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A nonlinear binary programming model for electric distribution systems reliability optimization

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ABSTRACT

This paper presents a new nonlinear binary programming model aiming to minimize the SAIDI and SAIFI reliability indices of a distribution feeder. Graph theory and a contingency simulation-based technique are used in the explicit formulation of the objective functions to accurately model the protection system response to faults and system reconfiguration practices. To ensure the solution's feasibility both technical and economic constraints are considered. An alternative economic constraint is proposed, taking into account the current locations of the protective devices and sectionalizing switches, which directly affect the utility costs for reliability improvement. To solve the proposed model, an optimization technique based on the branch-and-bound algorithm is used in this paper. Hence, this technique enables deterministic optimization of distribution feeder reliability by identifying types and locations of protection devices and sectionalizing switches, so that SAIDI and SAIFI reliability indices are minimized. Test cases are presented to illustrate the reliability optimization of a test feeder considering the use of different protection schemes and cost constraints. A value-based reliability optimization formulation is derived from the proposed model and its application to the test feeder is also illustrated. Additionally, the solutions obtained from the proposed model are compared with the solutions obtained from two other state-of-the-art models found in the literature. A comparative study is also carried out to evaluate the efficiency of the genetic algorithm in solving the proposed models.

1. Introduction

Electric utilities are continuously concerned with improving distribution systems reliability and performance, while dealing with the increasing customer demands for high quality supply service and regulatory pressures, without increasing electric distribution costs [1].

To evaluate system performance and provide the basis for establishing service continuity criteria, utilities and regulatory agencies use the calculation of reliability indices defined in [2]. Among all, the most frequently used reliability indices are the System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI). Since SAIDI and SAIFI calculations rely directly on both the protection system's response to faults and utility restoration practices, the selection and allocation of protection devices and sectionalizing switches on distribution feeders can improve the indices. This enables to minimize the number of customers affected by protection device operation while maximizes the number of customers restored through system reconfiguration.

Improving reliability by identifying the types and location of protective devices and switches in distribution systems has been the focus of extensive research in recent years. Most methodologies address the problem by formulating implicit models for reliability indices and/or reliability costs minimization. Solving implicit models usually requires the use of stochastic search methods, at the expense of at most being able to provide a probabilistic convergence guarantee [3]. These approaches include the use of genetic algorithms [4], simulated annealing [5], evolutionary algorithms [6] and ant colony optimization [7] for optimal allocation of sectionalizing switches in distribution systems. Additionally, the tabu search is used in [8] and the multiobjective ant colony optimization method is used in [9] to solve the problem of optimal allocation of both protective devices and switches. As this paper proposes an analytical approach for distribution systems reliability optimization, the literature review will focus on explicit formulations of mathematical programming models.

Ref. [10] presented a nonlinear binary programming (NLBP) model, reduced to a linear binary programming model using a simple linearization technique. The objective was to minimize the SAIFI index by identifying the locations of reclosers and fuses on the distribution feeder. As the model does not consider the allocation of sectionalizing switches, it is not suitable to be used in minimizing interruption duration-related indices, such as SAIDI. In order to

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limit the complexity of the problem to be solved, the authors propose the division of a feeder in a main line and a number of laterals, which are classified in one of three categories. Category one lateral is short and has its reliability parameters added to its tap point. Categories two and three are treated separately from the main feeder, which requires a protective device to be installed in the tap of the lateral branch. However, it should be noted that distribution feeders usually have a large number of branches, both in the main circuit and laterals, which require a large number of protective devices to be installed. This may greatly increase the implementation cost of a solution, as well as the fact that the installation of many devices in series often complicates coordination. Additionally, the branches classification is a heuristic decision that burdens the decision-maker and can lead to suboptimal solutions [11].

In [12], model [10] was used to minimize SAIFI, ASIFI (Average System Interruption Frequency Index) or the cost of protective devices acquisition, while a desired level in the indices was treated as a constraint. Also based on [10,13] presented a fuzzy goal programming technique in order to determine the trade-offs between SAIFI, ASIFI and MAIFI (Momentary Average Interruption Frequency Index).

In [14] the NLBP model to minimize the total cost of reliability, including the outage costs and the investment in protective devices and switches is presented. The authors derived models for SAIFI and SAIDI indices based on this formulation. However, the SAIDI model only partially accounts for the sectionalizing switches effects on the interruption duration, because it does not consider the downstream restoration practice. Also, NLBP models are developed in [15,16] to minimize SAIFI and the total cost of reliability, respectively.

All the models presented above depend on the heuristic feeder division as first proposed by Soudi and Tomsovic [10]. In [11] a more generalized NLBP model is proposed to minimize the SAIFI index. By departing from the heuristic feeder division the authors showed that the model is able to find better solutions than the model [10] for the problem of minimizing the SAIFI index. A model for SAIDI is also proposed based on the SAIFI model, but it does not consider the effect of sectionalizing switches on the interruption durations.

This paper presents a new explicit NLBP model aiming to minimize the SAIDI and SAIFI indices of a radial distribution feeder. The model does not require heuristic decisions about feeder division and branches classification. Graph theory and a contingency simulation-based technique are used in the formulation of the objective functions to accurately model the protection system response to faults and system reconfiguration practices, as functions of basic reliability parameters and locations of reclosers, fuses and sectionalizing switches. To ensure the solution's feasibility both technical and economic constraints are considered. Furthermore, an alternative economic constraint is proposed, taking into account the current locations of the protective devices and sectionalizing switches, which directly affect the investment costs for reliability improvement. To solve the proposed model, an optimization technique based on the branch-and-bound algorithm is used in this paper. Test cases are presented to illustrate the reliability optimization of a test feeder considering the use of fuse saving and fuse blowing protection schemes, showing the impact of using these reclosing practices on the reliability of the distribution test feeder. A value-based reliability optimization formulation is derived from the proposed model and its application to the test feeder is also illustrated. Additionally, the solutions obtained from the proposed model are compared with the solutions obtained from two other state-of-the-art models found in the literature. A comparison between the (deterministic) branch-and-bound and the (stochastic) genetic algorithm is also carried out in order to evaluate the efficiency of both solution techniques in solving the proposed models.

2. Problem formulation

This section presents some concepts related to distribution systems reliability and operation, required to define the problem and the formulation of the proposed model.

2.1. Failures and interruptions

The failures that occur in distribution systems can be classified as temporary or permanent. A temporary failure will clear itself if the circuit is de-energized (allowing the arc to de-ionize) and then re-energized after a short period of time (usually a few seconds). A permanent failure causes a short circuit that will persist until repaired by human intervention [1]. This paper focuses on interruptions that have been caused by protection system operation due to failures. An interruption is defined as the complete loss of service (power supply) to one or more customers, and is classified by its duration as either momentary or sustained. A momentary interruption is defined as an interruption with a total duration of less than 5 min. Otherwise, the interruption is classified as a sustained interruption [2].

2.2. Electric distribution reliability indices

The indices commonly used to evaluate electric distribution systems reliability are formally defined in [2]. Most electric utilities and regulatory commissions use SAIDI and SAIFI to measure reliability in terms of total duration and frequency of sustained interruptions for an average number of customers, respectively. For a fixed number of customers, SAIDI can be improved by reducing the number of sustained interruptions or by reducing the duration of those interruptions. Since both of these reflect reliability improvements, a reduction in SAIDI indicates an improvement in reliability. The only way to improve SAIFI is to reduce the number of sustained interruptions experienced by customers [1].

2.3. Distribution protection and reconfiguration practices

In general, protection of a distribution system consists of a circuit breaker with overcurrent and automatic reclosing relays at the substation, and line reclosers, sectionalizers, interrupters and fuses installed at strategic locations along the feeders.

The recloser has fault current sensing, interrupting and automatic reclosing capabilities, operating with a predetermined sequence of opening and reclosing, followed by its lockout. Reclosers are installed in the main circuit and feeder laterals, and are also used as switching devices. In this paper the term recloser will be used to identify three-phase automatic sectionalizing devices: substation breaker, reclosers, sectionalizers and interrupters. Interrupters and sectionalizers are similar to line reclosers, except that they do not have automatic reclosing capability. Additionally, sectionalizers do not have fault interruption capability and therefore can only automatically isolate a faulted section after the operation of an upstream recloser or breaker.

The fuse does not have automatic reclosing capability. It can only perform an open-circuit function, separating the faulted circuit by melting its fuse-link. Hence, the fuse is not able to clear the momentary faults by itself. Fuses are installed only on lateral feeder sections, and do not have a switching function.

Two basic reclosing practices are commonly used in recloser-fuse coordination: fuse saving (also referred to as feeder selective relaying) and fuse blowing (or fuse clearing). These schemes are usually implemented setting the fast curve on a recloser (or the instantaneous relay on a breaker) unblocked or blocked, so that the recloser (or breaker) operates before or after the downstream