method is able to handle the islanding of single nodes within the calculation. Afterwards, a linearization is presented using the superposition theorem and Newton Raphson load flow calculations. A new linearization of the power flow is used to consider reactive power flows. Based on this, AC line outage distribution factors can be calculated using the normal operation state of the grid. The analyzed sensitivity of the distribution factors to the load and generation scenario is low. Therefore, the linearized method shows a good congruency. Additionally, the proposed method identifies correctly the worst case conditions in massively reduced computation time. A comparison between the (n – 1)-secure probabilistic method and today's deterministic planning methods show that the high penetration of renewable energy sources leads to an under dimensioning of the grid.

1. Introduction

The necessary network expansion is often derived by using the results of contingency analysis of high voltage distribution grids as well as transmission grids in the case of traditional deterministic network expansion planning studies. However, due to the high penetration of distributed generation (DG), frequently based on renewable energy sources (RES), the traditional deterministic planning approach is unsuitable for modern active distribution grids [1]. Thus, owing to the additional boundary conditions, there are new requirements for the network expansion planning process [1–4]. As discussed in [1], the future network expansion planning methods are going to be primarily based on probabilistic techniques which are often applied with a probabilistic load flow (PLF). In today's planning studies, the (n – 1)-criterion is used to guarantee a security of the system, since the electric system is able to "withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements" [5]. To keep the well-established (n – 1)-criterion in the future planning studies, new efficient calculation methods are necessary since a contingency analysis for all load and generation scenarios in a PLF is a very time consuming process and is a limiting factor in the planning process. The (n – 1)-security is a requirement of the Distribution System Operators (DSO), which makes an efficient calculation method necessary to integrate probabilistic methods in the planning process of the DSO. The main effort of the new method is to transform the (n – 1)-security as deterministic reliability criteria to a condition suitable for the network expansion planning of active high voltage distribution grids.

The traditional, deterministic planning approach uses a small number of load and generation scenarios. Usually, only two scenarios, one for high load vs. no generation and one for low load vs. high generation, are considered within the planning process. The (n – 1)-security can be verified with a contingency analysis, where the power flows are analyzed if one line is out of service. By applying probabilistic methods to the planning process, like e.g. the PLF calculation, either only random outages are considered, like in [6], or only a contingency analysis is performed for selected load and generation scenarios [7]. Both approaches do not examine the (n – 1)-security for all possible load and generation scenarios as well as grid components. By using random outages, the calculation of probabilistic reliability criteria like the LOLE (loss of load expectation) and EENS (expected energy not served) seems reasonable for network expansion planning like in [8], although it is difficult to define the costs for reliability. The calculation of an adequate security margin in the transport capacity is very difficult, when

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using probabilistic reliability criteria and is one of the main benefits of the (n − 1)-criterion [9]. Additionally, standardized planning guidelines define the necessary grid reinforcement by using the (n − 1)-criteria [9]. To take advantage of the benefits of the (n − 1)-security and to reduce the computational burden, an efficient way to prove the (n − 1)-criteria is necessary within the planning process of the active high voltage distribution grids.

This paper presents a new efficient method to integrate the (n − 1)-security into modern probabilistic network expansion planning methods. Based on the method of branch outage simulation by fictitious injection powers of [6], a new method to consider multiple segment outages is proposed. A multiple segment outage consists of more than one line and is a typical structure in German high voltage distribution grids (110 kV). The number of multiple segment outages will arise in the future, since more wind farms will be directly connected to the high voltage distribution grid. The mathematical formulation in the literature, of e.g. [6], is not suitable for multiple segment outages since the problem is an islanding node within the multiple segment. The islanding of a node would lead to errors in the calculation of the power flows in the outage state of the system. Therefore, a new mathematical formulation is presented in this work which is able to handle an islanding of nodes. The islanding of some nodes is additionally a problem for sensitivity factor calculations as described in [10].

Furthermore, an approximation method for power flow calculations made by using AC distribution factors (ACDF) is presented and used to determine an approximation of the (n − 1)-system states of the network. The aim of the ACDF is the consideration of the reactive power flows and is, therefore, not comparable to power transfer distribution factors. By using the ACDF, the computational effort can be massively reduced, while providing an acceptable accuracy. The proposed method is applied to a small test system and a grid model of a real high voltage grid in southern Germany. The results are analyzed and discussed and, finally, a comparison between today's deterministic approach for grid planning and the presented (n − 1)-secure probabilistic approach is presented.

2. Network expansion planning for active distribution grids

2.1. Background

Often, time-series based and probabilistic methods are applied to the network expansion planning to deal with active distribution grids and the operational aspects of different network elements and actively managed networks [1,3]. A further objective in the planning process is the optimization of the allocation of DG [11,12] or the minimization of investment cost [13,14]. Due to the unbundling rules in Germany, the DSO is only able to plan the structure of his grid under the uncertainty of the increase of the installed capacity of DG. The planning of the DSO depends on technical constraints and on the optimization of economic targets [4]. For active distribution grids, probabilistic reliability criteria (e.g. LOLE, EENS) [8] or the calculation of PLF or time-series based load flow is used [7,15,16].

2.2. Probabilistic reliability criteria

Typically, only deterministic reliability criteria as (n − 1) are used in traditional planning studies because of missing data for the calculation of realistic probabilistic reliability criteria [8]. By using probabilistic reliability criteria, a minimization of costs for network expansion planning can be achieved by a fixed reliability level (e.g. LOLE = 50 h/yr) [17] or by considering costs for EENS [8]. The results of the optimization problem are very sensitive to the chosen costs for EENS [8]. Therefore, the calculated system reliability, based on customer outage cost and construction costs, depends strongly on the chosen specific costs for EENS and cannot sufficiently answer which reliability is the optimal solution for the DSO. A similar problem exists, if a fixed system reliability level is considered [17]. By using probabilistic reliability criteria, the DSO can hardly determine, which reliability is economically reasonable. Additionally, the deterministic (n − 1)-security has been effectively used as network expansion planning in regulated environments [17].

2.3. Probabilistic load flow calculation

PLF was first proposed by Borkowska in 1974 [19] and the main benefit of it is the consideration of possibly all load and generation scenarios. For planning of active distribution grids, PLF can be used to analyze the influence of modern grid components and new operation approaches, like e.g. the electric vehicles [16] or new voltage regulation methods [21]. For planning of active distribution networks, a Monte Carlo Simulation as PLF is beneficial, since several controllers can be modelled in detail and their interactions can be considered.

2.4. (n − 1)-security in network expansion planning

One of the main benefits of the (n − 1)-security is the compliance with planning guidelines in the fully liberalized energy markets [9]. According to [9], the (n − 1)-security has to be applied in transmission and high voltage distribution grids. An additional benefit of the (n − 1)-security is the evaluation of a security margin in transport capacity in the normal operation state of the grid [9]. This is necessary for the operation of the distribution grids since reconfigurations are sometimes necessary for tasks like e.g. maintenance of overhead lines. Therefore, the (n − 1)-security is a request of the DSO when integrating probabilistic methods in the planning process of high voltage distribution grids. When combining PLF with (n − 1)-security, a Monte Carlo simulation is only suitable, since the deterministic reliability criterion is defined by the power flows in the corresponding load and generation scenario. Other solutions of PLF as e.g. in [18,20] are not possible, since only the probabilities of the occurrences of power flows are known as the only solution of such convolution techniques. A calculation of the power flows in the (n − 1)-state is not possible if only the probabilities of occurrences of the power flows in the normal states are known. By using the (n − 1)-security for probabilistic network expansion planning as security requirement, the security margin in transport capacity will be standardized like in traditional planning studies. For the combination of PLF with (n − 1)-security, new efficient ways for the calculation are necessary to reduce the computational burden and make such methods applicable in the network expansion planning.

3. Simulation of branch outages

3.1. Background

One of the obvious investigation methods for contingency analysis is the well-known load flow technique for each individual outage in the considered power system. For current power systems, with a high number of transmission lines, the non-linear load flow solution has to be obtained for many cases, which is a very time consuming process [22–25]. In all cases the topology of the power system is different, which makes it necessary to define the non-linear load flow equation for each system separately. The simulation of branch outages use fictitious power injections at the corresponding nodes and calculate the sensitivity of the branch outage