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Multiobjective formulation of the integration of storage systems within distribution networks for improving reliability

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ABSTRACT

A new approach to improve reliability in distribution networks using energy storage systems is presented in this paper. Electric utilities have been using switching devices in distribution networks mainly to improve network reliability considering sustained interruptions. Temporary interruptions have been relegated to second place. However in modern societies appliances with electronic components are becoming more sensitive to temporary interruptions. Because of this, reliability indexes like the Momentary Average Interruption Frequency Index (MAIFI) that considers temporary interruptions are receiving more attention by electric utilities. The integration of storage systems into the multiobjective planning of distribution networks is proposed in this paper, to improve the reliability index MAIFI. This approach considers the optimization of storage systems integrated in a problem with multiple objective functions. The reliability index MAIFI is the first objective function, minimized by optimally choosing the size and location of battery banks in the distribution network. The second objective function, System Average Interruption Frequency Index (SAIDI) is optimized by finding the optimal number and location of switching devices. The third objective function consists on the minimization of the equipment cost. The optimization of these conflicting functions is achieved by the use of the Non-Dominated Sorting Genetic Algorithm II (NSGA-II).

1. Introduction

One of the most important concerns of electrical companies and consumers is related with power quality. In fact, in the last years this topic has become a critical issue for electrical companies and customers. Concern with power quality may be attenuated by improving distribution network reliability. An important number of interruptions experienced by the consumers come from faults in the distribution grid [1]. In distribution systems, especially in overhead lines, many of the faults occur during adverse weather conditions such as lightning storms. These result in momentary or sustained interruptions of the connected load. In distribution electrical companies momentary interruptions are becoming a matter of great concern, primarily because of its impact on new types of fault sensitive loads. The increasing sensitiveness of customer loads to momentary outages has forced electrical utilities to consider momentary interruptions more carefully. These interruptions may cause loss of production in a variety of industrial plants that require uninterruptible power supply, and in residential loads, computers and electronic devices are usually sensitive to momentary interruptions. They can also reduce customer satisfaction.

Reliability in distribution network systems is usually measured using reliability indexes. The most commonly used by utilities are described in the IEEE Standard 1366—"Guide for Electric Power Distribution Reliability Indices". This standard recommends among others indexes, for long interruptions the index SAIDI (System Average Interruption Duration Index) and the index SAIFI (System Average Interruption Frequency Index). Due to the importance of these reliability indexes several works have been proposed. In most of these works, it was used multi-objective optimization algorithms to optimize several objective functions in conflict. In Ref. [2] a memetic multi-objective algorithm is used to enhance reliability in distribution networks considering the optimization of three objective functions, SAIDI, SAIFI and equipment cost. The network expansion taking into account a multi-objective approach was analyzed in Ref. [3]. In this work it was considered the investment and operation costs as well as system reliability indexes SAIFI, SAIDI and AENS. These objective functions are minimized by net-

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work reconfiguration, installations of new lines and new generating units. The optimal switch placement in radial distribution networks was addressed in Ref. [4]. This work considered the cost of switch allocation and the reliability index ENS (energy not supplied) as objective functions. In Ref. [5] is presented a probabilistic method to solve the Volt/Var control problem in distribution system with windfarms. The objective functions considered were the cost of generated electricity, the losses and the associated emissions. An optimal approach to improve distribution network reliability using energy storage systems was considered in Ref. [6]. In this work the minimization problem considered the cost of ENS as well as Energy Storage Systems costs subject to safe operation of the network. The results indicate a significant reduction in ENS by the use of Energy Storage Systems. Under the point of view of reliability it was considered the guarantee of the network safe operation through satisfying security constraints such as voltage and line-flows limits. However, the problem related to the network interruptions reflected on the reliability indexes such as SAIDI and SAIFI was not addressed.

Besides the long interruption indexes, the IEEE Standard 1366 also considers short interruption indices. Two of these indexes are the MAIFI (Momentary Average Interruption Frequency Index) and $MAIFI_E$ (Momentary Average Interruption Event Frequency Index). However, momentary interruptions are a recent concern of electrical companies in comparison to sustained interruptions. Under this context, there are relatively few papers where minimization of the reliability index MAIFI is carried out. One of the strategies that were used to improve the reliability index MAIFI was through the reduction of voltage sags. In Ref. [7] was proposed a network reconfiguration to improve power quality by the reduction of voltage sags and network reliability through the improvement of the reliability indexes SAIFI and MAIFI. This is done using a quantum-inspired binary firefly algorithm. In Ref. [8] this problem was addressed through the use of a binary gravitational search algorithm. The minimization of reliability indexes by optimal sizing and placement of dynamic voltage restorer was addressed in Ref. [9]. A different strategy was proposed in Ref. [10] with the use of reclosers and auto-sectionalizers to reduce costs (ENS and equipment cost) and enhance network reliability through the use of these equipment's. The network reliability is evaluated in respect to SAIDI, SAIFI and MAIFI. A particle swarm optimization algorithm was used to minimize the objective functions. In Ref. [11] was used an artificial bee colony algorithm, in Ref. [12] a Non-dominated Sorting Genetic Algorithm II and in Ref. [13] a fuzzy logic dynamic programming. The reduction of the reliability indexes where is included the MAIFI index, was also addressed through the optimal placement of unified series shunt compensator in Ref. [14]. This approach used a genetic algorithm. Distribution reliability was also studied in Ref. [15] by the analysis of the reliability technology. In Ref. [16] the reliability of the distribution networks due to lightning storms was assessed. In several problems of power systems engineering as in many real-world optimization problems, there are several conflicting performance criteria's or objectives. These often are computationally demanding, imposing special requirements on the optimization methods used. In this context, a multi-objective optimization algorithm considering a Pareto-optimal concept, will seek to approximate the set of solutions to the Pareto-optimal solutions. These solutions are related with a set of objectives and are characterized by the nonexistence of no other solution in the decision space that improves on all of the objectives at once. Beside the consideration of reliability indexes in the distribution network planning, nowadays due to the wide spread of distributed energy resources (DER), distribution planning associated to multiobjective optimization also considers the optimal placement of DER in the network as part of the improvement of network reliability [17–19]. Storage systems are starting to become important in the distribution networks. Thus, in the last years many research works have been focused on the use of these systems in distribution networks [20,21]. However, the use of storage systems related with the reliability problem and associated to short time indexes such as the MAIFI have not been addressed. Under this context this work presents a new approach to improve radial distribution network reliability. In this approach it was considered the reliability indexes associated to the long and short interruptions. One of the reliability index considered to be minimized is the one associated to momentary interruptions (MAIFI). To achieve this reduction it is proposed the use of battery banks associated to switching devices, to create micro-grids during the short-time interruptions. The implementation of this strategy is achieved through the minimization of the reliability indexes and investment in equipment. Since there is a minimization conflict between the reliability indexes and investment costs in equipment, the optimization is accomplished through the use of a multiobjective algorithm, more specifically the Non-dominated Sorting Genetic Algorithm (NSGA-II). Beside the minimization of short interruptions, long interruptions are also minimized using the reliability index SAIDI, by optimally choosing the number and placement of switching devices. The proposed optimization algorithm allows to find the size and location of the batteries taking into consideration the minimization of the following objectives: MAIFI, SAIDI and equipment cost (EC). The algorithm finds a set of solutions that represents the Pareto front. In order to verify the validity of this approach several tests were made over a real distribution network.

This paper is organized as follows. In Section 2, the multiobjective optimization problem is formulated considering the storage systems and short interruption indexes. In Section 3 the proposed planning approach using the algorithm NSGA-II is presented. In Section 4 is presented the results that were obtained from the application of the proposed approach to a real distribution network. The analysis and comments to these results are also presented in this section. In the final section are presented the conclusions of this paper.

2. Problem formulation

Momentary interruptions in electrical distributions networks affect customers as above explained. When a fault occurs in the network, the protective device tries to eliminate the problem and if by successive connection and disconnection operations the fault disappears, the interruption is considered a momentary interruption. But while the protective device is operating, all downstream customers are affected by this momentary interruption. This can be seen in Fig. 1. While the protective device (PD) tries to eliminate the fault all customers in load points (LP) LP1, LP2, LP3, LP4, LP5 and LP6 are affected.

Network reliability can be increased by reducing the number of customers affected by a momentary interruption. This may be accomplished with the use of battery banks in the network. The process is explained through Figs. 2 and 3. If a battery bank associated with a switching device is placed in LP2 (Fig. 2), in case of an outage located upstream of LPT2, while the PD tries to eliminate the problem, customers downstream LP2 are not affected by the fault. The battery bank powers clients downstream LP2 during the time while the PD is connecting and disconnecting, typically between two to three minutes.

Instead of having one battery bank, two or more battery banks can be considered. Each battery bank will be sized to supply energy to the downstream clients till another load point with a battery bank or end of the line is reached as can be seen by Fig. 3. In this example if an outage occurs upstream of LP2, the switching device associated with battery system 2 isolates the area downstream. While the PD attempts to eliminate the fault, clients in LP2 and