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Three-layer seasonal reliability analysis in meshed overhead and underground subtransmission networks in the presence of co-generation

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ABSTRACT

This study presents a reliability assessment tool for meshed subtransmission networks in a three-layer structure. In this model, the three critical zones of influence, containing four blocks, are determined, described and quantified as reliability parameters. Moreover, this work is framed on the distinction between subtransmission networks consisted of underground cables (UGC) and overhead lines (OHL), accrediting attributed failure rates, repair times and intrinsic features under multiple circumstances and the seasonal variation of load and co-generation within them. For this achievement, the current analysis ascribes differentiation between adverse and normal weather conditions and the impact on considered equipment, as well as division of time period of analysis into different scenarios. This method is tested in the IEEE 30-bus network, as underground and as overhead networks, and in a typical Nordic 25-bus subtransmission network; and the influence of each of the four blocks is described at the end of this paper. As results, underground parts of the network exhibit more homogeneous outage time throughout the year than the overhead parts and the presence of co-generation improved reliability both in the directly connected substations and in the entire network. Furthermore, the block constituted by the substation equipment presents the largest influence on the system reliability. Similarly, common-mode failures in overhead networks introduce significant decrease on network availability.

Introduction

Reliability analysis has long been a well-known topic to power systems engineers [1]. Studies have concerned in evaluating reliability at all hierarchy levels of the grid and in providing strategies to minimize interruption to the end-consumer [1–4]. For that, the correct modeling of the main equipment between load and power source and detailed description of load data are requisite to a successful reliability analysis [1,5,6]. In this context, accurate parametric selection and a multilayered investigation must be sorted in order to integrally assess equipment influence on the overall system reliability and propagated interruption to customers from subtransmission networks.

Previous studies [7–12] developed methodologies to quantify customer-oriented reliability indices through several approaches in composite systems. A traditional mean to calculate system reliability is by employing Monte Carlo simulation and a combination of this with other techniques [6,11–13]. However, in modern subtransmission networks, inspection is required in differentiated fashion, due to its topology, intermediate position in the power systems, dependability on local generation, type of substation (whether it is outdoor or indoor), presence of both overhead lines (OHL) and underground cables (UGC) as well as the presence of different types of customers. For that, this study classifies failures regarding origin from different weather conditions and regards co-generation within the network, such as combined heat and power (CHP), connections to other subsystems (EHV/HV and HV/HV connections), substation arrangement as well as power flow scenarios in different seasons to provide a multivalent reliability analysis.

Abbreviations: EHV, extra-high voltage (transmission level); HV, high voltage (subtransmission level); k_{load}, discount factor linearly related to load growth; MV, medium voltage (distribution level); P_{dem}, demanded power in the considered part (MW); P_{PNS}, probable power not supplied (MW); P_{PNSIII}, probable power not supplied at delivery point (kW); P_{PS}, probable power supplied (MW); P_{Ti}, transferred power at each state with failure (MW); R_i, probability at risk state "*i*".

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Similar works have been focused on reliability and economic assessment in subtransmission systems [14–16]. These papers report on reliability techniques at substation level using branch-node model [14], algorithms on emergency response to faults [15] and on penetration of distributed generation [16]. However, they do not cover seasonal and weather variations nor the divergences between underground and overhead networks. The reliability tool in this study is structured on four different blocks: adjacent connections, local generation, infeed (distinguished by UGCs and OHLs) and substation arrangements. Featuring each of these blocks, arranged in layers, by several indices at each the delivery point of each substation, the herein developed method assesses both the local and the system reliabilities, identifies areas of vulnerability (or layers) within the subtransmission network, returns equivalent partial parameters in these areas for comparison and provides input for the economic assessment to plan subtransmission networks. This study is supported by specific data collected from the regional utility companies and operators and relies on the nature of failure from the considered equipment [17–22].

This paper is divided into six sections. After the introduction, Section Model description delineates the three-layer four-block reliability technique developed, defining each of them. Moreover, Section Model description shows the significant considerations for subtransmission networks, including weather and season characteristics and equipment failure rate parameterization. Section Description of the Test Networks characterizes the tested networks (IEEE 30-bus OHL, IEEE 30-bus UGC and Nordic 25-bus). Sections Results and Discussions contain the results and the discussion achieved by applying the developed method. And Section Conclusion finalizes this study by drawing pertinent conclusions.

Model description

The reliability analysis developed herein consists of a four-block three-layer structure representing any subtransmission network projected to any delivery point (in this paper, secondary of the HV/MV transformers, dealt as load) within its limits. Fig. 1 schematizes this representation.

The four blocks introduced in this model embody the main considered components, grouped according to their position and function in the subtransmission network. A block is defined as the set of adjacent equipment and devices that cause partial or total interruption of power to the end customer when out of operation. Each block is associated as individual components to subsequently obtain the equivalent outage rate, the average outage time and the power not supplied to the delivery point at each substation. These values provide input for the economic assessment of this network. This simulation is performed individually at each substation.

A layer is defined as the critical point of any subtransmission network through which power must flow in order to reach the end customer. The three layers in Fig. 1 represent the three most important points where partial reliability values are obtained to identify network performance.

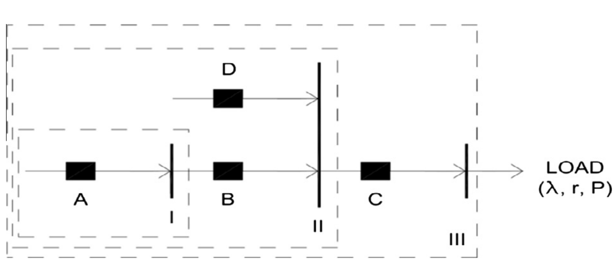

Fig. 1. Three-layer schematic for subtransmission networks. Each of the four blocks is considered as one single device mutually arranged in series or parallel.

The techniques employed to obtain failure rate "λ" and average outage time "r" at delivery points and critical points (layers) include series and parallel associations and the method of minimal cuts in this analysis. These techniques are detailed, for instance, in [1]. System parameters, including customer-oriented and load-oriented indices, are calculated according to [23]. The equivalent power not supplied is obtained at each block and will be described subsequently.

The four blocks

The substations of any subtransmission network can be represented by using blocks A, B and C (ABC-substation) or, in the case of presence of generation units, by using blocks A, B, C and D (ABCD-substation). This analysis is initially performed at each individual substation and thereafter the system indices are obtained for the entire network. These blocks are:

Block A (adjacent system connections and remote generation)

Block A is composed of all connections between the subtransmission network and its adjacent transmission and subtransmission networks that can inject power into the considered network, EHV/HV transformers and generation units, including CHP facilities, present within the network but outside the considered substation, *i.e.*, the remote generation. The availability of each connection and power transfer capacity are individually calculated by determining the series association of the bay components. Subsequently, these components are associated in parallel with other connections to compose the parameters of block A.

Block B (infeeding lines)

Block B consists of the infeeding lines directly connected to the considered substation. It is subdivided into block Ba, consisting of the lines connected to busbar A, and block Bb, to busbar B. Moreover, all combinations of failures of lines within this network, not directly connected to the considered substation, must be added to block B. In meshed networks, usually higher-order failures must occur in order to cause load curtailment. However, particularly in the cases of common-mode failures and cables in parallel with overhead lines, load outside the connected substations may have to be curtailed while equipment is in repair to prevent overloading of lines.

Fig. 2 depicts the two considered busbar arrangements and the position of busbars A and B in both cases. The parameters of block B is obtained by associating these lines in parallel. Each infeeding line bay includes two circuit breakers (the local and the remote) and the line itself (OHL or UGC).

Block C (substation configuration)

Block C represents the substation configuration, as shown in Fig. 2. The transformer bays (including the HV/MV transformer), the line bays (busbar A and busbar B sides), HV busbars and the circuit breakers between the busbars (both in the HV and the MV side) are associated by employing the minimal cuts technique and the equivalent parameters are drawn as block C.

It is important to underline that both transformers are connected to each other in the medium-voltage side via a manual normally-open circuit breaker. In addition, the parameters for each of the four blocks are mutually independent, by the exception of blocks B and C. In the case of calculating block C, the blocks Ba and Bb are used in the minimal cuts technique. However, this dependency is very low, for it is a sum of first and second-order failures with third and fourth-order values, to which block B is included, and therefore block C can be regarded as independent from block B.