Optimal Distribution Protection Design Considering Momentary and Sustained Reliability Indices

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Abstract—**Today momentary interruptions are an important customer issue and most distribution engineers consider them a reliability issue. This paper considers reliability as all aspects of customer interruptions, including momentary interruptions. A methodology for multiobjective optimization is proposed to minimize SAIFI, SAIDI and $MAIFI_E$ indices simultaneously. This goal is achieved considering both the optimized allocation of protective devices and switches, and the definition of the protection scheme to be employed in the reclosers and substation breaker, fuse saving or fuse blowing. The constraints considered include technical and economic limitations. In the search for the better solutions is employed the Nondominated Sorting Genetic Algorithm - II. The methodology was tested in a real distribution system with 51 buses, and the results compared with the current configuration of the protection system.**

Keywords-Power distribution systems; reliability; protective devices; switches; multiobjective optimization; genetic algorithms.

I. INTRODUCTION

Reliability of distribution systems is a continuous concern for electric utilities and is usually evaluated and regulated by utility boards and similar commissions. The reliability indices most commonly used to quantify the quality of the utilities' services are related to sustained interruptions: System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) [1]. Today, the increasing sensitivity of customer loads to brief disturbances has forced the utilities to consider momentary interruptions that occur on their systems. This has resulted in renewed interest in momentary reliability indices such as Momentary Average Interruption Frequency Index (MAIFI) and Momentary Average Interruption Event Frequency Index ($MAIFI_E$).

The optimal placement of switches and protective devices in distribution networks allows better operation and improvement on the system reliability indices [2]. However, it is a combinatorial constrained problem, difficult to solve by traditional linear or nonlinear programming methods due its nonlinear, discontinuous and nondifferentiable characteristics [3]. The genetic algorithm and simulated annealing were proposed in [4] and [5] respectively, to find the optimal solutions to the problem of optimized placement of switches in distribution systems. A procedure based on Bellmann's optimality principle was presented in [6], to minimize the outage costs and the investment costs on automatic sectionalizing switching devices. In [3, 7] the authors demonstrated the application of ant colony system and evolutionary algorithm in the optimal switch relocation problem, to minimize the customer interruption costs.

Regarding the optimal placement of protective devices, in [8] was presented a nonlinear binary programming (NLBP) model with the objective of minimize the reliability index SAIFI. To simplify the objective function, the methodology considered a heuristic division of distribution feeder in one main feeder and lateral branches, which are classified in one of three categories. A shortcoming of this model is that it does not take into account the interrelated effects of failures between the main feeder and the laterals, which can lead to suboptimal solutions. Based in this model, in [9] was presented a technique that initially considered the establishment of numerical goals for both SAIFI and ASIFI (Average System Interruption Frequency Index) indices, by solving two independents optimization problems. The results were considered as constraints in the goal programming method, in order to find the trade-off between the SAIFI and ASIFI indices. From the solution obtained, was selected the reclosers where a fuse saving scheme should be applied, based on the trade-offs between decreases in the SAIFI index and increases in the MAIFI index. Based in [8], [10] and [11] proposed a NLBP model in order to minimize SAIFI, and SAIFI or SAIDI indices, respectively. However, in [10] was considered the interrelated effects of failures between the main line and the laterals, and [11] depart from the established feeder division of [8].

Also based in [8], but considering the optimized allocation of protective devices and switches, in [12] and [13] were proposed a NLBP model to minimize the total cost of reliability. Reactive tabu search was applied in [2], to solve this problem. The candidate points to the allocation of protection devices and switches were selected based on heuristic rules of engineering operation and planning. Models [12], [13] and [2] employed the same form of feeder division of [8]. Finally, in [14] was presented a multiobjective optimization methodology to determine the locations of protective devices and switches resulting in the simultaneous minimization of SAIFI, SAIDI and reliability costs. To find a set of good solutions in the Pareto front, the multiobjective ant colony system was employed.

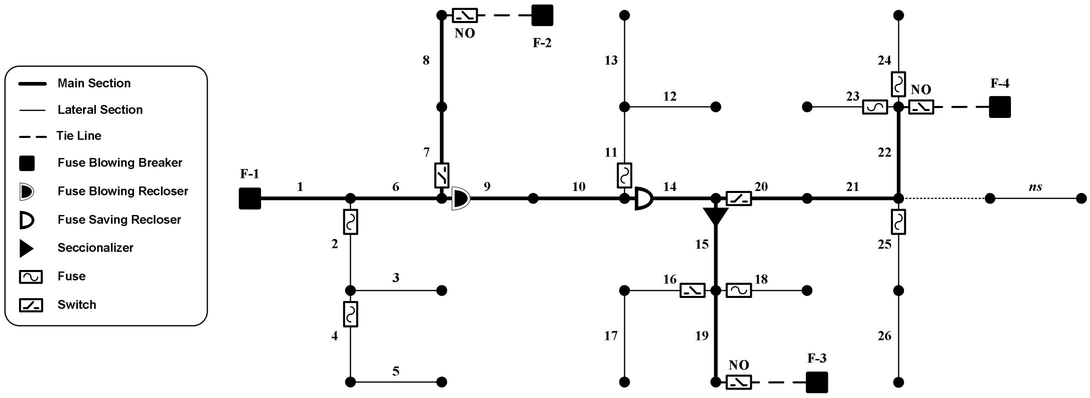

Figure 1. Topology representation of the radial distribution feeder.

In this paper, distribution reliability is considered as all aspects of customer interruptions, including momentary interruptions. A methodology for multiobjective optimization is proposed in order to minimize SAIFI, SAIDI and $MAIFI_E$ indices simultaneously. This goal is achieved considering both the optimized allocation of protective devices and switches, and the definition of the protection scheme to be employed in the reclosers and substation breaker, fuse saving or fuse blowing. These reclosing schemes have a substantial impact on customer reliability, and utilities should consider them in the design of the feeder protection system [15, 16]. The constraints aggregated to the problem include technical and economic limitations. In the search for the better solutions is employed the *Nondominated Sorting Genetic Algorithm* (NSGA – II) [17], which represents one of the state-of-the-art algorithms in multiobjective optimization. Hill climbing local search is performed on all members of the final Pareto-set to ensure global optimality. The methodology was tested in a real distribution system with 51 buses, and the results compared with the current configuration of the protection system.

II. Problem Formulation

A. Pareto Optimality Concepts

A general multiobjective optimization problem can be described as a vector function **f** that maps a tuple of *m* parameters (decision variables) to a tuple of *n* objectives. Formally:

$$\begin{aligned} &min\ \mathbf{f}(\mathbf{x}) = \left[f_1(\mathbf{x})\ \ f_2(\mathbf{x})\ \ \dots\ \ f_n(\mathbf{x}) \right]^T \\ &\mathbf{x} = \left[x_1\ \ x_2\ \ \dots\ \ x_m \right]^T \in X \end{aligned} \tag{1}$$

where **x** is called the decision vector and X is the parameter space. The problem usually has no unique solution, but a set of nondominated solutions. When a minimization problem and two solution vectors **x**, **y** $\in X$ are considered, **x** is said to dominate **y**, as denoted $\mathbf{y} \prec \mathbf{x}$, if:

$$\begin{aligned} &\forall i \in \{1,2,\dots,n\}: f_i(\mathbf{x}) \le f_i(\mathbf{y}) \wedge \\ &\exists j \in \{1,2,\dots,n\}: f_j(\mathbf{x}) < f_j(\mathbf{y}) \end{aligned} \tag{2}$$

All decision vectors which are not dominated by any other decision vector of a given set are called nondominated regarding this set. The solution set of a multiobjective optimization problem consists of the decision vectors that are nondominated within the entire search space, denoted as Pareto-optimal set or Pareto-optimal front.

B. Distribution Feeder Model

Figure 1 illustrates the one-line diagram of the overhead radial distribution feeder (F-1), consisting of a main feeder and lateral branches. The feeder has interconnection points (tie points) with adjacent feeders (F-2, F-3 and F-4), characterized by the existence of normally open (NO) tie switches, through which can be supplied all or part of the load feeder F-1. The feeder can be represented as a graph, where nodes represent derivation, interconnection or load points. Since each edge has a unique end node, the system can be represented in terms of edges, or sections of the feeder arbitrarily numbered.

Tie points are identified by the set TP, containing the identification of the feeder sections ending in a tie point. In the case of Figure 1: TP = {8, 19, 22}. Each tie point has associated a transfer capacity TC(TP), defined as the maximum load [kVA] that can be supplied through the tie point, without violation of system operating constraints, such as exceeding equipment emergency ratings, or maximum allowable voltage drop.

C. Faults and Interruptions

The faults that occur in distribution systems can be classified as *temporary* or *permanent*. A temporary fault will clear if deenergized and then re-energized, and a permanent fault will persist until repaired by human intervention [18]. An interruption is the loss of service (power supply) to one or more customers, and is classified as *momentary* or *sustained*. Despite the use of the term *momentary interruption*, in this work will be considered the concept of *momentary interruption event*. A momentary interruption event is one or more interruptions of total duration limited to the time period of 5 minutes. A sustained interruption is any interruption not classified as a part of a momentary event [1].

D. Protective devices and switches

The relations between faults and interruptions are determined according to the type of protective device that acts to clear the fault. These relations are described below, as well as the most relevant characteristics of protection devices and switches shown in Figure 1, considered in the formulation of the proposed problem.

A feeder *circuit breaker*, phase, ground and automatic reclosing relays are the devices installed at the substation. In this work, these devices will be represented as a recloser allocated in the first section of the feeder. Therefore, the characteristics of reclosers described below are equally applicable.

The *recloser* has switching and protective functions. It has automatic reclosing capability, enabling the device to clear temporary faults that occur in its protection zone. The recloser can be operated under the *fuse saving* or *fuse blowing* protection scheme. Fuse saving (also referred to as *feeder selective relaying*) is usually implemented with the fast curve on a recloser (or the instantaneous relay on a breaker), so that the recloser (or breaker) operates before the downstream lateral fuses for faults in the laterals. For a temporary fault in a lateral, all customers downstream the recloser experience a momentary interruption. If the fault is permanent, customers downstream the recloser experience a momentary interruption and customers downstream the fuse experience a sustained interruption. In the fuse blowing (or fuse clearing) scheme, the fast curve of recloser (or the breaker instantaneous relay) is blocked. The fuse operates for both temporary and permanent faults, with the customers downstream the fuse experiencing a sustained interruption, and the rest of the feeder is prevented from experiencing an interruption. In this paper, we use the terminology *fuse saving recloser* and *fuse blowing recloser*, in references to the breaker and reclosers operating under the fuse save and fuse blowing protection schemes, respectively.

The *sectionalizer* has switching and protective functions, and is designed to isolate automatically a feeder section under permanent fault. Customers experience interruptions equivalent to a fuse saving scheme. The sectionalizer does not have fault interruption or automatic reclosing capability, so must be installed within the protection zone of recloser or breaker.

The *fuse* has only a protection function and do not present switching capability. If installed in the protection zone of fuse saving recloser fuse acts only to clear permanent faults otherwise, acts to clear both temporary and permanent faults.

The *switch* has no protective function, and is used to restore the upstream and downstream sections of the faulted section. The feeder reconfiguration reduces the duration of interruptions to restored customers, by isolating only the faulted section.

In order to identify the sections of the feeder where the fuse saving reclosers, fuse blowing reclosers, sectionalizers, fuses and switches are located, are defined the sets R_S, R_B, S, F and D, respectively. For example, for the feeder of Figure 1: $R_S = \{14\}$, $R_B = \{1, 9\}$, S = {15}, F = {2, 4, 11, 18, 23, 24, 25} and D = {7, 16, 20}.

E. Objective Function

Given a set of possible locations on distribution feeder and sets of various protective devices and switches, the proposed multiobjective optimization problem is to define a subset of the locations at which to install a specific device. At the same time, the protection scheme to be employed in reclosers is defined considering two independent models of reclosers' faults response. The specific objective of the procedure is the simultaneous minimization of the objective functions defined by the reliability indices SAIFI, ASIDI and $MAIFI_E$, formally defined in [1].

The mathematical formulation of objective functions is based on the application of two operators, defined below. Let $p(i)$ be the immediate predecessor of edge i on the graph that represents the distribution feeder. The operator $P(i, j)$ is defined by

$$P(i,j)=\left\{ i,\, p(i),\, p\big(p(i)\big),\, p\Big(p\big(p(i)\big)\Big),\ldots, j \right\} \tag{3}$$

i.e., $P(i, j)$ defines the set formed by the feeder sections that precede i (upstream of i) to j. Let $s(i)$ be the immediate successor of edge i on the graph that represents the distribution feeder. The operator $S(i, j)$ is defined by

$$S(i,j)=\left\{ i,\, s(i),\, s\big(s(i)\big),\, s\Big(s\big(s(i)\big)\Big),\ldots, j \right\} \tag{4}$$

i.e., $S(i, j)$ defines the set formed by the feeder sections that succeed i (downstream of i) to j. The operator $S(i)$ (with only one input argument) denotes all succeeding sections of i. For example, considering the Figure (1): $P(13,6)$ = {6, 9, 10, 11, 13}, $P(24, D)$ = {20, 21, 22, 24}, $S(14, D)$ = {14, 15, 18, 19} and $S(15)$ = {15, 16, 17, 18, 19}. Note that $P(24, D)$ returns the sections upstream of section 24 until a element of set D is reached.

Based on these definitions, the mathematical model of the objective function defined by the indicator SAIFI can be established by the following equation:

$$SAIFI = \frac{1}{N_T}\left[\sum_{i=1}^{ns}(\lambda_i + \gamma'_i)\,\ell_i \sum_{j\in\Omega_i} N_j\right] \tag{5}$$

where N_T is the total number of customers on the feeder, ns is the number of feeder sections, ℓ_i is the length of section i [km], λ_i and γ_i' are the permanent and temporary failure rates of section i [failures/km.year], N_j is the number of customers of section j and Ω_i is set formed by the feeder sections subject to sustained interruption due to failures in section i, according to the expression (6).

$$\Omega_i = S\big(P(i, R_S \cup R_B \cup S \cup F) \cap (R_S \cup R_B \cup S \cup F)\big) \tag{6}$$

From the characteristics of protective devices in Section II-D, the temporary failure rate (γ_i') in (5) can be determined by (7):

$$\gamma_i' = \begin{cases} 0, & \text{if} \quad P(i,R_S) \cap R_S \neq \varnothing \\ & \text{or} \quad P(i,R_S \cup R_B \cup F) \cap R_B \neq \varnothing \\ \gamma_i, & \text{otherwise.} \end{cases} \quad (7)$$

The mathematical model of the objective function defined by the indicator ASIDI is established by (8):

$$SAIDI = \frac{1}{N_T} \sum_{i=1}^{ns} \ell_i \left(\lambda_i + \gamma'_i\right) \left(\sum_{j \in \Omega^s_i} N_j r_s + \sum_{j \in \Omega^r_i} N_j r_r \right) \quad (8)$$

where r_s is the mean time to switch, and represents the expected time it will take for a crew to isolate the faulted section and conclude the upstream and downstream restoration, and r_r is the mean time to repair, and represents the expected time it will take for a failure to be repaired [18]. Ω^s_i and Ω^r_i denote the sets formed by the feeder sections subjected to interruption with duration equal to r_s and r_r respectively, due a fault in section i. These sets are determined by the expressions (9) and (10). The first term that defines the set Ω^s_i corresponds to the case where a protective device is allocated immediately upstream of section i. In this case, $S(k)$ defines the sections to be restored downstream of i, where k is the section where a switching device (recloser, sectionalizer or switch) is allocated. This sections can be restored if downstream of k there are one or more tie points with sufficient transfer capacity to supply the load to be restored. The second term of Ω^s_i corresponds the case where a switch is allocated immediately upstream of section i. Thus, in addition to downstream restoration $S(k)$, can be restored the sections between the protective device that clear the fault and the switch, in the so-called upstream restoration. The set Ω^r_i defined in (10) is formed by all the sections downstream of the protective device or switch located upstream the faulted section i, excluding the sections belonging the set Ω^s_i.

The mathematical model of the objective function defined by the indicator $MAIFI_E$ is established by (11):

$$MAIFI_E = \frac{1}{N_T} \sum_{i=1}^{ns} \ell_i \left(\lambda_i \sum_{j \in \Omega^\lambda_i} N_j + \gamma_i \sum_{j \in \Omega^\gamma_i} N_j \right) \quad (11)$$

where Ω^λ_i e Ω^γ_i denote the sets formed by the feeder sections subjected to temporary interruption due permanent and temporary faults in the section i, respectively. The set Ω^λ_i is defined by the expression (12), where the first term models the fault clearing attempts by the fuse saving reclosers. Note that if $k \in R_S$ and $r \in R_S$, $S(k) - S(r) = \emptyset$, because permanent faults in the primary protection zone of reclosers causes its lockout, and a sustained interruption. If $k \in R_S$ and $r \in R_B$ is considered that, after the reclosing operations (in the fast curve) performed by recloser in the section k, the coordination between reclosers in sections k and r will allow the operation (in time-delayed curve) and lockout of recloser in section r, clearing the permanent fault. The second term of (12) is related with the incidence of permanent fault downstream the sectionalizer, and the last term with a fault downstream a fuse, when the upstream device is a fuse blowing recloser. The set Ω^γ_i is defined by the expression (13), where the first and second terms corresponds to the temporary fault clearing by the fuse saving and fuse blowing reclosers, respectively. Third term is related to temporary fault clearing by fuses, not being generated temporary interruption, but a sustained interruption.

F. *Constraints*

The constraints incorporated to the reliability optimization problem are of technical and economic nature. The constraint of economic nature reflects the installation and operation costs of protective devices and switches, considered by limiting the maximum number of each type of device available for allocation in the feeder. Maintaining the solutions feasibility

$$\Omega^s_i = \begin{cases} S(k), & \text{if} \quad P(i,\mathrm{R_S} \cup \mathrm{R_B} \cup \mathrm{S} \cup \mathrm{F} \cup \mathrm{D}) \cap (\mathrm{R_S} \cup \mathrm{R_B} \cup \mathrm{S} \cup \mathrm{F} \cup \mathrm{D}) \in (\mathrm{R_S} \cup \mathrm{R_B} \cup \mathrm{S} \cup \mathrm{F}) \\ S(k) \cup S\big(P(i,\mathrm{R_S} \cup \mathrm{R_B} \cup \mathrm{S} \cup \mathrm{F}) \cap (\mathrm{R_S} \cup \mathrm{R_B} \cup \mathrm{S} \cup \mathrm{F}),\, P(i,\mathrm{D}) \cap \mathrm{D}\big), & \text{otherwise.} \end{cases} \quad (9)$$

where $k = S(i,\mathrm{R_S} \cup \mathrm{R_B} \cup \mathrm{S} \cup \mathrm{D}) \cap (\mathrm{R_S} \cup \mathrm{R_B} \cup \mathrm{S} \cup \mathrm{D}):\ max\big(\mathrm{TC}(S(k) \cap \mathrm{TP})\big) \geq \sum_{j \in S(k)} L_j$

$$\Omega^r_i = S\big(P(i,\mathrm{R_S} \cup \mathrm{R_B} \cup \mathrm{S} \cup \mathrm{F} \cup \mathrm{D}) \cap (\mathrm{R_S} \cup \mathrm{R_B} \cup \mathrm{S} \cup \mathrm{F} \cup \mathrm{D})\big) - \Omega^s_i \quad (10)$$

$$\Omega^\lambda_i = \begin{cases} S(k) - S(r), & \text{if } k \in \mathrm{R_S} \text{ and } r \in (\mathrm{R_S} \cup \mathrm{R_B} \cup \mathrm{S} \cup \mathrm{F}) \\ S(q) - S(r), & \text{if } k = \varnothing \text{ and } q \in \mathrm{R_B} \text{ and } r \in (\mathrm{R_B} \cup \mathrm{S}) \\ \varnothing, & \text{if } k = \varnothing \text{ and } q \in \mathrm{R_B} \text{ and } r \in \mathrm{F} \end{cases} \quad (12)$$

where $k = P(i,\mathrm{R_S}) \cap \mathrm{R_S}$, $q = P(i,\mathrm{R_B}) \cap \mathrm{R_B}$ and $r = P(i,\mathrm{R_S} \cup \mathrm{R_B} \cup \mathrm{S} \cup \mathrm{F}) \cap (\mathrm{R_S} \cup \mathrm{R_B} \cup \mathrm{S} \cup \mathrm{F})$

$$\Omega^\gamma_i = \begin{cases} S(k), & \text{if } k \in R_S \\ S(q), & \text{if } k = \varnothing \text{ and } q \in R_B \\ \varnothing, & \text{if } k = \varnothing \text{ and } q \in F \end{cases} \quad (13)$$

where $k = P(i,R_S) \cap R_S$ and $q = P(i,R_B \cup F) \cap (R_B \cup F)$

regarding this constraint is an inherent characteristic of the genetic algorithm encoding method, as described in Section III. Technical constraints are related to the topology of the system, and coordination of the protective devices. As regards the former, the circuit breaker (represented by a recloser) must be allocated in the first section, and fuses cannot be allocated in the main circuit of the feeder. The solutions feasibility regarding these constraints is maintained by the genetic operators employed in the Genetic Algorithm. The coordination of protective devices is considered by limiting the maximum of reclosers in series in 3. The number of fuses in series is also limited to 3, and these devices cannot be allocated upstream of a recloser. Such constraints are evaluated by the following equation:

$$c = \sum_{k \in \{R_S \cup R_B\}} max\left(0, \left|P(k) \cap (R_S \cup R_B)\right| - 3\right) + \sum_{k \in F} max\left(0, \left|P(k) \cap F\right| - 3\right) + \sum_{k \in \{R_S \cup R_B\}} \left|P(k) \cap F\right| \quad (14)$$

where the vertical bars denote the cardinality (number of elements) of the sets, hence $c \in \mathbb{N}$.

III. Genetic Algorithm-Based solution Technique

The nonlinear, discontinuous and nondifferentiable characteristics of the objective functions (5), (8) and (11) makes difficult the application of traditional linear and nonlinear programming methods to solve the proposed multiobjective problem. Moreover, the fact that they are conflicting objectives also creates difficulties with regard to the application of classical techniques of objectives aggregation for solving multicriterial problems (that alone have already some drawbacks), such as objective weighting, distance functions, Min-Max formulation and Lexicographic approach [19].

By maintaining a population of solutions, genetic algorithms (GAs) can search for many Pareto-optimal solutions in parallel. This characteristic makes GAs very attractive for solving MO problems. The Pareto-based GAs, attempts to promote the generation of multiple nondominated solutions, directly making use of the Pareto-optimality concept (2). Among these, the *Nondominated Sorting Genetic Algorithm* (NSGA – II) [17] (which represents one of the state-of-the-art algorithms in multiobjective optimization) was selected as a search mechanism of the optimal solutions to the proposed problem. The main features of the version of NSGA-II dedicated to solving the problem of allocation of protection devices and switches are described below. Further details about the implementation of the algorithm are presented in [17]. Details about the general terminology, biological inspiration and conception philosophy of the GA are presented in [20].

The application of GA in solving a specific problem depends initially on defining the genetic representation of potential solutions to the problem. Let $\mathbf{x}_i$ the *i*-th individual (chromosome) belonging to the population $\mathbf{P}_g$ in generation *g*. The individual $\mathbf{x}_i$ is composed by the sets R_S, R_B, S, F and D, concatenated in this order in a row vector form (15):

$$\mathbf{x}_i = \left[R_S \mid R_B \mid S \mid F \mid D \right] \qquad (15)$$
$$\forall \mathbf{x}_i \in \mathbf{P}_g, \quad i = 1 \ldots ni.$$

where *ni* is the population size of individuals at generation *g*.

NSAG-II uses two key concepts, nondominated ranking and crowding-distance. The former consists in the classification of every chromosome in the population in several fronts, by assigning a rank (*r*) to each solution. The first front is composed of the nondominated solutions (*r*=1). Chromosomes belonging to the second front (*r*=2) are solutions which are only dominated by at least one solution in the first front. Those belonging to the third front (*r*=3) are solutions only dominated by solutions in the first front and at least one of the second, and so on. Crowding-distance (*d*) is a value also assigned to each solution, which estimate the density of solutions surrounding the solution. It is the average side length of the cuboid formed by using the nearest neighbors as the vertices. Based on these concepts, NSGA-II defines the crowded-comparison operator ($\prec_n$) that is slightly modified to handle the constraints (14). This operator guides the selection process in two stages of the algorithm toward a uniformly spread-out Pareto-optimal front, and is defined as (16), where $\mathbf{x}_i$ and $\mathbf{x}_j$ are two solutions.

$$\mathbf{x}_j \prec_n \mathbf{x}_i \Rightarrow \left(c_i < c_j\right) \vee \left(\left(c_i = c_j\right) \wedge \left(r_i < r_j\right)\right) \vee \left(\left(c_i = c_j\right) \wedge \left(r_i = r_j\right) \wedge \left(d_i > d_j\right)\right) \qquad (16)$$

That is, $\mathbf{x}_i$ is said constrained-dominate the solution $\mathbf{x}_j$ if: 1) $\mathbf{x}_i$ is feasible and $\mathbf{x}_j$ is not or $\mathbf{x}_i$ has a smaller constraint violation, 2) both solutions are feasible or violate the same number of constraints, and $\mathbf{x}_i$ has lower (better) rank, or 3) both solutions are feasible or violate the same number of constraints, both solution belong to the same front (equal ranks) and $\mathbf{x}_i$ is located in a lesser crowded region than $\mathbf{x}_j$.

The search process performed by the NSGA-II, local search and decision making phases follow the procedures listed in the Figure 2, which are described below.

1) Generation of initial population ($\mathbf{P}_g$)*, evaluation of fitness* (**f**) *and constraints* (**c**)*:* the initial population is formed by *ni* individuals randomly generated. To each individual is associated a vector function **f**, with the individual fitness evaluated accordingly the objective functions (5), (8) and (11). The evaluation of the constraints (14) originates the vector $\mathbf{c} = [\, c_i \,]$, $i = 1 \ldots ni$.

2) Nondomination rank (**r**) *and crowding-distance* (**d**) *assignment:* population is sorted based on nondomination by assigning to each individual a rank equal to its nondomination level (1 is the best level, 2 the next best level, and so on). In the crowding-distance assignment, the boundary solutions (solutions with smallest and largest function values) are assigned an infinite distance value. All other intermediate solutions are assigned a distance value equal to the absolute normalized normalized difference in the function values of two adjacent solutions. solutions. The evaluation of these

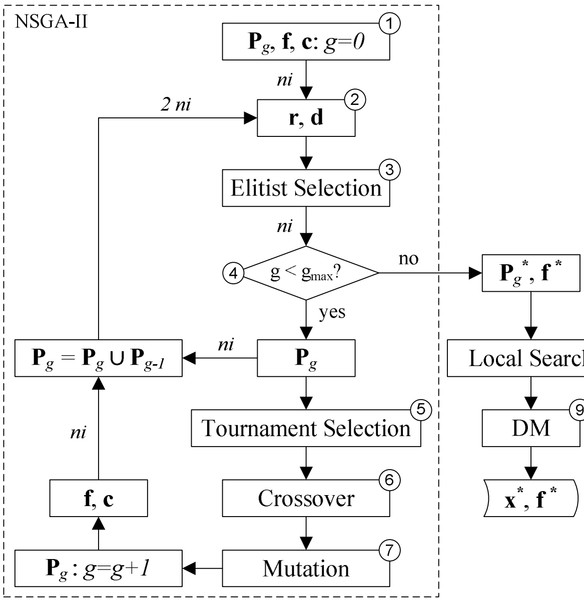

Figure 2. Search procedures performed by the NSGA-II, local search and decision making phases.

parameters originates the vectors $\mathbf{r} = [\ r_i\ ]$, and $\mathbf{d} = [\ d_i\ ]$, $i = 1...ni$.

3) Elitist selection: a crowded-comparison operator-based procedure is employed to reduce to *ni* the number of individuals in the population, which at this stage is equal to 2*ni* for *g*>0. Since all previous and current population members are included in the population, elitism is ensured.

4) Stopping criterion: consists in the maximum number of generations (g_{max}). When this criterion is reached, the Pareto-optimal set ($\mathbf{P}_g^*$) and its objective vectors ($\mathbf{f}^*$) are returned.

5) Tournament selection: the binary tournament selection based on the crowded-comparison operator is used to select *ni* individuals.

6) Crossover: was used the single-point crossover method.

7) Mutation: was implemented a mutation method that acts in two steps. The first consists in the *random resetting method*, which the allele of the mutant gene (selected with probability equal to the mutation rate) is replaced by a randomly selected value from a set of feasible values. The second step consists in the elimination of repeated alleles on chromosome. When this situation is detected the random resetting method is applied to the duplicated alleles, chosen randomly.

8) Local search: Hill climbing local search is performed on all members of the final Pareto-set to ensure global optimality. At each step of the search a solution component is replaced by a feasible value of the search space (feeder section), and the solution is evaluated. If the new solution dominates the old, the new solution is kept. The process is repeated until all components of the solutions are replaced by all the feasible values associated with these. The feasible values include sections of the feeder not occupied by other devices, where a given device can be allocated without constraint violations.

9) Decision-making (DM) phase: consists in selecting the most appropriate solution of the Pareto-optimal front. After analyzing the set of nondominated solutions, a planner can select the final nondominated solution, considering the most satisfactory values of the three objectives and according to his/her experience and professional point of view. For demonstration purposes, in this paper a max-min approach [14] is used to select the best (final) multiobjective problem solution ($\mathbf{x}^*$). The method is defined by Equation (17).

$$\mathbf{x}_i^* \in \mathbf{P}_g^*:$$
$$max\left[\min_i\left(\frac{f_1^{max} - f_1^i}{f_1^{max} - f_1^{min}}, \frac{f_2^{max} - f_2^i}{f_2^{max} - f_2^{min}}, \frac{f_3^{max} - f_3^i}{f_3^{max} - f_3^{min}}\right)\right] \quad (17)$$
$$\forall i = 1...np$$

where f_k^{max} and f_k^{min}, k=1, 2, 3 are the "removal" values of the maximum and minimum values obtained for the objective functions SAIFI, SAIDI and $MAIFI_E$ respectively, and *np* is the number of Pareto-optimal solutions.

IV. Test Case

To illustrate the application and evaluate the performance of the optimization algorithm was used the distribution feeder presented in [14], shown in Figure 3. In the figure is shown the original locations of protection devices and switches, and is considered that the circuit breaker and reclosers operate under the fuse blowing protection scheme. The feeder is formed by 51 sections (ns = 51) and has four interconnection points with neighboring feeders, which individual transfer capacities considered sufficient to supply the entire load of the feeder F-1. Permanent and temporary failure rates considered are λ = 0,17 e γ = 0,25 failures/km.year. The mean time to switch (r_s) is 0.5 hours, and the mean time to repair (r_r) is 2 hours. Length (ℓ) and the number of customers of each section are listed in the Appendix.

The selected parameters values of the NSGA-II are: population size ni=2ns=102 individuals, g_{max}=100 generations, crossover rate 0,85 and mutation rate 0,01.

The tests were performed considering the following cases:

- Case 1: relocation of the existing 2 reclosers, 18 fuses and 7 switches in the feeder.
- Case 2: aggregation of two sectionalizers to case 1.
- Case 3: aggregation of one recloser to case 2.

The base case – which corresponds to the original locations of protection devices and switches in the feeder – and the solutions obtained for each case are shown in Table 1, where SAIFI is in interruptions per customer per year, SAIDI in hours per customer per year, and $MAIFI_E$ in momentary interruptions events per customer per year.

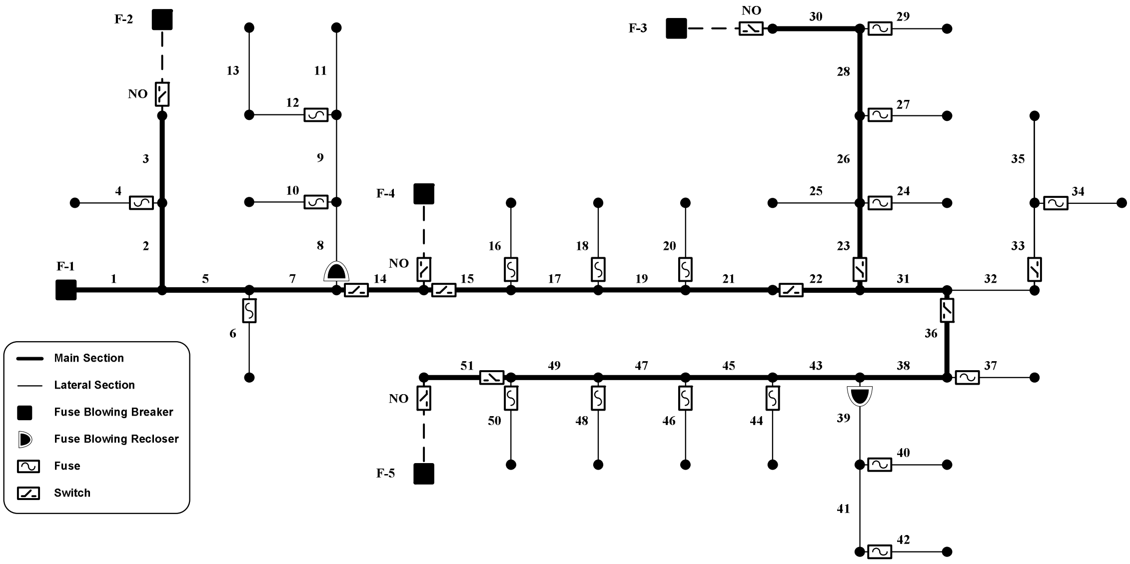

Figure 3. Distribution feeder used in the tests (22 kV, overhead three-wire).

The results obtained in case 1 demonstrate the possible reduction of 44,70%, 44,13% and 23,69% in the SAIFI, SAIDI and $MAIFI_E$ indices in relation to the base case, respectively. These results can be achieved by considering only the relocation of 2 reclosers, 5 fuses and 6 of the existing switches on the feeder. And furthermore, changing the protection scheme used on reclosers. With the aggregation of two sectionalizers in case 2 the indices SAIFI and SAIDI were reduced in 52,19% and 50,25% respectively, in relation to the base case. Sectionalizers have no effect on the $MAIFI_E$ index, which show a reduction of 6,25%.

Case 4 resulted in similar results to the case 3, with reclosers, sectionalizers and switches allocated in the main circuit of the feeder, and fuses at the beginning of lateral branches. SAIFI, SAIDI and $MAIFI_E$ shown reductions of 53,73%, 51,96% and 23,52% respectively, in relation to their original values. In cases 1-3 was determined the operation of circuit breaker under the fuse blowing scheme, preventing that all feeder customers experience momentary interruptions due the occurrence of temporary faults in the feeder. Fuse saving scheme was selected in reclosers at sections 31 and 38 (approximately in the half of the feeder), establishing a balance between the sustained interruptions indices (SAIFI and SAIDI) and the momentary interruption index $MAIFI_E$.

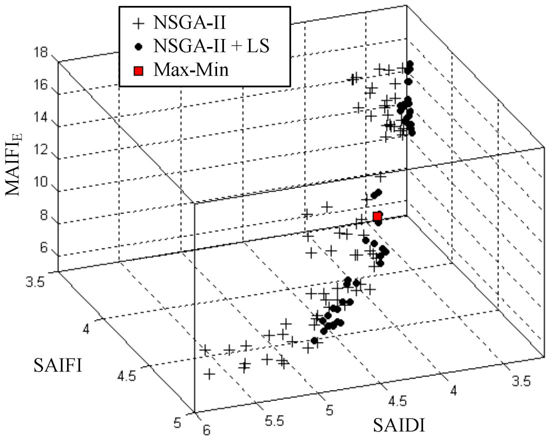

Figure 4. Pareto-optimal fronts solutions obtained by NSGA-II, NSGA-II + local search and solution selected by max-min operator in case 3.

Figure 4 shows the Pareto-optimal solutions obtained by NSGA-II, NSGA-II and local search and the selected solution by the max-min operator (17), in case 3. The application of local search reduced the number of nondominated solutions in Pareto-optimal front from 72 to 51 solutions.

TABLE I. BASE CASE AND SOLUTIONS OBTAINED IN THE OPTIMIZATION PROCESSES.

Case	R_S	R_B	S	F	D	SAIFI	SAIDI	$MAIFI_E$
Base	–	1, 8, 39	–	4, 6, 10, 12, 16, 18, 20, 24, 27, 29, 34, 37, 40, 42, 44, 46, 48, 50	14, 15, 22, 23, 33, 36, 51	8.9220	8.0653	12.4674
1	23, 38	1	–	4, 6, 8, 11, 12, 16, 18, 20, 24, 32, 33, 37, 40, 41, 44, 46, 48, 50	5, 14, 19, 28, 31, 43, 45	4.9339	4.5055	9.5142
2	31	1, 23	26, 43	4, 6, 8, 10, 11, 12, 16, 18, 20, 24, 25, 32, 37, 39, 41, 44, 48, 50	5, 14, 19, 30, 38, 45, 49	4.2653	4.0125	11.6878
3	31, 43	1, 23	2, 26	6, 8, 11, 12, 16, 18, 20, 24, 27, 29, 32, 37, 40, 41, 44, 46, 48, 50	7, 14, 19, 30, 38, 45, 49	4.1279	3.8744	9.5355

V. CONCLUSION

This paper has presented a multiobjective optimization technique to minimize SAIFI, SAIDI and $MAIFI_E$ distribution reliability indices simultaneously. This goal was achieved through the optimized allocation of protective devices and switches, together with the definition of the protection scheme to be employed in the reclosers and substation breaker, fuse saving or fuse blowing. The best solutions search process was done by the Nondominated Sorting Genetic Algorithm (NSGA – II), and a local search procedure performed on all members of the final Pareto-set to ensure global optimality. The performance of the optimization algorithm was tested in a 51 buses distribution feeder. The results showed that the algorithm is able to find a set of feasible and good quality Pareto-optimal solutions. The solutions showed that substantial improvements can be obtained in the reliability indices when a systematic procedure is employed to select and allocate the protection devices and switches along the distribution feeder.

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APPENDIX

TABLE II. LENGTH (ℓ) AND NUMBER OF CUSTOMERS (N) OF EACH SECTION OF THE TEST FEEDER.

Section	ℓ (km)	N	Section	ℓ (km)	N	Section	ℓ (km)	N	Section	ℓ (km)	N
1	3.4	0	14	0.3	0	27	0.9	110	40	3.0	450
2	0.5	0	15	2.9	150	28	4.2	590	41	2.7	150
3	0.1	0	16	3.0	50	29	0.7	90	42	3.0	110
4	0.4	150	17	1.7	60	30	2.3	170	43	9.3	60
5	0.5	0	18	1.3	310	31	2.8	480	44	3.5	150
6	1.0	220	19	2.0	340	32	1.5	2400	45	1.2	50
7	1.0	0	20	1.4	30	33	1.3	210	46	2.0	140
8	3.0	1250	21	1.0	2130	34	0.6	50	47	0.9	36
9	0.5	90	22	0.4	250	35	0.5	100	48	1.3	60
10	0.3	90	23	2.3	780	36	0.1	0	49	1.3	30
11	1.2	445	24	4.0	610	37	2.5	100	50	5.0	160
12	1.0	720	25	0.7	80	38	3.2	480	51	2.0	1350
13	1.0	30	26	1.5	60	39	0.8	500			