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RESEARCH ARTICLE

Optimal Location of Reclosers in Electrical Distribution Systems Considering Multicriteria Decision Through the Generation of Scenarios Using the Montecarlo Method

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ABSTRACT This work presents a novel methodology for the optimal location of reclosers in electric distribution systems. The proposal uses a multicriteria analysis to evaluate the reliability indicators for this level 3 (distribution) by generating scenarios from pseudo-random variables. The reliability indicators considered in the study are the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), and Average Energy Not Supplied (AENS). It is employed a deterministic random generation in a defined range associated with each analysis variable (failure rate by elements and loads, failure duration, number of customers per load point, mean power consumed at each load point, etc.) The reliability indicators (criteria) are calculated for every possible location of a recloser in the candidate primary sections, thus obtaining the decision matrix, normalized and weighted by the CRITIC method to find the optimal location according to a minimum criterion. This analysis is repeated N times through the generation of scenarios using the Montecarlo method, establishing the probability of occurrence of each winning alternative and choosing the final optimal location of the first recloser within the distribution system. The methodology also proposes the switching coordination repeating the previously described analysis for locating a second recloser considering that the first was already a winning alternative within the generation of "many" scenarios. The scope of the proposed methodology is the number of reclosers that it is desired to analyze considering cost constraints and is general for any distribution system. The analysis is carried out with comprehensive programming in the Matlab software environment. The results successfully respond to the maneuver and switching tests with the joint criterion of minimizing all reliability indicators for level 3 (distribution). With this proposal, knowledge gaps in reliability studies are solved. The absence of data is completed with generations of pseudo-random variables, and the optimal location of the reclosers responds to all reliability criteria in distribution with weighting alternatives. The novel proposed methodology is validated with an exhaustive search analysis where all possible single or multiple reconnection scenarios are analyzed. The winning location alternative found coincides with the one determined by the proposed methodology in more than 90% of the generated random scenarios.

INDEX TERMS Distribution electric systems, Montecarlo, multicriteria analysis, optimal location, reclosers, reliability, switching coordination.

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I. INTRODUCTION

Electric distribution systems are extensive and complex, they have many loads, and many external factors may have an incidence on these systems; hence these are the electric systems more susceptible to electric failures of multiple causes, which are primarily associated with lack of maintenance, aging of electric networks, the vulnerability of the system in the face of the environment, lack of frequent pruning, insufficient human and material resources, lack of isolator cleaning, animals, electric storms, defective managing equipment, accidents, overloads, and fortuitous causes. In the occurrence of an electric failure, the consumer of the electric energy is affected in two ways due to the frequency of electric service interruptions and the duration of such interruptions [1]. Therefore, electricity distribution companies aim to reduce the frequency and duration of failures in distribution systems. This presupposes substantial investments such companies should make to guarantee the energy reaches the final user with desired reliability indicators. Such reliability indicators for the level 3 (distribution level) in electric power systems are known as the System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), and Average Energy Not Supplied (AENS) [2]. These are all ''negative'' undesired indicators calculated through probabilistic methods that define the expected reliability value with a particular level of uncertainty [3]. To minimize the expected value of these indicators to the largest extent possible, electric distribution companies have proposed a group of measures focused on reducing failure rates and the repair times of interruptions through the execution of preventive and corrective maintenance and through the investment in human and technical resources for the repair [4]. However, the execution of switching maneuvers in an electric distribution network employing devices designed for such purpose enables not all users of a particular electric system to be affected by a failure. For this reason, most of the studies aimed at minimizing reliability indicators in level 3 (distribution) seek to find the optimal location of switching devices to enable that some failures in particular distribution system elements do not affect all users of such a system [5]. The reliability analysis in level 3 (distribution) often becomes very complex due to the lack of data for defining reliability indicators. Most authors that have addressed this topic propose fictitious data, often based on personal experiences, to be able to stand for their models in validated test systems (case studies). It is possible that the analysis of this unique proposed scenario does not respond correctly, and much less optimally, to the problem of determining the location of switching devices in distribution systems [6]. But even knowing current data does not guarantee to know them in the future, which is why this problem is highly uncertain and depends on a probabilistic analysis. Among the probabilistic (stochastic) methods used in reliability evaluations, the most robust and most frequently used are the Markov chain and the Montecarlo method [7]. Energy distribution companies have often decided the location of the switching devices empirically in electric distribution systems since there is no clear methodology that defines verified steps that should be followed and that responds to probabilistic data criteria giving special importance to the topology of the distribution network. The fast growth of the demand for electric systems and the topology changes due to improvement actions or new investments is another factor contributing to increasing the uncertainty about evaluating reliability in distribution systems [8]. Many researchers have proposed optimization algorithms based on search metaheuristics to find the optimal location of switching devices according to one, or in some cases, more than one, reliability indicator [9]. However, these objectives have been unilateral, with a predominant interest in satisfying users that deserve good electric service. Still, in this analysis, the energy not supplied to the user is seldom considered due to a failure, which is energy the company did not sell. Considering what was previously said, this work proposes that the decision about the optimal location of switching devices should respond to all reliability criteria for distribution systems (level 3), certainly considering a weighting of each criterion and such weighting on the decision may be defined mathematically by the data dispersion in each scenario or simply by a human manipulation according to particular interests. The multicriteria decision will enable an optimal solution for locating the switching device. Still, it also enables individual decisions about each criterion's results, providing more flexibility and knowledge about possible solutions [10].

This paper establishes a very novel methodology based on describing reliability as what it is, a probability [11]. For this purpose, deterministic pseudo-random variables are defined, which respond to behaviors in ranges established which are known, and that may be manipulated. These pseudo-random generations will describe a bounded probabilistic situation of the analysis variables: failure rate per recloser (load point to users) and failure rate per elements of the primary, repair time of each failure, number of consumers per load point, and mean power consumption in kW for each load point. Suppose this experiment is repeated ''many'' times (scenarios). In that case, it is possible to have the probabilities of occurrence of all reliability indicators in different scenarios of the analysis variables, but for the same distribution network, a concept that responds to the Montecarlo method [7]. The proposed methodology is iterative, and each scenario is analyzed using the multicriteria method; the method processes extended to the number of reclosers desired to connect according to a cost criterion (availability of investment). Each iteration of the technique analyzes many scenarios (Montecarlo) with a novel consideration of recloser coordination, defined as selecting a new location since a recloser was previously located. This concept also applies to networks with existing reclosers or without protection devices and planning new networks. In addition, the proposed model enables carrying out the same calculation knowing the real values of the variables, precisely describing the phenomenon, and determining the optimal location of the recloser. Still, in this case, the Montecarlo method would be omitted if the client prefers that the result depends on current known data and not on the network's topology, considering the load's uncertainty and variability and the number of users. The proposed methodology is very flexible and responds with a multicriteria decision to any particular comment or consideration desired by the client about the optimal location of switching devices in distribution systems to minimize reliability indicators. Furthermore, if desired, the indicators may be voided as analysis criteria, or their weighting in the decision calculation may also be manipulated. When comparing the proposal with the other studies on the optimal location of reclosers, it can be highlighted that this novel methodology solves the uncertainty in these problems due to the need for more historical data. A new concept of Sectioning Coordination is also proposed, reducing the search space in these problems and computation times. On the other hand, the multicriteria decision method guarantees correct decision-making considering all the reliability indicators and their weightings with the flexibility of human intervention.

II. LITERATURE: RELIABILITY ANALYSIS IN DISTRIBUTION SYSTEMS

A. STUDY OF THE RELIABILITY IN ELECTRIC DISTRIBUTION SYSTEMS

As a concept, reliability in electric power systems is the probability of a network or electric equipment guaranteeing its uninterrupted operation. However, all systems are affected by interruptions (failures) that affect consumers and electric distribution companies. This reliability at the different levels of analysis is measured by performance indicators based on the study of the duration and frequency of the interruptions and by economic indicators that study the financial loss incurred by the company due to energy not supplied [12]. These indicators are estimated through stochastic prediction and analysis that defines the probability that a system operates in different timelines. With this prediction established about reliability indicators, expansion plans are developed, and decisions are made verifying that the different parts of the electric power systems fulfill the reliability indicators despite the future load increase. Indeed, other aspects are less controlled and mostly external to electric power systems, contributing to the deterioration of reliability indicators. However, having optimal switching contributes to improving reliability indicators despite the existence of electric failures [13].

The reliability analysis is carried out by levels, where level 1 evaluates the sufficiency of the generation, level 2 evaluates the adequacy of the generation plus the availability of transmission lines, and level 3, which is the objective of this research, evaluates the reliability in electric energy distribution. The reliability in level 3 (distribution) is analyzed by distribution systems and not by the user since consumers are connected to different points of loads (transformers). Each one is affected differently by failures that may occur in the distribution system. Due to this, it is impossible to conceive a unique function for calculating reliability indicators for all distribution systems since each analysis mostly depends on the topology of the electric distribution network and on how every load point is affected by failures in the different network elements. The development of information technologies has enabled to evaluate the reliability with iterative and more complex mathematical techniques that will allow a better approximation in the prediction; one of these techniques is the known Montecarlo method. This method is used for calculating the probability of occurrence of a particular result when many possible randomly generated scenarios are analyzed; as most scenarios are analyzed, the process is more efficient, and it enables knowing the probability of occurrence of a particular scenario with high accuracy [14].

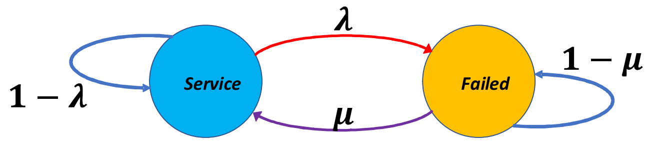

FIGURE 1. Representation of the Markov chain for analyzing a system in failure and service (operation) states.

Most authors that have addressed reliability evaluation conclude that the main problem for this analysis is the availability of historical data that enable establishing failure rates and failure duration times for the elements that constitute the distribution system. Due to this lack of data, many reliability studies are carried out with measures established by manufacturers and typical behavior ranges.

B. TECHNIQUES FOR COUNTING FAILURE FREQUENCY AND DURATION

The Markov chain is one of the most attractive probabilistic methods to define the probability of occurrence of a particular operating state of the electric system. This method performs probabilistic calculations within the reliability to determine frequencies and duration of failure states [15]. Figure 1 represents transitions between service and failure states for a reliability analysis through the Markov chain. These transitions between states are the ones that generate the analysis variables for studying the reliability, where λ represents the failure rate of a system as a transition from a service state to a failure state, and μ describes the restoration rate as a transition from a failure state to a service state. Note that μ is the inverse of the repair time of a failure ($\mu = 1/r$), where r is the time during which the system is being repaired [16].

From this analysis, it is possible to determine the steady state ($t = \infty$) probability for each state of the Markov chain (Service Probability or Failure Probability), as shown in Eq. 1 and Eq. 2 [15].

$$\boldsymbol{PS^S} = \frac{\mu}{\lambda + \mu} \tag{1}$$

$$\boldsymbol{PF^S} = \frac{\mu}{\lambda + \mu} \tag{2}$$

Using the same principle of the Markov chain, it is possible to determine the duration and frequency of the failure state in a probabilistic manner utilizing Eq. 3.

$$Di = Pi * Ti = \frac{Pi}{Fi} \tag{3}$$

where: Di is the duration of the state i, Ti is the period of state i,, d Fi is the frequency of state i.

The frequency of state i may be determined using the frequency balance equations for Markov chains, shown in Eq. 4 [17].

$$Fi = Pi^{(S)} \sum_{\substack{j=1 \\ j\neq i}}^{n} Ts(ij) = \sum_{\substack{j=1 \\ j\neq i}}^{n} Pj^{(S)} Ts(ji) \tag{4}$$

where: $Ts\,(ij)$ is the probability of the transition from state i to the remaining states j and $Ts\,(ji)$ is the probability of the transition from any state j to state i.

Even though the method defined by the Markov chain to determine the duration and frequency of the interruptions is very accurate and used in almost all reliability evaluation studies, failure rates and restoration rates are still nondeterministic data used for evaluating the reliability using the Markov chain. For this reason, it would be advantageous to evaluate the reliability in level 3 based on the topology of the network and assuming multiple scenarios for generating these indices (rates) when they are not known in a deterministic manner; this concept responds to the Montecarlo method as a proposal of this research.

The proposal using the Montecarlo method consists of creating pseudo-random numbers established in known ranges, thus creating pseudo-random variables that are the foundation of multiple possible scenarios in which the failure rates occur and the duration of these failures for each element of the system. The method presents a relative error given by $1/\sqrt{N}$, where N is the number of components of the random variable (scenarios); note that this relative error decreases as the number of scenarios under analysis increases [18]. The Montecarlo method is a potent tool for this analysis since it is simpler to know the limits of a range that will generally contain analysis variables such as failure rates and duration of these failures for each element of the electric system under analysis, simplifying the central problem of reliability that precisely is the absence of these data.

C. SWITCHING IN ELECTRIC DISTRIBUTION SYSTEMS

The equipment for switching and opening and closing maneuvers are installed in electric power systems to establish sections of the circuit that can be separated from each other, seek that, in the case of a fortuitous or planned de-energization of any part of the system, it can be isolated without affecting the rest of the circuit. These sections are established using cut-switching devices that, in most cases, operate manually, remotely, or automatically in the presence of an electric failure (in general: short circuit, overload, or phase loss) [5]. In general, the recloser is the switch primarily used in electric distribution systems (primaries); it may be installed at any place (poles) of the distribution system and may be one-phase or three-phase. Automatic reclosers constitute essential support for the protection of electric distribution networks because they provide automatic restoration and remote operation and enable the isolation of electric failures, thus contributing to minimizing reliability indicators [19].

III. MATERIALS AND METHODS

Without data about the reliability analysis variables in electric distribution systems, the proposed studies on this topic have been very scarce and uncertain. For this reason, this research suggests a novel methodology that defines the data as pseudo-random variables valued in many scenarios, prioritizing the solution as a function of the network topology. This is achieved through the Montecarlo method, which generates pseudo-random variable failure rate variables and the duration of these rates for each element of the distribution system (primary sections and load points). Each random generation has different analysis scenarios for which the switching locations are evaluated in each primary section proposed as candidates, thus obtaining a three-dimensional solution. In turn, the results obtained in each randomly generated scenario are analyzed using the multicriteria decision to define the optimal multicriteria location of the recloser in that particular scenario. The resulting optimal location of the recloser for each random scenario generates a new vector of solutions. The Montecarlo method defines which of these scenarios has the highest probability of occurrence, which becomes the final winning alternative to locate the first recloser. Based on the explanation above, the probability that the first recloser is situated optimally would be known precisely based predominantly on the network's topology. This process may be repeated to connect a second recloser since the first one was already located in a particular section of the existing primary as a winning alternative from the multicriteria analysis in the individual scenario, and by counting and by the study of the probability of all scenarios using Montecarlo. Afterward, as many switchings (reclosers) as desired can be further analyzed, fulfilling only the cost constraint posed in the design. As explained above, the proposed methodology is general, scalable, and finite; moreover, it responds to a cost criterion that determines the number of devices to be connected following a ‘‘switching coordination’’ in distribution systems. This novel concept responds to the connection of a particular switching, considering that another one was already previously connected in a specific location. The proposed methodology presupposes the rupture of knowledge barriers in this topic and enables decision-making about the location of reclosers in distribution systems, knowing the effectiveness with high accuracy. In addition, note that the method keeps its validity if the data about failure rates and duration of these failures are known accurately for each distribution system element. However, in reality, failures are not counted by elements of a primary. Still, they are generally assigned to the primary, and in this real situation, this method proposes a valid and novel alternative.

The multicriteria optimization technique is applied to the solutions obtained for the reliability indicators in each scenario under consideration. The algorithm assigns a particular location to the switching device (recloser) in each of the candidate primary sections, eliminating the final sections of the radial circuit that uniquely respond to the switching of a load point already determined by the own switching of the load point (transformer). For each switching assignment, the reliability indicators (SAIFI, SAIDI, CAIDI, AENS) are recalculated, obtaining an individual scenario result for each objective criterion; this process is iterative and repeated until the completion of all primary sections proposed as candidates. After this analysis, a discrete vector with as many solutions as the analysis scenario was obtained. The decision matrix is constructed with each reliability indicator in a column (criteria) for each solution vector of each criterion. Based on the Exhaustive Search (Brute Force) algorithm, it should be considered all candidate scenarios (primary sections that do not end of the circuit) present in the system since this guarantees that all feasible scenarios are explored and that the solution is optimal. The switching connection scenarios in the final sections of a distribution system are discarded since they are already covered by the switching of the transformer. Still, it has also been found in tests conducted that the probability that they become the winning alternative is very low. It would only happen if the failure rate in that section was very high and that load point had the highest number of users of the whole distribution system. The number of scenarios to be considered defines the length of the rows of the decision matrix when the rows of this matrix correspond to the scenarios and the columns to the criteria results. Still, this decision matrix may be obtained either way. It would only change the analysis of weighted sums if rows or columns carried it out. In addition, since it is a problem of future planning of the location of the switches, the computational times are not very demanding.

It is necessary to establish the decision matrix to obtain an individual result per scenario as a function of the optimal switching location. The n rows of this decision matrix show the suitable alternatives among all switching location options that fulfill the criteria of being different and exclusive. The m columns show the criteria (reliability indicators) as objective functions. According to the established decision criteria, the optimal option is selected, discarding at first instance all solutions that are inferior to any other according to the dominance criterion [20].

The solution to this optimization problem is finding the best vector X of the set of switching location scenarios. The results of each criterion in each switching alternative may be normalized using statistical methods for numeric normalization; for this case, the normalization by range (min-max normalization method) is proposed, as shown in Eq. 5 [10].

$$X_{iNorm} = \frac{X_i - X_{min}}{X_{max} - X_{min}} \tag{5}$$

The CRITIC method [21] is proposed for selecting the winning alternative based on the weighted sums of the criteria for each switching scenario. The CRITIC method defines an assessment to establish weightings for each of the decision criteria (reliability indicators), and it may be calculated as shown in Eq. 6 [22].

$$W_i = S_i \sum \left(1 - r_{ij}\right) \tag{6}$$

where:

W_i is the weight for criterion i.

S_i is the standard deviation of the alternative results for each criterion i.

r_{ij} is the correlation coefficient between row i and column j.

Finally, the decision vector contains the weighted sum for all scenarios, which is obtained by multiplying the result of each criterion in a switching location scenario time the weighting of such criterion and then adding these results. Since all criteria are variables to be minimized, it will be chosen as the winning alternative that contains the minimum value within the resulting vector of weighted sums; this calculation is shown in Eq. 7 [10].

$$Pond_i = \sum_{i=1}^{m} \sum_{j=1}^{n} \left(Wi * X_{ij}\right) \tag{7}$$

In addition, a calculation tool is proposed within the algorithm where, if desired, the user may define a weight for each variable. The decision will be subject to this choice defined by human intervention.

The proposed multicriteria optimization method will be solved within a technique of enumeration of scenarios that define by counting the incidence on load points (users) of the failure rates and the duration of these failures in each element of the distribution system.

Table 1 shows the description of the variables used in the Algorithm implemented for the optimal location of reclosers with a multicriteria decision based on the Montecarlo method. Table 2 shows the simplified algorithm of the proposed methodology.

Table 2 shows the algorithm to determine the optimal location of the reclosers, using multicriteria decisions based on Monte Carlo scenario exploration. The algorithm defines the proposed methodology in pseudocode steps. Initially, the input variables are declared as pseudo-random numbers, which describe the operation of the test system. The reliability indicators (SAIFI, SAIDI, CAIDI, AENS) are calculated with these values. Then, many possibilities in which these variables can be presented are verified (states of operation of the system) through the Montecarlo method. In each iteration of Montecarlo, the reliability indicators are recalculated, and the individual location of a recloser in each candidate section of the test system is evaluated to define the optimal solution globally. Then, using a sectioning coordination methodology, this procedure is repeated to calculate a new recloser since the winning alternative previously described the first one. Finally, Montecarlo defines the scenario with the most winning options, thus identifying the following pre-established location.

TABLE 1. Variables of algorithm I.

Symbology	Variable
P	Candidate locations within the primary
λ ~	The failure rate of each element of the primary (Pseudo-random variable with defined ranges)
D ~	Duration of the failures for each element of the primary (Pseudo-random variable with defined ranges)
average kW	Mean consumption per load point in kW
U	Number of Users per load point
N	Several interactions are to be carried out (Montecarlo).
Rec.	Number of Reclosers to be installed (Cost Criterion)
Primary Elements	Number of Primary Elements
Load Points	Number of load points (Transformers)
Total Consumers	Total number of consumers (all load points)

IV. CASE STUDY

As a case study for evaluating the proposed methodology, it was used the 15-bus IEEE electric distribution test system that operates at medium voltage. This IEEE test system was taken from [23]. This system has 14 primary sections and 14 load points. Among these 14 primary sections defined with the letter (P), section P1 already has a general recloser (R) that operates in case of any interruption in the primary sections of this circuit. Also, among the 14 primary sections, all seven end sections (P4, P6, P7, P9, P12, P13, and P14) are discarded as candidate sections for installing a recloser and considering there is a recloser already installed in P1, the primary sections that remain as candidates are: P2, P3, P5, P8, P10, and P11. The end sections have been discarded as candidates because they only supply a load point that has its protection at the transformer. Moreover, general simulations have shown that the probability of these alternatives becoming winning is very low. The 14 load points (distribution transformers) in this case study are defined in the single-line diagram by letter (S). Each load point has an independent switch that operates in case of failures in the separate secondary system. The 15 buses of the system are detailed by simple numbering within the single-line diagram. Figure 2 shows the detailed single-line diagram according to the conditions previously established in this 15-bus IEEE test system.

V. RESULTS AND DISCUSSION

A. ANALYSIS AND EVALUATION OF THE RELIABILITY AT INITIAL CONDITIONS CONSIDERING ONLY THE RECLOSER EXISTING IN P1

First, the random values generated for the base case will be established, and the reliability indicators will be calculated at initial conditions without considering any switching location additional to the one existing in P1. The results obtained in the pseudo-random analysis variables and reliability indicators will be shown for this base case. Figure 3 shows data on failure rates and duration times of these failures for each load

TABLE 2. Algorithm I.

Algorithm: Optimal location of reclosers with the multicriteria decision based on the Montecarlo method.

Step 1: Input: $\{P, \lambda\sim, D\sim, average\ kW, U, N\}$;
Step 2: count {Incidence of failure rates and failure durations on each User};
Step 3: Output: $\{SAIFI, SAIDI, CAIDI, AENS\} \in R$; Initial conditions.
Step 4: $for\ i = 1\ to\ N$ (Monte Carlo scenarios)
Step 5: $for\ j = 1\ to\ Rec$ (Reclosers to be installed. Cost Criterion.)
Step 6: $for\ k = 1\ to\ P$ (Sectioning alternatives in candidate primary sections.)
$\lambda \sim ijk, D \sim ikj$; (Generation of random variables for each scenario)
$count\_i\_j\_k$ {Incidence of failure rates and failure durations on each User};
Step 7: Output: $\{SAIFI\_i\_j\_k, SAIDI\_i\_j\_k, CAIDI\_i\_j\_k, AENS\_i\_j\_k\} \in R$;
Step 8: Input: $\{Decision\ matrixj$ (Reliability indicators for each scenario K)};
Step 9: $for\ x = 1\ to\ dimension\ (Decision\ matrixj\ (1,:))$
$for\ y = 1\ to\ dimension\ (Decision\ matrixj\ (:,1))$
$normalized\ matrixj\ (j,:) = (1 / \sum(A(y,:))) * A(y,:)$;
$normalized\ matrixj\ \_Rango\ (y,x) = (A(y,x) - min\ (A(y,:))) / (max\ (A(y,:)) - min\ (A(y,:)))$;
$end;\ end;$
Step 10: $for\ n = 1\ to\ dimension\ (Decision\ matrixj\ (:,1))$
$\sigma\ (n,:) = \sum normalized\ matrix\ (n,:)) - normalized\ matrix) / P$;
$end;$
Step 11: $R = corrcoef\ (normalized\ matrixj\ ')$;
$for\ m = 1\ to\ dimension\ (Decision\ matrixj\ (:,1))$
$Weighing = \sigma.* \sum(1 - R\ (:,m))$; $end;$
$Normalized\ Weighting = (1 / \sum (Weighing\ )) * Weighing$;
Step 12: $for\ f = 1\ to\ y$
$Weighted\ Sums = normalized\ matrixj\ \_Rango\ (f,:). * Normalized\ Weighting\ (f) + cont$;
$Cont = Weighted\ Sums$; $end;$
Step 13: $win\_case = min\ (Weighted\ Sums)$;
$[row, col] = find\ (Weighted\ Sums == win\_case)$;
Step 14: $Return$: $win\_case\_i\_j$; end;
Step 15: Repeat the calculation for the next recloser, considering that the first one was decided by a winning alternative (Coordination of Sectioning)
$end;$
Step 16: Calculation the probabilities of each Montecarlo scenario;
end;

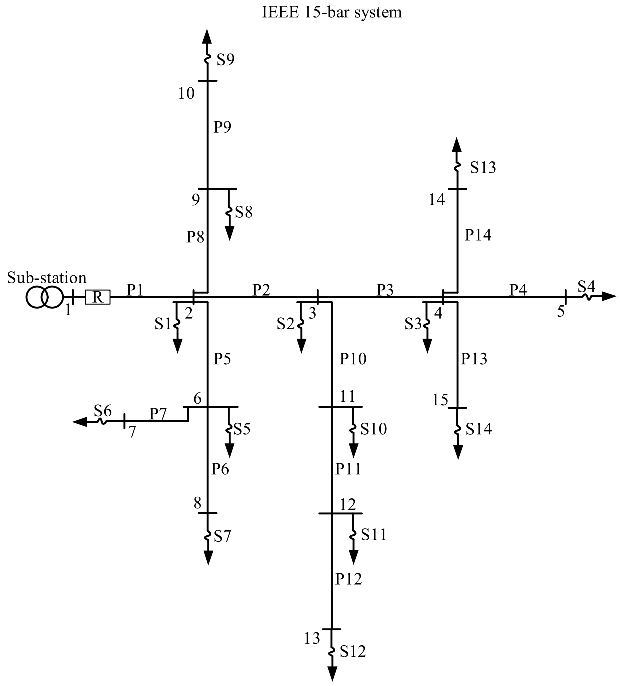

FIGURE 2. **15-bus IEEE test system.**

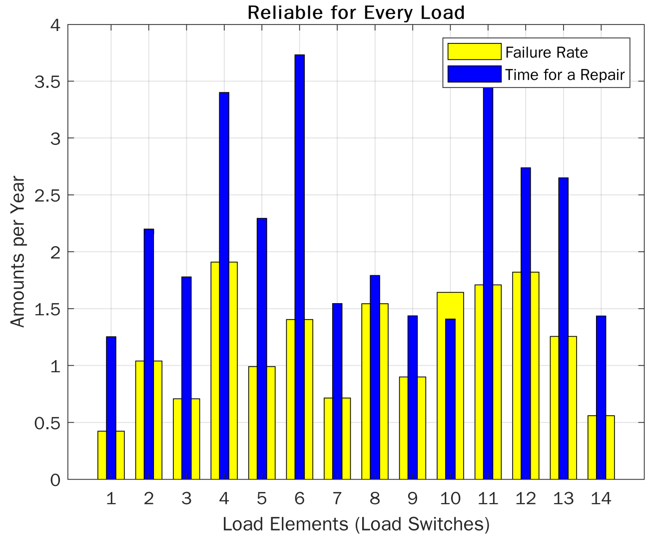

FIGURE 3. **Fault data per year and fault repair times for each test system's load point (transformer).**

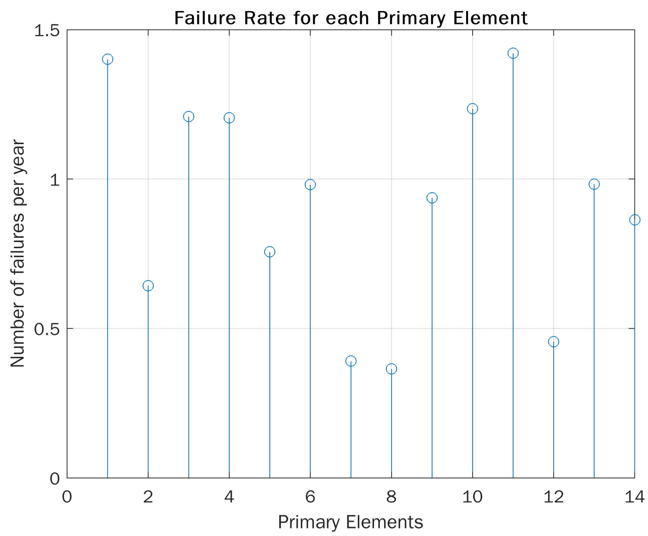

FIGURE 4. **The failure rate for each primary element.**

point of the test distribution system. These data were obtained by generating pseudo-random variables in defined and modifiable ranges. Figure 4 and Figure 5 show, respectively, the failure rates and the interruption repair times for each of the primary elements (sections P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, P11, P12, P13, and P14); these data were also generated using pseudo-random variables defined in modifiable ranges.

Residential users were considered for the proposed example; however, the proposed model is open for manipulation to establish real values of data in case these are known. As input data to the problem at initial conditions, scenarios of the number of users and average consumption of these users are also known. Figure 6 shows the number of residential consumers of electric power connected to each transformer and the mean power consumption at each of these load points (S1, S2, S3, S4, S5, S6, S7, S8, S9, S10, S11, S12, S13, and S14).

This analysis uses a counting technique on the possible incidences of all elements failing on each user (load point). Based on this input data, it is calculated the total number of failures in a year that may affect a user of a particular transformer (load point) due to failure rates at each load point and each section of the primary. This is shown in Figure 7.

For any user, these failures may occur due to the operation of their transformer switch or the operation of the only existing recloser (P1), which interrupts the power supply to the entire circuit when there is a failure in any primary section of the test system. Similarly, and due to all failures that may occur in the system under study and the repair time of these failures, a particular user is affected by the total duration of failures in the year as the sum of the repair times of all failures of the system that may interrupt their service. The entire time of failures in a year that may affect each system user can be observed in Figure. 8.

The average duration time of any single system failure for each user (load points) may also be obtained from this data of total failure rates and total duration of these failures that may affect a particular user of the test distribution system in a year. This result is obtained from the division between pseudo-random variables of the total duration of failures in a year per user and the total failure rate in a year per user. This result can be observed in Figure 9.

Using these initial conditions, it is possible to determine the reliability indicators (SAIFI, SAIDI, CAIDI, and AENS) [2] for the test electric distribution system, considering a single recloser in P1.

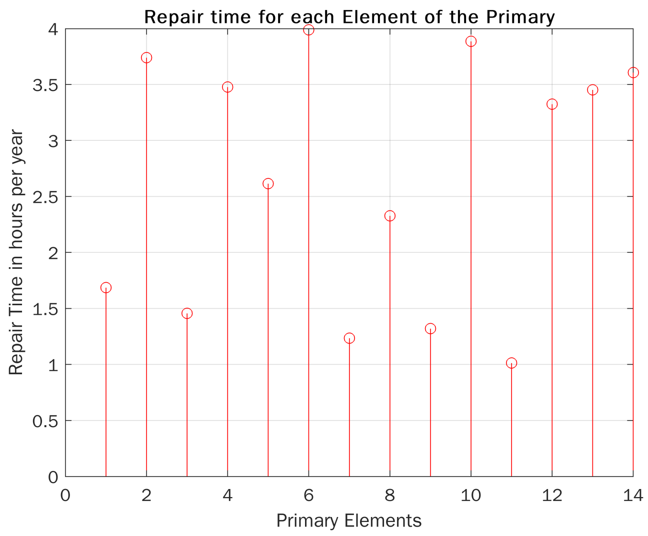

FIGURE 5. Repair time for each element of the primary.

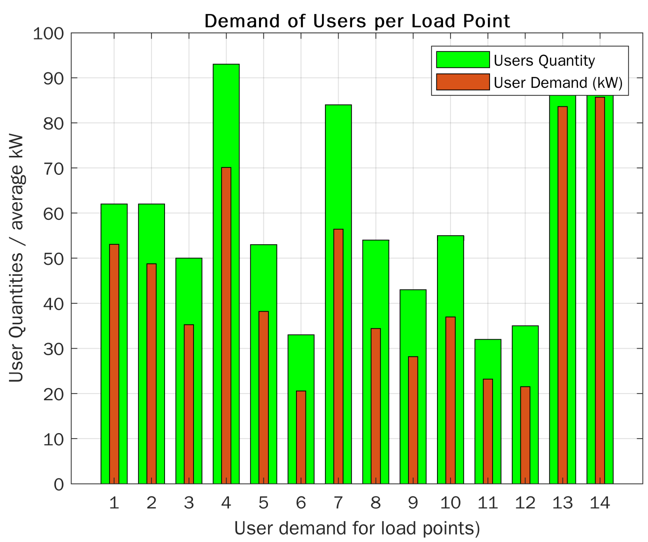

FIGURE 6. Number of power consumers per electric load point and average total consumption per load point.

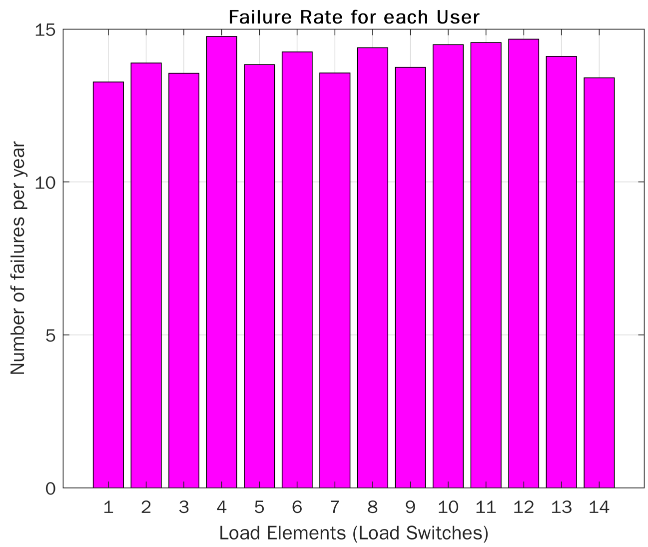

FIGURE 7. The total failure rate for each system user (load point).

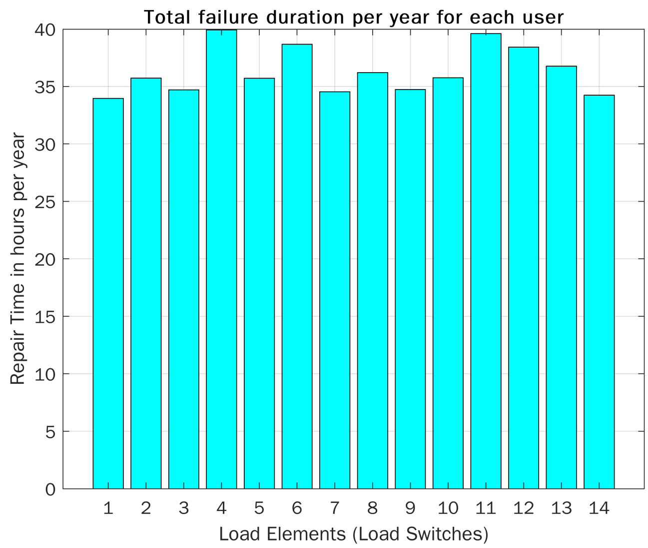

FIGURE 8. Total failure duration per year for each user.

SAIFI: System Average Interruption Frequency Index.

$$\boldsymbol{SAIFI} = \frac{\sum_{i=1}^{n} \lambda iNi}{Nt} = \frac{\textit{Total number of interruptions for all users}}{\textit{Total number of users served}} \tag{8}$$

where λi is the failure rate, Ni is the number of users per location, and Nt is the total number of users served. SAIFI is measured in average outage units per customer over a year for a given study system.

SAIFI = 13,0018 failures per year

SAIDI: System Average Interruption Duration Index.

$$\boldsymbol{SAIDI} = \frac{\sum_{i=1}^{n} UiNi}{Nt} = \frac{\textit{Sum of the duration of the interruptions of all users}}{\textit{Total numberof users served}} \tag{9}$$

SAIDI is measured in time units, often hours. It is usually measured over the course of a year. Where Ni is the number of clients in location i, Ui is the yearly interruption time for location i, and Nt is the total number of users served.

SAIDI = 31,0908 hours of failures per year

CAIDI: Customer Average Interruption Duration Index.

$$\boldsymbol{CAIDI} = \frac{SAIDI}{SAIFI} = \frac{\sum_{i=1}^{n} Ui\ Ni}{\sum_{i=1}^{n} \lambda i\ Ni} = \frac{\textit{Sum of the duration of the interruptions of all users}}{\textit{Total number of interruptions per user}} \tag{10}$$

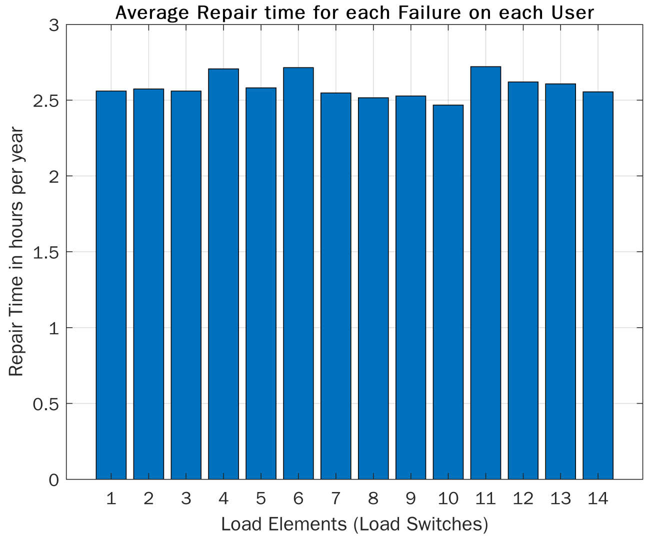

FIGURE 9. The average duration of a single failure for each system user.

CAIDI is measured in time units, often minutes or hours, and provides the average interruption duration that any client would experience. CAIDI may also be seen as the average restoration time.

CAIDI = 2,3913 hours

AENS: Average Energy Not Supplied.

$$\boldsymbol{AENS} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} k\overline{W}i\ \boldsymbol{Ui}\,(kWh) \qquad (11)$$

AENS is a measure of the average energy not supplied per user. AENS is a reliability index used for electric power systems, generally expressed in kWh per user.

$\boldsymbol{AENS} = \mathbf{24,9538}\frac{\boldsymbol{kWh}}{\boldsymbol{year}}$ for each user (independent consumer) of the test system.

The results of the four indicators analyzed show that the system is unreliable. Those actions should be taken for the optimal location of additional switching to reduce total failure rates and system restoration times, variables that would minimize the values of the reliability indicators.

B. RELIABILITY ANALYSIS AND EVALUATION CONSIDERING A RECLOSER ADDITIONAL TO THE ONE IN P1

The optimal location of a recloser, in addition to the one in (P1), will be analyzed in this optimization study. To establish the multicriteria analysis, the previous calculation will be simulated for the initial conditions, but this time for various scenarios where each of them simulates the location of an additional recloser in the candidate primary sections that do not correspond to circuit end sections (Scenario 1: Recloser in P2, Scenario 2: Recloser in P3, Scenario 3: Recloser in P5, Scenario 4: Recloser in P8, Scenario 5: Recloser in P10 and Scenario 6: Recloser in P11). For this study, Figure 10 compares the failure rates obtained for the base case (Recloser only in P1) and scenario 1 (Recloser in P1 and P2). In contrast, Figure 11 compares the failure duration times per user for the scenario of a single recloser (P1) and scenario 1 (Recloser in P1 and P2). Figure 12 compares the failure rates obtained for the base case (Recloser only in P1) and scenario 2 (Recloser in P1 and P3). In contrast, Figure 13 compares the failure duration times per user for the scenario of a single recloser (P1) and scenario 2 (Recloser in P1 and P3). Figure 14 compares the failure rates obtained for the base case (Recloser only in P1) and scenario 3 (Recloser in P1 and P5). In contrast, Figure 15 compares the failure duration times per user for the scenario of a single recloser (P1) and scenario 3 (Recloser in P1 and P5).

Fig. 16 compares the failure rates obtained for the base case (Recloser only in P1) and scenario 4 (Recloser in P1 and P8). In contrast, Figure 17 compares the failure duration times per user for the scenario of a single recloser (P1) and scenario 4 (Recloser in P1 and P8). Figure 18 compares the failure rates obtained for the base case (Recloser only in P1) and scenario 5 (Recloser in P1 and P10). In contrast, Figure 19 compares the failure duration times per user for the scenario of a single recloser (P1) and scenario 5 (Recloser in P1 and P10). Figure 20 compares the failure rates obtained for the base case (Recloser only in P1) and scenario 6 (Recloser in P1 and P11). In contrast, Figure 21 compares the failure duration times per user for the scenario of a single recloser (P1) and scenario 6 (Recloser in P1 and P11).

A multicriteria analysis was carried out with the analysis variables for these six scenarios under study corresponding to possible locations in candidate buses of a recloser in addition to the one in P1. The decision matrix in Table 3 is constructed with these results; if the base case results are not counted, the resulting matrix is six-by-four. The minimum value obtained for each decision criterion is highlighted in bold font. Note that this is only a random result of many scenarios that will be analyzed multicriteria.

After the matrix is normalized using the criteria's maximum and minimum values, as explained in the methodology section, the graphical result of this decision matrix may be visualized in Figure 22.

Using the normalized decision matrix, a vector of weighted sums is established where the results of each criterion are added in each of the six scenarios presented in this case study of optimal switching location. These results may be graphically observed in Figure 23. This graphical result verifies that the weighted minimum value is obtained in scenario 1, which corresponds to the location of a recloser in the primary section P2 and the recloser already connected in the primary section P1.

The same result is obtained if the multicriteria decision as a multi-objective optimization method is extrapolated to the optimal Pareto analysis. Figure. 24 presents the multi-objective optimization analysis graphically considering Pareto, and it may be evidenced that the minimum value is precisely the scenario of connecting a recloser in P2. The value of this solution (P2) is the overall minimum among all scenarios analyzed. The value is so small (close to zero) that it is not visually considered in the Pareto representation.

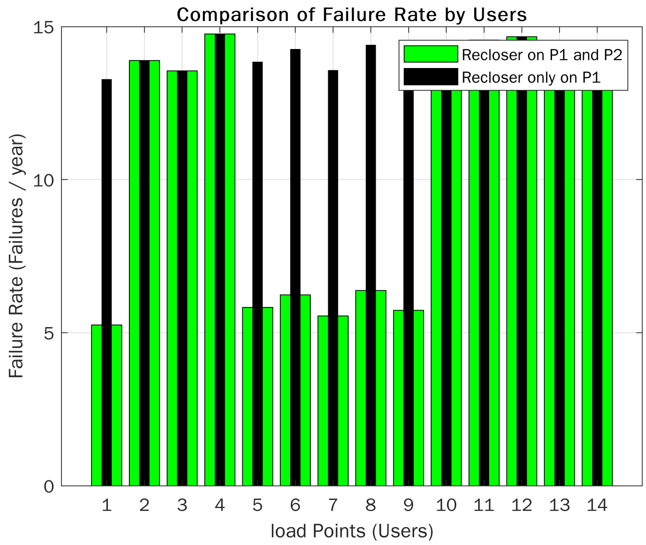

FIGURE 10. Comparison of failure rate by a user (P1 and P2).

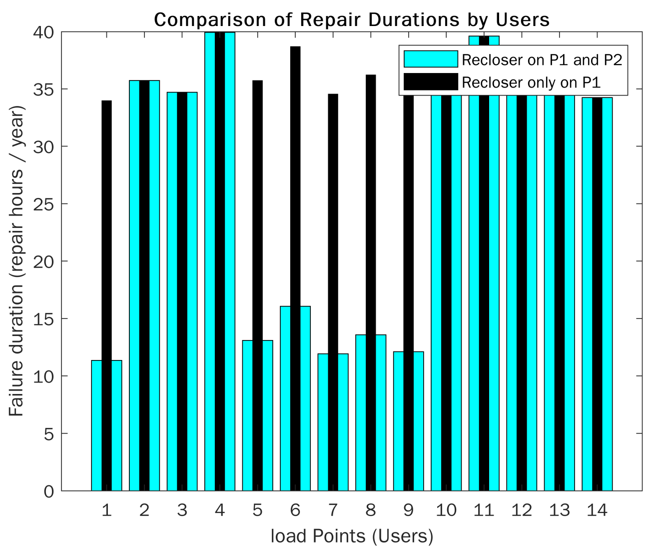

FIGURE 11. Comparison of repair durations by a user (P1 and P2).

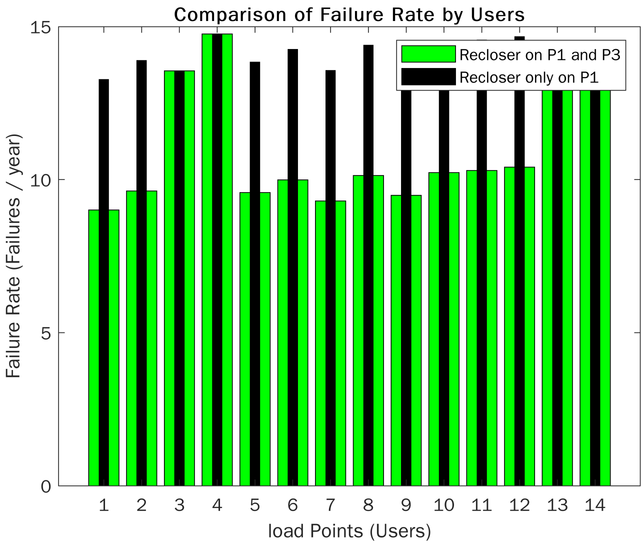

FIGURE 12. Comparison of failure rate by a user (P1 and P3).

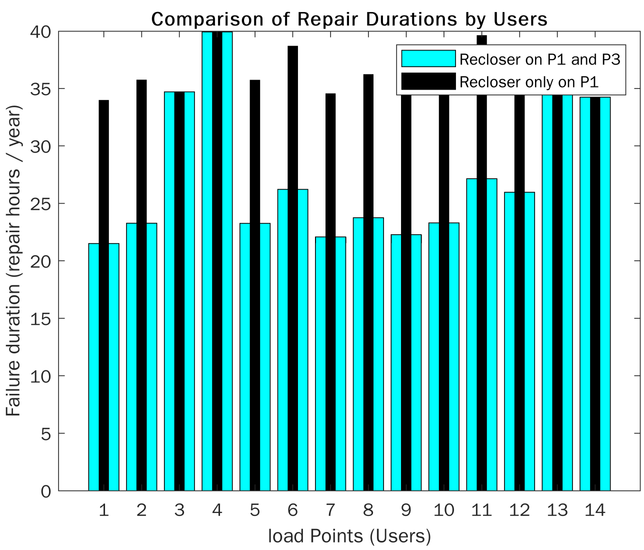

FIGURE 13. Comparison of failure rate by a user (P1 and P3).

To reduce the problem uncertainty and obtain a result that, although stochastic yields a very accurate prediction (with minimum error), this result is shown for only a random scenario and is evaluated in 100,000 scenarios with pseudo-random data in defined ranges using the Montecarlo method. Each scenario defined by new pseudo-random variables is evaluated by calculating the reliability indicators for each switching location and obtaining a final result as a winning alternative. Table 4 shows the numerical and percentage analysis of the count of switching winning alternatives for each of the 100,000 Montecarlo scenarios. This result may also be visualized graphically in Figure. 25

This analysis enables us to conclude that for a large number of variations in the data of failure rates and duration times of the interruptions for each element of the circuit, there is a predominance, according to the topology of the circuit, that the winning alternative is the location of a recloser in P2, with a probability of 64 %. From this individual result of locating a first recloser additional to the one in P1, it can also be concluded that the alternative of locating this recloser in P11 is smaller the 1 %, because this is a primary section before the final section of the circuit without intermediate connections between these sections; this result confirms the selection of the candidate sections for switching location. In case precise data by system elements are unknown and based on the topology of the test circuit, this methodology enables establishing an optimal solution based on probabilistic criteria.

C. RELIABILITY ANALYSIS AND EVALUATION CONSIDERING A RECLOSER ADDITIONAL TO THE ONES EXISTING IN P1 AND P2

The results obtained previously for the optimal location of a recloser in addition to the one in P1, defined as the winning

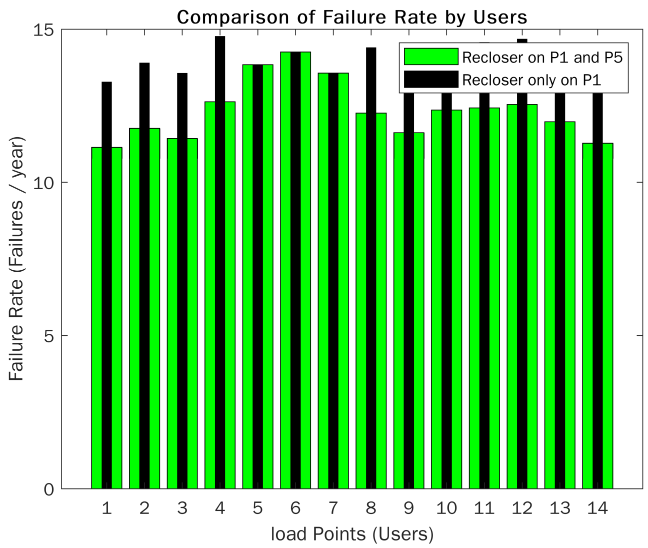

FIGURE 14. Comparison of failure rate by a user (P1 and P5).

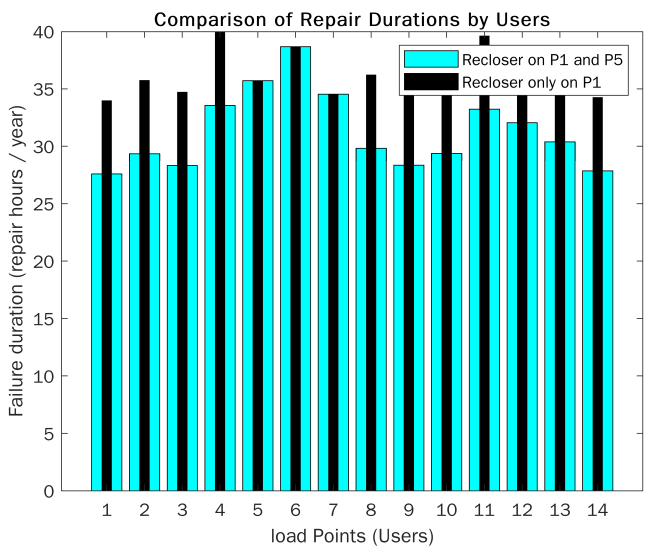

FIGURE 15. Comparison of repair durations by a user (P1 and P5).

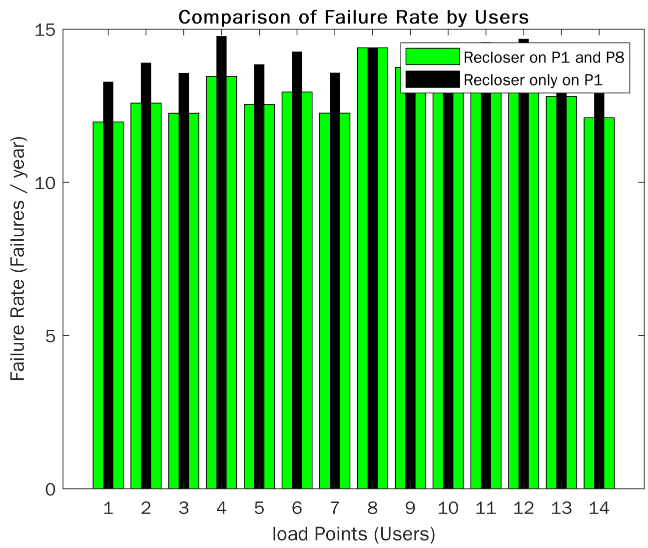

FIGURE 16. Comparison of failure rate by a user (P1 and P8).

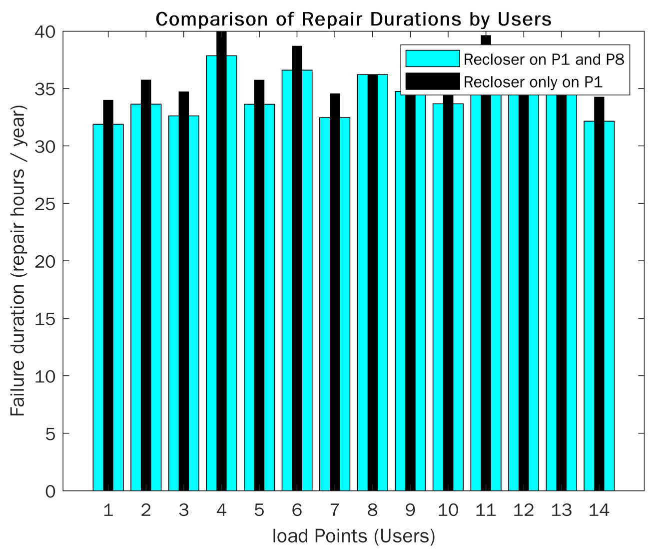

FIGURE 17. Comparison of repair durations by a user (P1 and P8).

alternative, with the highest probability of occurrence, and with the multicriteria optimization analysis, the location of another recloser in the primary section P2. Considering the available cost for purchasing and installing another recloser, this analysis may be iterative with a stopping condition defined by the number of reclosers required to be installed or by verifying the marginal value of gain on the criteria with the following location. This form establishes a new concept that responds to coordination between switchings, calculating a new recloser simulating the existing recloser in the previous winning alternative. To establish the multicriteria analysis for the new switching, the calculation will be simulated under conditions of reclosers existing in the primary sections P1 and P2. Still, this time the options of candidate sections for the installation are reduced to four possible scenarios within this case study, restricting the location alternatives in final primary sections as it was previously explained (Scenario 1: Recloser in P3, Scenario 2: Recloser in P5, Scenario 3: Recloser in P8 and Scenario 4: Recloser in P10). As it was already demonstrated, the alternative location in P11 has a probability below 1 % of becoming the winning alternative, and for this reason, it is also discarded in this analysis. For each of the newly known scenarios, the total failure rates per load point (transformers) and the total duration times of the interruptions that these users may experience at each load point are recalculated due to possible failures in the different elements of the system. The analysis is repeated using the counting technique for the four switching alternatives. The results will be shown graphically, comparing the improvements obtained in the reliability indicators for each additional switch.

Fig. 26 compares the total failure rates for each user (load point) in one year and the duration times of interruption for

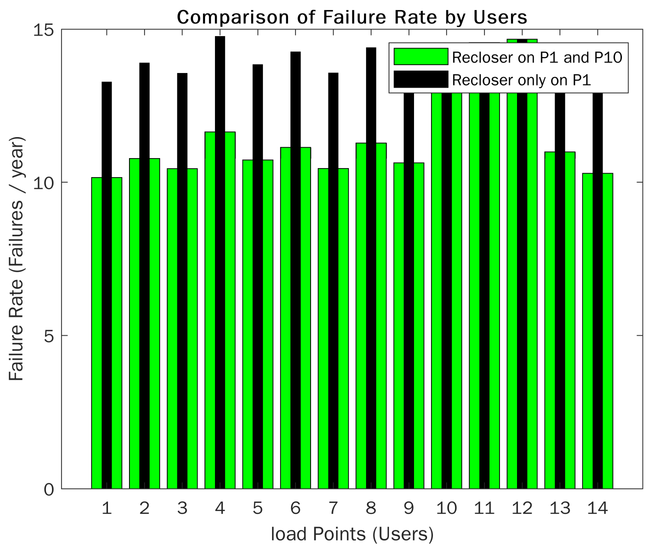

FIGURE 18. Comparison of failure rate by a user (P1 and P10).

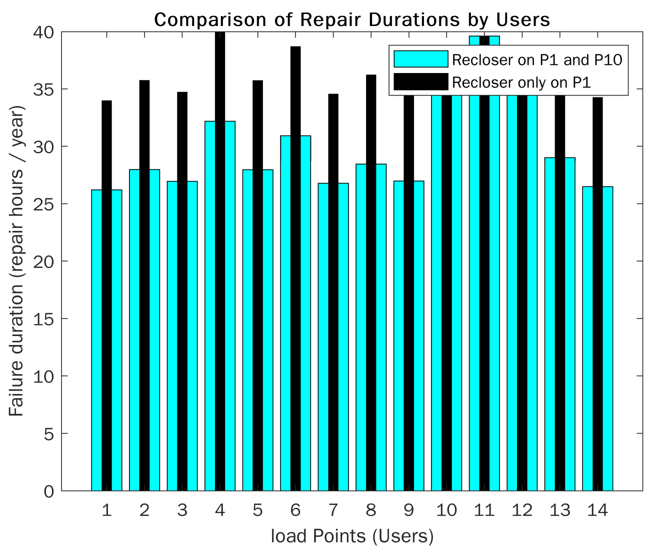

FIGURE 19. Comparison of repair durations by a user (P1 and P10).

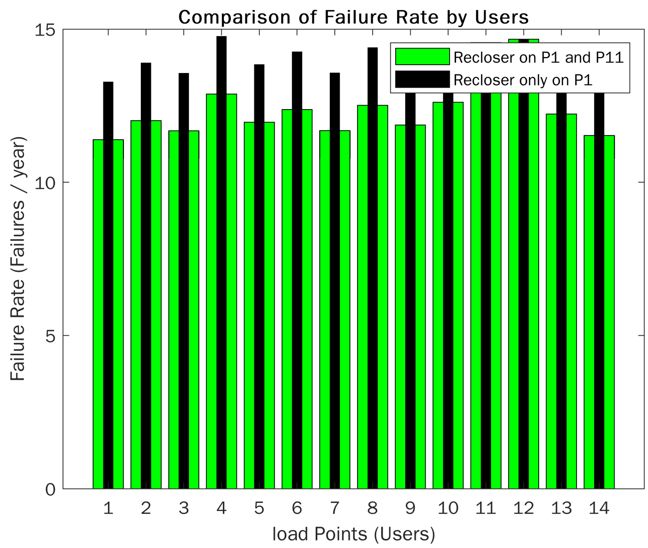

FIGURE 20. Comparison of failure rate by a user (P1 and P11).

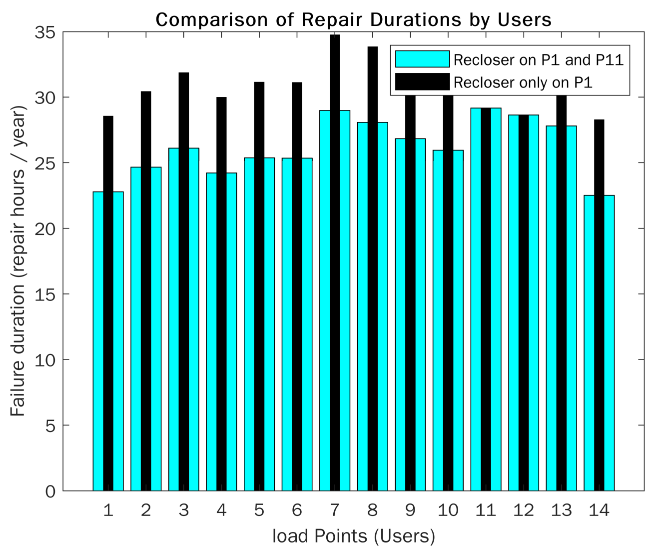

FIGURE 21. Comparison of repair durations by a user (P1 and P11).

each user (load point) in one year. The graphical result of these two variables is compared by colored bars between the base case with the recloser only in P1, the case of an additional recloser in P2 as a prior winning alternative, and a new recloser proposed in P3. Figure. 27 shows the same previous comparison, but between the base cases with the recloser only in P1, the case of an additional recloser in P2 as a prior winning alternative, and a new recloser proposed in P5.

Fig. 28 compares the total failure rates for each user (load point) in one year and the duration times of interruption for each user (load point) in one year. The graphical result of these two variables is compared by colored bars between the base case with the recloser only in P1, the case of an additional recloser in P2 as a prior winning alternative, and a new recloser proposed in P8. Figure 29 shows the same previous comparison, but between the base cases with the recloser only in P1, the case of an additional recloser in P2 as a prior winning alternative, and a new recloser proposed in P10.

After analyzing the results of any of the four scenarios, it may be noted that both the total failure rates and the interruption duration decrease for some load points (transformers), contributing to the minimization (improvement) of reliability indicators. However, it is necessary to know in an optimal manner which of these switching alternatives would better contribute to the joint minimization of reliability indicators; for this purpose, it is carried out the development of the multicriteria decision.

With these four studied scenarios of possible locations in the candidate buses of a recloser additional to P1 and P2, a multicriteria analysis is carried out, considering the four (4)

TABLE 3. Reliability variables for each scenario were analyzed.

Analysis Scenarios	**SAIFI** Number of failures per year per user	**SAIDI** Interruption time per year per user	**CAIDI** The average duration of a failure	**AENS** kWh of energy not supplied by the user
Only P1	**13,0018**	**31,0908**	**2,3913**	**24,9538**
P1 and P2	9,8731	22,848	2,3142	18,3766
P1 and P3	10,8148	24,5457	2,2696	19,7278
P1 and P5	11,4933	28,3197	2,464	22,7166
P1 and P8	11,8652	29,1752	2,4589	23,4363
P1 and P10	10,5382	25,5031	2,4201	20,4462
P1 and P11	10,7625	26,2085	2,4352	20,9988

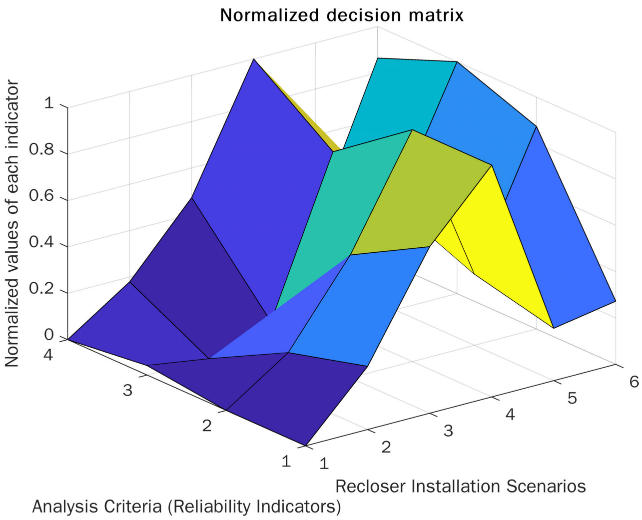

FIGURE 22. Normalized decision matrix.

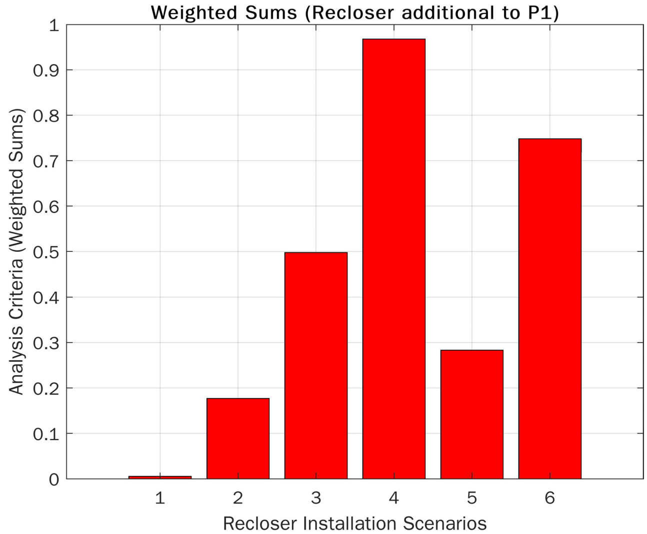

FIGURE 23. Result of the weighted sums for each scenario.

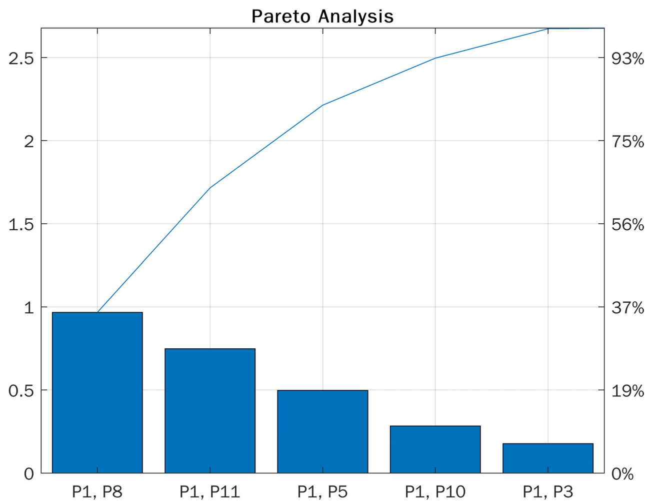

FIGURE 24. Analysis of Pareto optimal scenarios (Consideration of Maximum to Minimum).

reliability indicators again as decision criteria. A new 4 × 4 decision matrix is constructed with these results (without counting the previous comparative result of reclosers in P1 and P2 and the base case of a recloser only in P1); this decision matrix is shown in Table 4. The minimum value obtained for each decision criterion is highlighted in bold font. This is a random result among many scenarios that would be analyzed multicriteria, considering data defined in pseudo-random variables with manipulable ranges. From this result shown in Table 5, it may be verified that with the location of the second recloser additional to the one in P1, the minimum value for each indicator starts to be smaller, and this analysis enables to establish the cost criterion defined by the user as stopping condition to the proposed model.

After normalizing the matrix using the criteria's maximum and minimum values, as explained in the methodology section, Figure 30 shows the graphical result of this decision matrix for the second recloser in addition to the one in P1. This visual result shows the normalized values for the four reliability indicators in the four switching scenarios proposed as candidates.

With the normalized decision matrix obtained, a new vector of weighted sums is established, adding the results of each criterion (reliability indicators) in each of the four scenarios of optimal switching location presented in this case study for the second iteration of optimal recloser location. These results may be graphically observed in Figure 31. From this graphical result, it may be verified that the minimum weighted value occurs in scenario 2 (a value close to zero), which corresponds to the location of a recloser in the primary section P5 in addition to the reclosers in P1 and P2.

Fig. 32 graphically presents the multi-objective optimization analysis considering Pareto and i. Extrapolating this analysis to the multi-objective optimization by Pareto optimal, it is obtained the same result defined as the winning alternative (P5). The value of this solution (P5) is the

TABLE 4. Reliability variables for each scenario were analyzed.

Accounting	P2	P3	P5	P8	P10	P11	Total
Quantities	**63650**	15341	13680	2604	4467	258	100000
Odds (%)	**63.65**	15.341	13.68	2.604	4.467	0.258	100

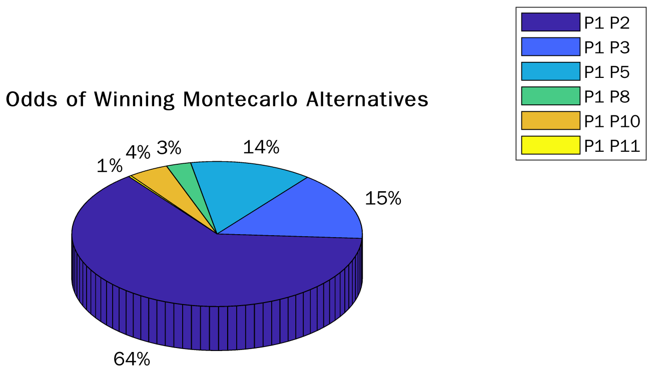

FIGURE 25. Odds of winning montecarlo alternatives.

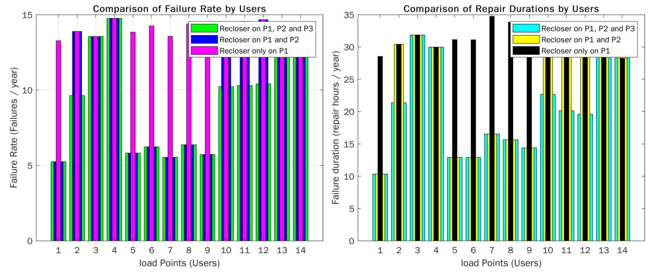

FIGURE 26. Comparison of failure rate by users (left) and comparison of repair duration by users (right). Recloser on P1, P2, and P3 (Alternative 1).

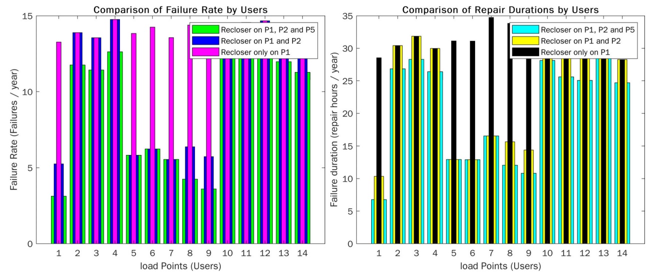

FIGURE 27. Comparison of failure rate by users (left) and comparison of repair duration by users (right). Recloser on P1, P2, and P5 (Alternative 2).

minimum among all scenarios analyzed in an organized manner, and it appears with a value so small (close to zero) that it is not visually considered in the Pareto representation. The minimum value appears precisely when connecting an additional recloser in P5.

With the objective stated previously in the first switching iteration, it is sought to reduce the uncertainty of the problem and obtain a result that, despite being stochastic, yields a very accurate prediction with minimum error, using the Montecarlo method with 100,000 analysis scenarios. Each scenario defined for these new pseudo-random variables is evaluated by calculating the reliability indicators for each switching location and obtaining a winning alternative as a final result. For this second iteration, Table 6 shows the numerical and percentage analysis of the count of winning switching alternatives for each of the 100,000 Montecarlo scenarios for the location of a new switching. This result may also be visualized graphically in Figure 33.

From this analysis and considering the proposed switching coordination, there is a predominance defined by the circuit topology that the winning alternative is the location of a recloser in P5, with a probability of 58 %. From this individual result of the location of a recloser additional to P1 and P2, it may also be concluded that the alternative of locating this recloser in P8 appears with a 39 % probability of becoming the winning alternative. The minimum probabilities of connecting a recloser in P3 or P10 are discarded. With this result obtained for two iterations of optimal switching location, it is recommended as a final solution to locate one recloser in P2 and another recloser in P5, in addition to the recloser in P1. The analysis may be carried out in a third iteration of switching coordination, which calculates the optimal location of another recloser since three are already installed (P1, P2, and P3). However, based on cost-benefit criteria, this third iteration is omitted for the current case study due to a cost constraint.

D. RESULTS VALIDATION

To validate the proposed sectioning coordination method, a performed using Exhaustive Search. For this validation analysis, all possible scenarios that allow the location of two reclosers, in addition to the existing one as a base case in section P1, will be considered. Equation 12 shows the calculation of the number of options to be analyzed, considering two (2) reclosers to be placed in five (5) candidate lines (P2, P3, P5, P8, P10).

$$counting = \frac{5!}{2!\,(5-2)\,!} = 10 \; options \tag{12}$$

The ten scenarios proposed for two additional reclosers to P1 are: P2 and P3, P2 and P5, P2 and P8, P2 and P10, P3 and P5, P3 and P8, P2 and P10, P5 and P8, P5 and P10, P8 and P10)

Following the same multicriteria analysis methodology, the incidence of each sectioning scenario on the reliability indicators will be studied. In the same way, the input data will be generated using random variables, and failure rates and duration of these failures will be calculated for each user. With the calculation of these variables, the reliability indicators (SAIFI, SAIDI, CAID, AENS) would be found for each scenario. These results form a new four-by-ten decision matrix that will be evaluated by the multicriteria method.

These results form a new four-by-ten decision matrix, as shown in Table 7. The minimum value obtained for each decision criterion (indicator) is highlighted in bold. It is worth noting that this is only a random result of many scenarios analyzed on a multicriteria basis, considering data defined in pseudo-random variables with manipulable ranges.

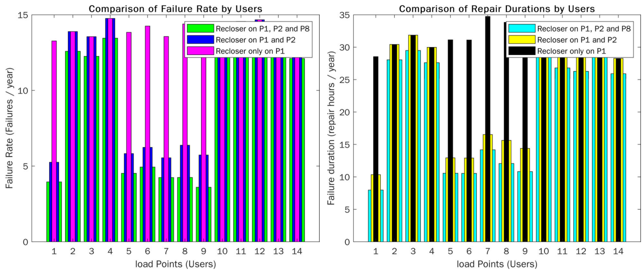

FIGURE 28. Comparison of failure rate by users (left) and Comparison of repair duration by users (right). Recloser on P1, P2, and P8 (Alternative 3).

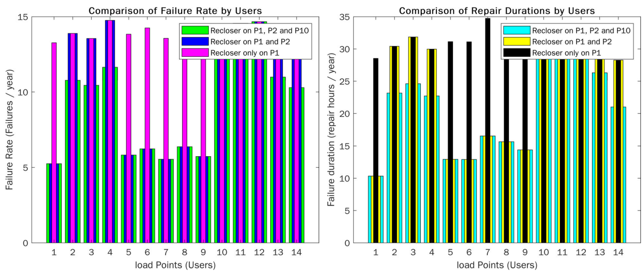

FIGURE 29. Comparison of failure rate by users (left) and Comparison of repair duration by users (right). Recloser on P1, P2, and P10 (Alternative 4).

After normalizing the matrix by maximum and minimum criteria, as explained in the methodology section, the graphic result of this decision matrix for the ten scenarios analyzed can be seen in Figure 34. This visual result shows the normalized values of the four reliability indicators in the four sectioning scenarios proposed as candidates.

With the new normalized decision matrix obtained, a new vector of weighted sums is established where the results of each criterion (reliability indicators) are added in each of the ten optimal location scenarios for two reclosers, in addition to P1. These results can be seen graphically in This result coincides with the one previously obtained by the proposed sectioning coordination method.

Weighted Sums can be seen in Figure 35. From the graphic result, it can be verified that the minimum weighted value is presented in scenario 2 (value close to zero), which corresponds to the location of a recloser in the primary section P2 and another recloser in section P5. This result coincides with the one previously obtained by the proposed sectioning coordination method.

Figure 36 presents the multi-objective optimization analysis graphically considering Pareto, showing that the minimum value is given in the scenario of additional connection of two reclosers, one in P2 and the other in P5. Extrapolating this analysis to the multi-objective optimization by Pareto optimal, we obtained the same result defined as the winning alternative (P2 and P5). The value of this solution (P2 and P5) is the minimum of all the scenarios analyzed in order, and it appears with such a small value (close to zero) that it is not visually considered in the Pareto representation.

With the same methodology declared for the study of 100,000 scenarios, using the Montecarlo method, the winning

TABLE 5. Reliability variables for each scenario were analyzed.

Analysis Scenarios	**SAIFI** Number of failures per year per user	**SAIDI** Interruption time per year per user	**CAIDI** The average duration of a failure	**AENS** kWh of energy not supplied by user
Only P1	13,0018	31,0908	2,3913	24,9538
P1 and P2	9,8731	22,848	2,3142	18,3766
P1, P2, P3	9,0559	20,4026	**2,2529**	16,4218
P1, P2, P5	**8,3646**	**20,0769**	2,4002	**16,1395**
P1, P2, P8	8,3665	20,2528	2,4207	16,2864

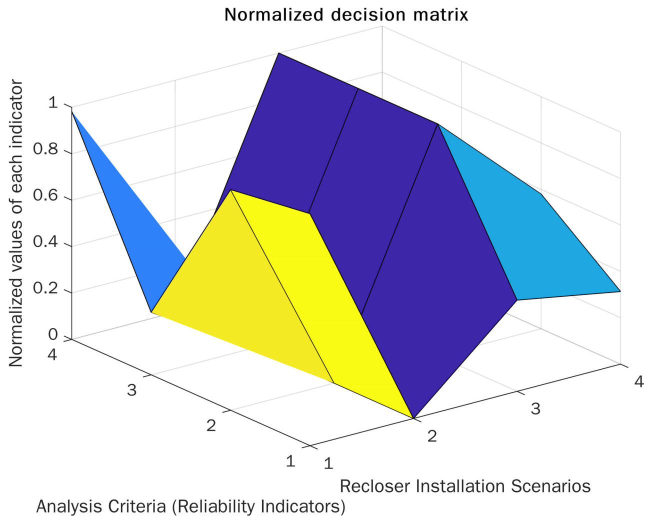

FIGURE 30. Normalized decision matrix for the four analysis scenarios considering existing sectioning in P1 and P2.

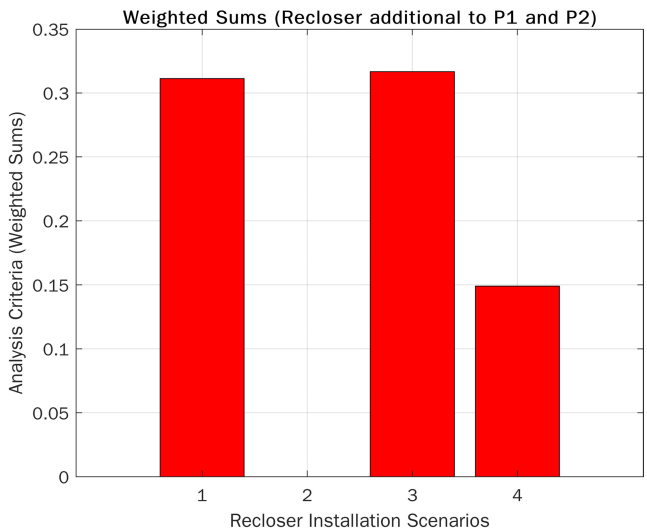

FIGURE 31. Weighted sums (recloser additional to P1 and P2).

alternative of all the proposed options is evaluated with an exhaustive search. The result obtained is the same as the one obtained by the proposed method of sectioning coordination. As shown in Fig37, the alternative that won the most times (42%) was the location of a recloser in P2 and another in P5,

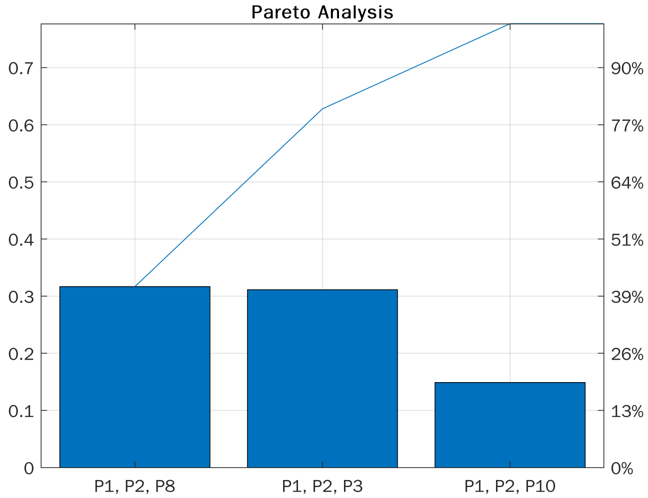

FIGURE 32. Analysis of pareto optimal scenarios (consideration of maximum to minimum).

TABLE 6. Monte Carlo analysis for an additional recloser to P1 and P2 (N=100,000).

Accounting	P3	P5	P8	P10	Total
Quantities	1784	**58121**	38712	1383	100000
Odds (%)	1,784	**58,121**	38,712	1,383	100

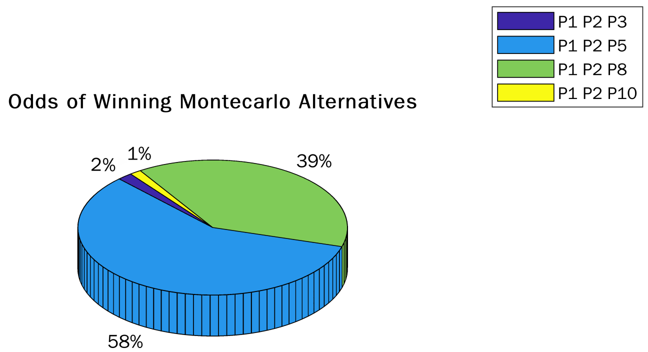

FIGURE 33. Odds of winning montecarlo alternatives.

TABLE 7. Reliability variables for each scenario analyzed (Exhaustive Search).

Analysis Scenarios	**SAIFI** Number of failures per year per user	**SAIDI** Interruption time per year per user	**CAIDI** The average duration of a failure	**AENS** kWh of Energy not supplied by user
Only P1	13,0018	31,0908	2,3913	24,9538
P1, P2, P3	9,7371	22,0125	2,2607	15,9375
P1, P2, P5	**8,3393**	**18,3639**	2,2021	**13,2114**
P1, P2, P8	8,7402	20,2842	2,3208	14,6680
P1, P2, P10	10,0356	23,1910	2,3109	16,6960
P1, P3, P5	9,3482	19,8393	**2,1223**	14,3064
P1, P3, P8	10,7359	27,1154	2,5257	19,5171
P1, P3, P10	9,2245	21,0792	2,2851	15,2320
P1, P5, P8	10,7359	24,0873	2,2436	17,2867
P1, P5, P10	9,7895	22,2959	2,2775	15,9926

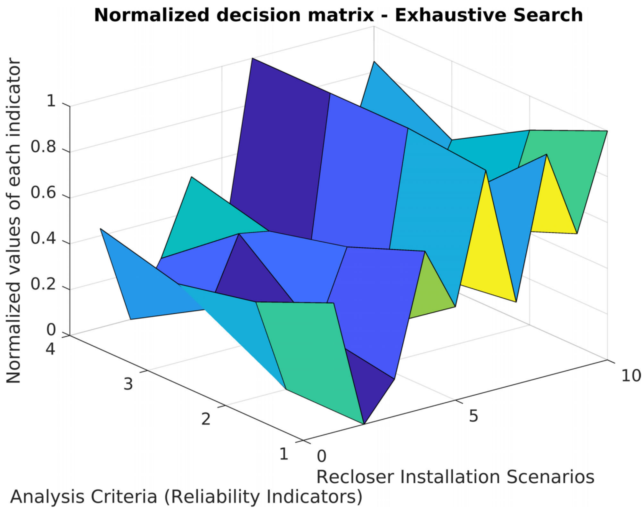

FIGURE 34. Normalized decision matrix for the ten analysis scenarios (Exhaustive Search).

in addition to the existing one in P1. The second sectioning alternative with the best results is the location of reclosers in P1, P2, and P8 (31%). This result also coincides with the second best found by the proposed sectioning coordination method.

From this validation analysis of the results considering all the scenarios, it can be concluded that:

The method proposed as coordination of sectioning using a study of many scenarios by Montecarlo does not present any loss of the optimal result. This is because the location defined as the second recloser located in P2 is a mathematically dominant result, which was presented as the winner in 64% of the alternatives studied. However, the alternative of locating two reclosers in P2 and P5, in addition to the existing one in P1, was presented as the winner in 58% of the analyzed alternatives. The analysis of random variables and the study using the Montecarlo method justify this sectioning coordination proposal without introducing error or loss of essential results.

The proposed method allows the study of the winning alternative with less computational time since exploring some of the alternatives would only be necessary. Still, the new solution would depend on a dominant previously found solution.

Through a fundamental and exhaustive mathematical analysis, it was possible to demonstrate that the result obtained using the sectioning coordination method is equal to that obtained considering all possible scenarios through an Exhaustive Search. In this way, the method is validated as a very efficient, novel, and robust alternative for studying the optimal location of sectioning in electrical distribution systems.

It was also verified that in each iteration analyzed by both methods, the result of the winning alternative was the same in most cases, despite the high uncertainty of the data.

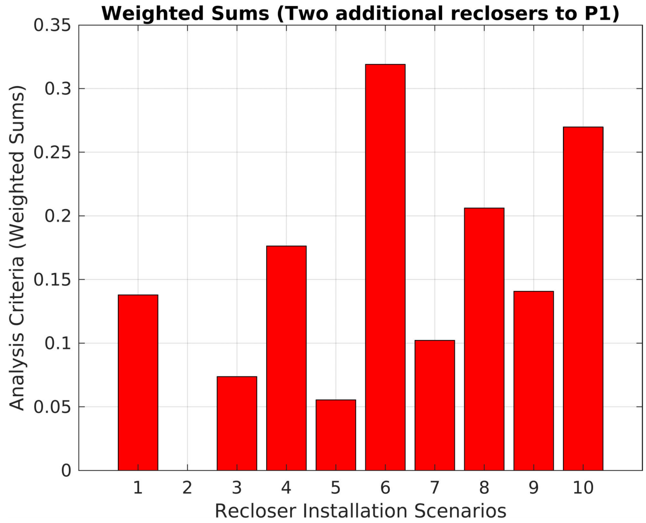

FIGURE 35. Weighted sums (exhaustive search).

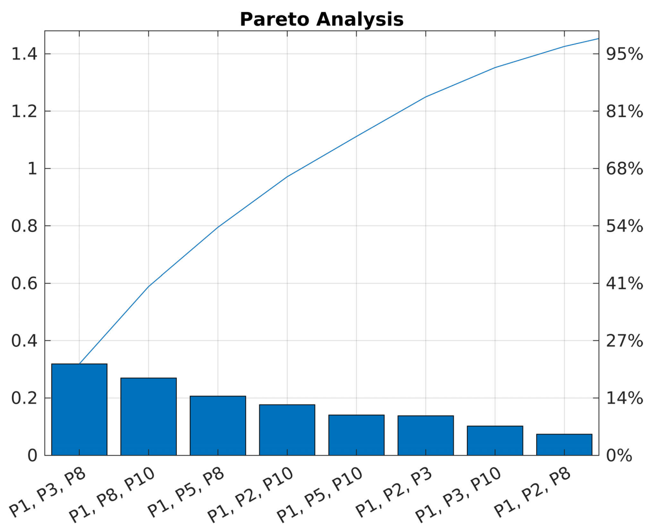

FIGURE 36. Analysis of pareto optimal scenarios (consideration of maximum to minimum.

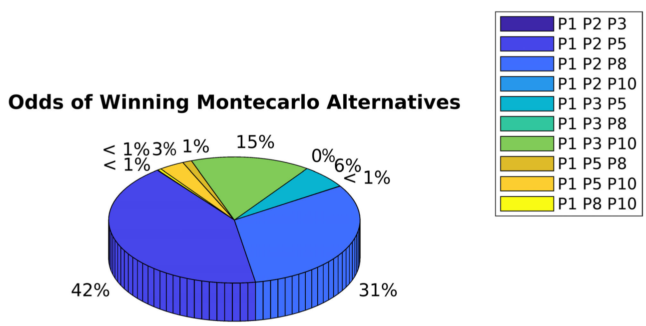

FIGURE 37. Analysis in Montecarlo of all the winning alternatives (exhaustva search).

VI. CONCLUSION

The applied research presents a novel methodology to define the optimal location of switching devices in electric distribution systems, considering reliability indicators as decision criteria. The proposal enables us to determine the location of switches optimally under multiple criteria, thus obtaining a switching solution that jointly responds to user susceptibility indicators (SAIFI, SAIDI, CAIDI) and the indicator of economic loss by energy not supplied (AENS). The study is generic and responds to a stopping condition of the algorithm, which is based on the cost constraint due to the number of switchings it is desired to connect. This cost constraint may be defined by the user (Electric Power Distribution Company) or may also be determined by marginal analysis of the exchange ratio obtained between the cost and the improvement of reliability indicators.

The proposal enables us to define the reliability analysis as what it is, a probability. In this sense and considering the lack of data about failures and duration times of these failures in each element of the system, it is proposed a novel methodology to generate these data as pseudo-random variables that are defined in a particular range that is often known at a general level of a specific circuit. Without these data (Montecarlo indicators: λ, μ), it is proposed to solve the problem with a very accurate approximation based on the available knowledge about the circuit's topology. This approximation solves the most significant problem of the reliability study at level 3 (distribution) with little uncertainty.

The optimization analysis by multicriteria decision is carried out for different pseudo-random generations of the data, which enables knowing more precisely the probability of becoming a winning alternative of each of the switching possibilities considered as candidates for the installation of a recloser. This analysis responds to the Montecarlo method as one of the more robust probabilistic theories for this type of study. The calculation of the winning probability of each alternative was simulated in 100,000 Montecarlo scenarios for an absolute error of 0.0032. The alternative of locating two reclosers in P2 and P5, in addition to the existing one in P1, was presented as the winner in 58% of the analyzed alternatives. The method proposed as section coordination was validated with an exhaustive search. It was shown that it does not present any loss of the optimal result, identifying the same winning alternative in 64% of the random scenarios studied.

It should be noted that the proposed model is also suitable for a distribution system in which data are known accurately. In this manner, the optimal location of the switching and its coordination is defined by the multicriteria method but accurately for the data presented.

VII. FUTURE WORK

This methodology is considered comprehensive and innovative. However, future work is proposed to replicate the analysis in different case studies that contemplate ring circuit topologies. The proposed method is entirely generic. However, the reliability indicators must be calculated differently in each study case depending on the circuit topology.

A. GLOSSARY OF TERMS

SAIFI: System Average Interruption Frequency Index.

SAIDI: System Average Interruption Duration Index.

CAIDI: Customer Average Interruption Duration Index.

AENS: Average Energy Not Supplied.

Montecarlo: This is a mathematical technique used to estimate the possible outcomes of an uncertain event.

Multicriteria Analysis: A set of mathematical procedures to select decision alternatives based on contradictory criteria.

Switching Coordination: It calculates the location of new sectioning, considering disconnectors that were previously located optimally.

Reliability: It is the probability that a piece of equipment or system will operate correctly as expected.

Pseudo-random Variables: These variables contain randomly generated values with a computational tool, but established limits delimit these values.

Reclosers: Automatic Circuit Reclosers (ACRs) are switchgear designed to detect and interrupt faults in electricity distribution networks.

Failure Rate: It can be defined as the anticipated number of times an item or system fails in a specified period.

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