Fault Indicator Placement in Distribution Systems: Improving the Criteria of Quality of Service

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***Abstract*—Distribution utilities need to ensure fast fault location to improve the energy supply service, given that, in the event of an outage scenario, the service restoration process starts after the fault has been localized. Minimizing the time required for fault location leads to a reduction in the system average interruption duration index (SAIDI), a crucial metric that all utilities strive to meet. The use of fault indicators can facilitate the fault location process in distribution systems. The challenge lies in determining the optimal placement of these fault indicators to facilitate the fault location process effectively. This paper presents a metaheuristic-based framework that takes into account both commercial and operational criteria to optimize the placement of fault indicators in distribution systems. This tool considers essential practical factors to assist utilities in achieving minimal SAIDI by optimizing the allocation of fault indicators. The method is tested for a 135-bus distribution feeder to verify its practicability. The numerical results demonstrate that the proposed methodology improves the expected SAIDI, leading to better energy supply service for customers.**

***Index Terms*—Distribution System, Reliability, Fault Indicator Allocation, Fault Location, Genetic Algorithm.**

I. INTRODUCTION

Distribution utilities are financially rewarded or penalized based on reliability indexes, among other factors. Two of the main continuity indexes considered by the utilities and regulatory agencies are system average interruption duration index (SAIDI) and system average interruption frequency index (SAIFI). Both SAIDI and SAIFI are affected by faults that occur in distribution systems (DSs) caused by adverse weather conditions, equipment failure, or any other exogenous reason [1], [2]. Thus, the utilities must develop means to mitigate the effects of such contingencies.

The fact that DSs are commonly operated using a radial topology contributes to the increase of the area affected by a fault. This happens because, as a general rule, every consumer downstream of the protective device (PD) that operates to clear the fault experiences an outage. In these situations, the control center initially faces the challenge of pinpointing the section under failure. Once the fault section is determined, the control center, with the assistance of repair crews, executes reconfiguration maneuvers to isolate the faulty section and restore the supply service to the healthy out-of-service sections that were affected by the operation of the PD [3]. It should be stressed that the development of service restoration plans, which ultimately lead to the recovery of healthy out-of-service sections, is only possible once the fault location within the outage zone is identified [4], [5].

It is common that new proposals for the service restoration problem found in the literature completely ignore the fault location step and consider it to be an input [3], [6]. Nonetheless, pinpointing the fault is a critical and very challenging step. If no fault location method is employed, identifying the exact location demands that the repair crew inspect all the elements of the section under fault. Not rarely, this is a time-consuming process, often taking hours, depending on the size of the outage area and its geographic characteristics. Furthermore, since no service restoration plan is available until this stage is concluded, the healthy out-of-service sections cannot be restored, which affects the SAIDI. Thus, if the actions taken to speed up the fault location process are insufficient, the distribution utilities can be financially penalized and have their commercial image affected [7], [8].

Although the substation relays usually have built-in impedance-based fault location algorithms, their accuracy is severely reduced by the lack of measurements along the DSs and the network's branched topology [9]. In this context, an alternative to expedite the fault location process is to install fault indicators (FIs) at different points of the network. The FI consists of an overcurrent sensor and a logic circuit that recognizes the fault condition and may be integrated with existing utility systems such as the supervisory control and data acquisition system (SCADA). Given the direct relationship between the fault locating time and the SAIDI, the allocation of FIs has the potential to impact this important reliability index. Furthermore, outage events also cause energy not supplied (ENS) events, which may reduce the utility's profit; thus, minimizing the fault locating time may also provide financial benefits for the utility.

In [10], a fault location method associated with an asset management system capable of dispatching repair crew to the estimated fault location to haste the service restoration leading to enhancement in customer experience. The fault location model uses data provided by FIs (fault flags and current magnitude measurements), the status of circuit breakers, and the loading of the network branches. The authors of [11] propose an outage management tool that integrates the information gathered by FIs, alarms, and reports from smart meters to narrow down the set of possible fault locations and activated protection devices for an event. The method is designed to be applied to large-scale DSs. Recently, the authors of [12] have proposed the use of artificial neural networks combined with fault indication signal provided by FIs without directional units to make this information useful even in the presence of bidirectional flow. The method presents an interesting solution to adequate old-fashioned FIs to the current operational reality of DSs. Nonetheless, it is crucial to stress that none of the proposals mentioned in this paragraph address the optimization of the allocation of FIs and other equipment. Thus, the efficiency of these methods is imperiled if there is no tool capable of effectively distributing the monitoring equipment throughout the network.

The authors of the works mentioned so far leverage the fact that some utilities have already installed FIs and other monitoring equipment on their DSs and use such information to ultimately enhance customer satisfaction or the utility's profit. Nonetheless, there have been approaches that propose the optimization of the allocation of FIs for over a decade [13]. The authors of [14], [15] and [16] propose formulations to optimally place FIs targeting cost-effectiveness maximization, i.e., simultaneous reduction of the costs associated with both equipment and ENS. However, it should be pointed out that systemic continuity indexes are disregarded as objective functions, which may benefit a few customers with high consumption at the expense of worsening the service of a large number of low-consumption clients. Furthermore, the authors disregard the existence of priority customers, instead the cost associated with the ENS is defined based on the kind of installation (i.e., residential, commercial, or industrial). In [17], two objective functions, representing the minimization of fault zones and the need to monitor load-wise dense areas, are weighted and added to determine optimized locations to install FIs. The number of FIs available for allocation is part of the input data and the method efficiently allocates FIs in a manner that the DS is divided into similar-sized regions. Still, this proposal also fails to directly address the enhancement of reliability indexes; instead, the authors focus on minimizing the size of the protection sub-zones (regardless of the number of customers) and monitoring high-consumption regions that may be composed of a single or a few clients.

Amongst the proposals in which reliability indexes are considered, the authors of [18] propose an optimization problem to maximize the cost-effectiveness of allocating FIs and automatic switches, i.e., minimization of the sum of equipment and interruption costs. Additionally, nodal reliability index targets are set and considered as constraints of the optimization problem. Nonetheless, the formulation does not address the minimization of systemic reliability indexes such as SAIDI and SAIFI; instead, the authors focus on ENS and a nodal reliability index referred to as load point long-term interruption frequency index (LLIFI), which was proposed to account for priority customers but disregards the number of clients connected to each node. In [19], a method to optimize both quantity and location of the FIs is proposed. The objective function is composed of two factors that must be minimized: 1) the costs associated with the customer interruption and FI acquisition/maintenance and 2) the SAIDI, for which the inspection time is considered to be minimized. However, the presence of priority customers is not considered. In this sense, FIs are allocated either to minimize the ENS, which tends to be related to high consumption or industrial clients, or to minimize SAIDI, which is related to regions with many customers regardless of their demand.

TABLE I
COMPARISON OF THIS PROPOSAL AND THE STATE OF THE ART

Reference	Aspect				
	IT	SAIDI	ENS	PC	ST
[13]	✗	✗	✓	✗	GA
[14]	✗	✗	✓	✗	MILP
[15]	✗	✗	✗	✗	MILP
[16]	✗	✗	✓	✗	GA
[17]	✗	✗	✗	✗	GA
[18]	✗	✗	✗	✓	–
[19]	✓	✓	✓	✗	MILP
This paper	✓	✓	✓	✓	CBGA

Note: IT - Minimization of inspection time; SAIDI - Minimization of SAIDI; ENS - Minimization of ENS; PC - Consideration of priority customers; ST - Solution technique; MILP - Mixed Integer Linear Programming; GA - Genetic Algorithm; CBGA - Chu Beasley Genetic Algorithm.

From the literature review presented thus far, it is possible to notice that there are many proposals for the allocation of FIs in DSs targeting the enhancement of different aspects important to the utilities. At the same time, one can observe that most approaches focus either on the minimization of the ENS (or monitoring regions with high demand), which tends to ignore systemic aspects and continuity indexes, or the complete opposite. Moreover, few works integrate the consideration of priority customers from a standpoint other than financially motivated. In this sense, this article bridges such gap by combining SAIDI (i.e., a systemic reliability index), close monitoring of high consumption areas, which indirectly leads to the minimization of the ENS, and the consideration of priority customers, regardless of their demands. The optimization is formulated as a minimization problem which is tackled using a Chu-Beasley genetic algorithm (CBGA) [20] that efficiently enhances the utility's SAIDI while considering practical aspects such as load density and priority loads. A comparison between this proposal and other approaches devoted to the allocation of FIs found in the literature is summarized in Table I.

The methodology is tested for a 135-bus DS, and the results, in terms of expected time for fault location, are validated using a Monte Carlo Simulation (MCS) to generate different fault scenarios. The remainder of this manuscript is divided into 5 sections. In Section II, we present the allocation problem and the proposed optimization formulation. The solving technique is addressed in Section III, while the numeric results are presented in Section IV. Finally, the main conclusions are drawn in Section V.

II. FAULT INDICATOR ALLOCATION METHODOLOGY

In this paper, the allocation of FIs is formulated as a minimization optimization problem. Thus, the optimal solution is the one that yields the lowest objective function (OF) while satisfying the problem's constraints. The mathematical formulation for this problem is presented in the following subsections.

A. Objective function

Equation (1) presents the OF, which incorporates, in our point-of-view, three of the most important factors for the utilities that can be affected by the allocation of FIs.

$$\text{OF} = \min \sum_{i=1}^{n} (SAIDI_i + Fld_i + Fpc_i) \tag{1}$$

where n represents the number of protection zones. The concept of protection zone adopted in this paper is the same as the one employed in [2], [21], i.e., the set of nodes and branches directly downstream of a PD or comprised between two PDs. $SAIDI_i$ is the annual SAIDI caused by the operation of the PD i, Fld_i is the load density factor for protection zone i and Fpc is the factor of priority customers connected to protection zone i.

It should be highlighted that the three components of (1) present different orders of magnitude. Thus, to avoid the minimization of a single factor due to its larger effects on the OF, all of them are normalized with regard to the power system's original values, i.e., values calculated disregarding the installation of FIs. The formulation of the factors comprising the objective function is provided in the next subsections.

B. Reliability factor

The SAIFI and SAIDI are internationally accepted reliability indexes that may also be indicators of the quality of service offered by distribution utilities to their customers. These indexes are managed at the level of the entire utility; however, these indexes may be calculated for each of the utility's feeders to identify the ones that are most affecting the company's global reliability indexes. This information can be used to define maintenance and intervention plans to enhance the feeder's indicators, aiming to comply with regulatory and corporate goals. Since the SAIFI can hardly be minimized by measures other than the allocation of PDs, in this paper, we focus on a SAIDI-based analysis. In this approach, the SAIDI is calculated as follows:

$$SAIDI_i = \frac{C_i \gamma_i T_i}{TC} \tag{2}$$

where C_i is the number of customers downstream of the PD that defines the protection zone i. γ_i is the expected annual number of operations of the PD[1] that defines zone i, which depends on the rate of failure of the branches comprising protection zone i and can be found in [22]. T is the expected outage time for a fault that occurs within protection zone i, and TC is the total number of customers connected to the feeder.

Observe that once the protective zones are defined, the only way to minimize the feeder's SAIDI without performing a service restoration plan, is to minimize the outage time. In this sense, it is important to stress that the total outage time is given by three terms, as follows:

$$T = t_1 + t_2 + t_3 \tag{3}$$

where t_1 represents the time required for isolating the faulty section (i.e., protection zone), t_2 is the time allocated for inspecting the faulty section by the repair crew, and t_3 denotes the time taken for actually repairing the damage and definitively restoring service.

Considering T as the sum of these three durations, it is possible to observe that the installation of FIs can only affect time t_2. To illustrate such claim, consider the radial topology shown in Fig. 1, which has a single protection zone (defined by the recloser R1) comprised of 9 nodes and 8 branches. Considering the devices installed in Fig. 1(a), if a fault occurs within this protection zone and disregarding the availability of any fault location estimator, the repair crew would possibly have to inspect the entire protection zone to find the outage source, which could take up to 8ι hours (considering the inspection time of every branch as ι). When analyzing the same event but considering the devices shown in Fig. 1(b), one can observe three "sub-zones". In this context, if a fault occurs within the blue zone, defined by the FI$_1$, the repair crew would know that the fault is either in branch 2-5 or branch 5-6, and the inspection time would be limited by a maximum of 2ι hours. The worst-case scenario would be a fault upstream of both FIs. In this context, none of the FIs would sensitize, and the crew would have to inspect branches 1-2, 2-3, 3-4 and 2-7, which could take up to 4ι hours. Observe that this worst case is much better than that of the topology shown in Fig. 1(a). Finally, if a third FI is allocated, as shown in Fig. 1(c), regardless of the fault location, the repair crew would have to inspect at most 2 branches, which would take up to 2ι. It is worth noting that t_1 and t_3 exhibit random behavior and are influenced by factors outside the scope of this methodology. Furthermore, in this paper, we consider t_2 to be the worst-case scenario (e.g., 8ι, 4ι and 2ι for the topologies shown in Figs. 1(a), 1(b), and 1(c), respectively). It should be highlighted that in this paper, we consider the installation of FIs with directional units. In this sense, it is possible to access the fault current direction on every FI sensitized by the event to narrow the faulty section. Thus, the method is not affected by reverse power flow.

C. Load density factor

It is crucial to highlight that each protection zone comprises a specific number of customers and their respective demands.

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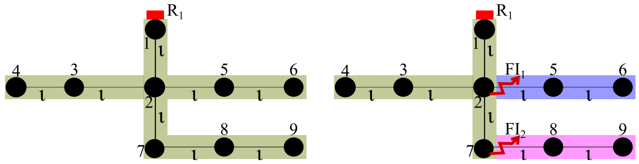
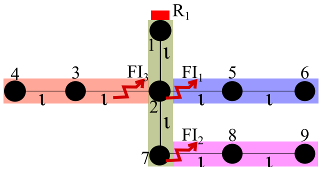
[1] In a DS, every fault is cleared by the operation of a PD; thus, given the DS radial topology, determining which PD clears the fault is crucial to establishing the outage area. The expected number of operations is equal to the sum of the number of faults expected to occur within a protection zone, which is a function of the failure rates and the size of the protection zone.



(a) Allocation of FIs - example A. (b) Allocation of FIs - example B.



(c) Allocation of FIs - example C.

Fig. 1. Illustration of the impacts of the allocation of FIs on the inspection time.

Additionally, given that feeders typically serve a mix of industrial, commercial, and residential clients, there are regions that present high consumption but few connection points. In this sense, a failure that affects such an area would significantly contribute to the ENS but may not affect the SAIDI in the same proportion. This situation is detrimental to both the utility and the customers. Therefore, while improving the SAIDI is a valuable goal, it should not be the only factor impacting a FI allocation methodology since it does not account for the consumption patterns of the various customers type.

The load density factor (Fld), calculated as shown in (4), was designed to account for these aspects, contributing to the ENS minimization.

$$Fld_i = \frac{\max_{j \in \mathbf{B}_i} [S_j l_j]}{S_f l_f} \tag{4}$$

where i is the protection zone index, $\mathbf{B}_i$ is the set of sub-protection zones comprised within protection zone i, S_j and l_j are, respectively, the total demand and the length of sub-protection zone j, S_f is the feeder's total demand, and l_f is the feeder's total length. It should be pointed out that sub-protection zones differ from the protection zone only if at least one FI is installed within the protection zone.

Observe that the allocation of k FIs in a protection zone increases the number of sub-protection zones by k + 1. Thus, the installation of FIs contributes to decreasing the numerator of (4), since the demands and lengths are divided amongst the sub-protection zones. Therefore, the allocation of FIs in areas with high load density enhances the objective function.

D. Priority factor

Distribution utilities employ various commercial strategies, one of which involves classifying their customers based on priority during restoration scenarios. The priority customers can be diverse, including but not limited to hospitals, high-consumption industries, delicate manufacturing processes, long-term contracts, and others. As a general rule, the utilities place equipment in the network to enhance the monitoring and control over sections with priority customers.In this proposal, the priority factor of protection zone i (Fpc_i) is calculated as follows. Observe that the same logic applied to explain why the allocation of FIs minimizes the load density factor can be employed to justify the benefits of minimizing (5) and its relationship with the installation of FIs.

$$Fpc_i = \beta \frac{\max_{j \in \mathcal{B}_i} PC_j}{PC_f + \alpha} \tag{5}$$

where i is the index for the protection zone, $\mathbf{B}_i$ is the set of sub-protection zones comprised within protection zone i, PC_j the number of priority customers connected to sub-protection zone j, and PC_f the total number of priority customers connected to the feeder. β is an adjustment parameter that falls within the range of 0 to 1 and was designed to provide the user with the capacity to moderate the level of influence exerted by this factor on the methodology. A more profound analysis of this topic is provided in section IV. α is a very small constant designed to prevent division by zero in cases where the feeder does not have any priority clients. In this paper, we adopt $\alpha = 0.01$.

E. Allocation constraints

In this subsection, we provide limitations for the allocation of FIs based on technical and economic aspects. Firstly, it should be stressed that digital PDs have an overcurrent unit capable of communicating with the SCADA. Thus, nodes with such PDs already have some kind of fault indication capacity. In this sense, (6) prohibits the allocation of FIs at the same location as a digital PD as a means to avoid unnecessary spending.

$$\sum_{d \in \mu_d} X_d = 0 \tag{6}$$

where μ_d is the set of nodes with digital PDs and X_d is a binary variable that indicates the allocation of a FI at node d.

Additionally, observe that the objective function does not consider a cost-benefit analysis, i.e., the acquisition costs are not considered. Instead, we directly impose a limit on the availability of FIs to be allocated in the DS via (7).

$$\sum_{i=1}^{n} X_i < Q \tag{7}$$

where Q is a parameter that indicates the number of FIs available for allocation and X_i is a binary variable that indicates the allocation of a FI at node i.

III. FAULT INDICATOR PLACEMENT WITH THE CHU–BEASLEY GENETIC ALGORITHM

The proposed methodology is solved using the CBGA. This version of the genetic algorithm (GA) features an additional constraint in comparison with the original formulation that prohibits the inclusion of duplicate solutions in the population. This feature ultimately leads to better exploring the search space and avoiding a premature convergence to local optima [20]. The formulation for the fitness of each individual in the population, shown in (8) is calculated as the sum of the OF, which is calculated as shown in (9), and a penalization factor due to violations of constraints (6) and (7), as per (10).

$$Fitness = OF + Inf \tag{8}$$

$$OF = \sum_{i=1}^{n} (SAIDI_i + Fld_i + Fpc_i) \tag{9}$$

$$Inf = \kappa \left(\sum_{d \in \mu_d} (X_d) + \max \left[0, \sum_{i=1}^{n} (X_i) - Q \right] \right) \tag{10}$$

where κ is a penalization factor.

The improvement of the fitness values in each iteration due to obtaining solutions in which the placement of FIs positively affects the utility's goals. As a general rule, these targets are reached by evenly distributing the FIs throughout the DS, but this may not be the case depending on the power system's characteristics. The subsequent sections provide a detailed explanation of the key steps involved in implementing the proposed method.

A. Codification

Given the binary nature of the problem since the decision variable is to either allocate or not allocate a FI at a specific location, binary coding was employed. Each branch is represented by a gene that constitutes the CBGA chromosome. Therefore, the size of the chromosome depends on the number of branches within the system. Under the adopted codification, a gene with a value of 1 indicates that the associated branch has an FI installed, whereas a gene with a value of 0 indicates the absence of a FI.

B. Generating the initial population

The genes of the individuals in the initial population are randomly generated, resulting in a diverse set of individuals. The population size is determined based on the nature of the problem. To ensure an adequately diverse population, a population size equivalent to 13 times the number of branches in the test system was chosen. With this population size, the algorithm consistently found two distinct parents for the recombination process in all of its iterations. Simultaneously, each individual in the population undergoes evaluation with respect to the OF, and their infeasibility is determined in accordance with the defined constraints. Consequently, each individual is accompanied by these two additional pieces of data,i.e., OF and penalization factor.

C. Parent selection and genetic operators

The tournament selection process was employed, as it is widely used in the literature for its simplicity and efficiency, as demonstrated in [1], [2]. In this paper, two distinct candidates are randomly selected from the existing population, and the one with the lowest infeasibility is selected as the winner; if the two candidates have the same infeasibility factor, then the one with the best OF is selected. The process is conducted twice to select two parents, always ensuring that the two selected individuals are different.

In this paper, the one-point crossover operator is employed to generate two children. The mutation operator has a 30% chance of occurrence and inverts a single gene (from 0 to 1 and vice-versa) of the children's chromosomes. The mutation point is randomly selected but is the same for both children.

D. Substitution criterion

Following the application of the genetic operators, the fitness of each child is determined. Subsequently, one of them is selected to integrate the current population based on their characteristics, i.e., the child with the lowest infeasibility or, if both children have the same infeasibility value, the one with the best OF is chosen.

The substitution criterion defines whether or not the selected child will replace the individual in the current population with the greatest infeasibility value (or lowest OF if all individuals share the same infeasibility). However, the selected child cannot be included in the current population if the same codification is already in the current population. Thus, the idea of the substitution process is to simultaneously improve the population's quality and maintain diversity. An additional advantage of the CBGA over the original GA is that it preserves the best individuals generated instead of eliminating every solution at each iteration as the conventional GA; thus, the best individuals are only discarded when new ones with better fitness values appear [23].

E. Stop criterion

The adopted stop criterion is the maximum number of iterations.

IV. NUMERICAL RESULTS AND DISCUSSIONS

The allocation method proposed in this paper is validated for the 135-bus test system adopted in [2], which is based on a real Brazilian DS. Since the allocation of protective and controlling devices affects the expected reliability indexes, we have considered the allocation of such devices presented in [2], which was designed to minimize ENS and SAIDI. Furthermore, the parameters of the PDs that compose this protection system have been optimized to ensure the coordination and selectivity of their operation. The CBGA was implemented in MatLab and the simulations were carried out in an Intel i7-7700 processor @3.6 GHz with 16GB of RAM.

In this section, we present the validation of the proposed method using four case studies, which have been designed to provide a sensitivity assessment of the number of available FIs, i.e., parameter Q of constraint (7), and the effects of changing the influence of the priority factor, i.e., parameter β in (5). A summary of the case studies is presented in Table II.

TABLE II
SUMMARY OF THE CASE STUDIES

	# FIs (Q)	Priority customers	Priority influence (β)
Case study 1	10	✗	–
Case study 2	20	✗	–
Case study 3	10	✓	1
Case study 4	10	✓	0.5

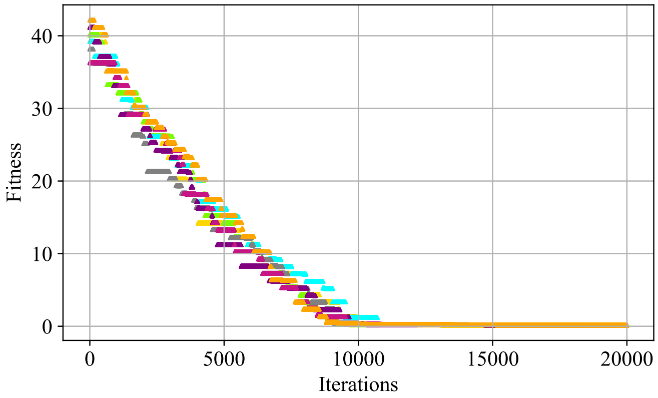


Fig. 2. Representation of the convergence of the CBGA case study 1.

A. Sensitivity analysis of parameter Q

The convergence graph for case study 1 is depicted in Figure 2. The y-axis represents the fitness value of the best individual in the population in each iteration (i.e., the one with the lowest fitness value), and the x-axis represents the number of iterations. It is important to highlight that Fig. 2 also illustrates the CBGA's capacity to converge to similar solutions in multiple runs, as even though each of the colors presented in the figure represents the results obtained in a different execution the methodology converges to very similar or identical fitness values. Additionally, despite considering 20,0000 iterations as the stop criterion, the algorithm's running time is approximately 415 seconds.

The placement of the FIs for this case is illustrated in Figure 3. The FIs are allocated on branches 3, 9, 18, 47, 68, 82, 91, 93, 104 and 113. The FIs positioning is adequately spaced to effectively create multiple sub-regions inside the already existing protection zones in a well-distributed manner, as shown in Table III, while complying with the established constraints.

Observe that, prior to the installation of the FIs, inspecting the protection zone delimited by the substation relay could demand up to 1.665 hours (the inspection time of each branch is available in [22]). Alternatively, considering the 4 FIs allocated by the CBGA in this protection zone, which divides the section into 5 search zones, the worst-case inspection time becomes 0.545 hours.

A direct comparison between the expected inspection times with and without FIs was conducted using Monte Carlo Simulation (MCS). In this analysis, 100,000 faults were applied in the system distributed in accordance with the fault rate of each branch (available in [22]). For each fault, and whenever possible, we considered the fault indication signal provided by the FIs to narrow the search area and considered that the repair crew would have to inspect the entire narrowed area. For instance, if the FI located at branch 18 indicates a fault, then we consider that the repair crew would have to inspect branches 18, 19, 20, 21, and 22, i.e., the section downstream of the FI. The expected searching times for the scenarios with and without FIs are presented in Fig. 4.

TABLE III
LENGTHS OF THE PROTECTION ZONES (KM)

Protection zone	Length without FIs	Length for case study 1	
		Subzone lengths	Critical length
1	3.300	{0.900;0.690;0.750;0.310;0.680}	0.900
4	0.100	{0.100}	0.100
25	0.370	{0.370}	0.370
40	0.100	{0.100}	0.100
41	0.250	{0.250}	0.250
50	0.290	{0.290}	0.290
62	2.540	{0.490;0.350;0.520;0.560;0.600}	0.600
80	0.445	{0.100;0.345}	0.345
89	0.050	{0.050}	0.050
130	0.070	{0.070}	0.070
95	0.040	{0.040}	0.040
100	0.110	{0.110}	0.900
106	1.650	{0.560;1.090}	1.090
130	0.070	{0.070}	0.070

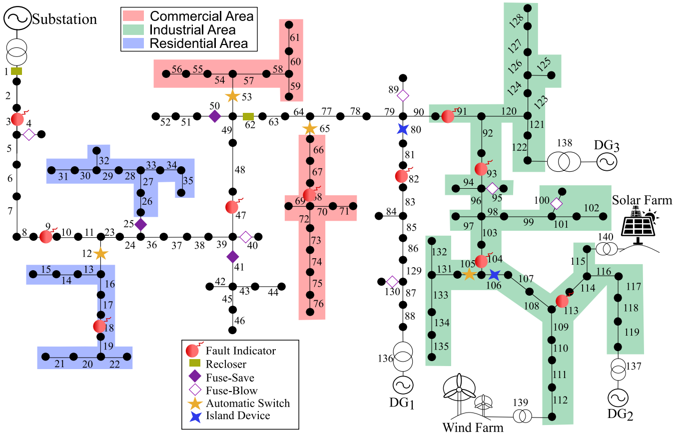
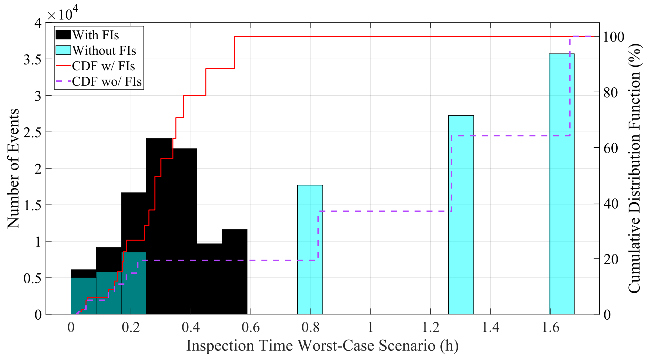
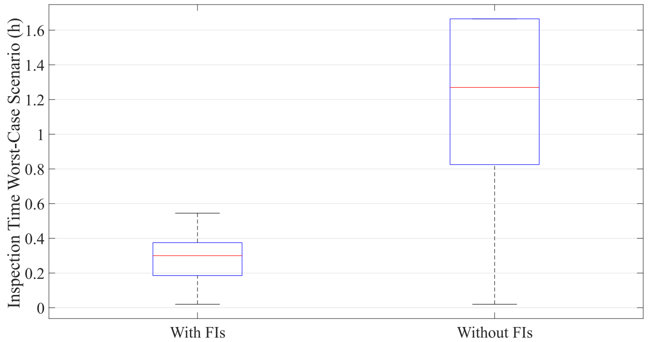


Fig. 3. Representation of the FIs installed for case study 1.

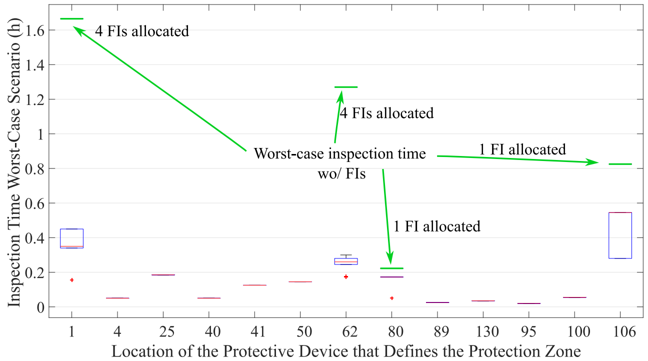
It is possible to observe in Figs. 4(a) and 4(b) that some faults demand the same amount of time with or without FIs. Notice that these events are rare and quickly identified (less than 0.2 hours). However, when there is no FI, the maximum inspection time for some events surpasses 1.6 hours, while the maximum inspection time observed for the scenario with FIs is less than 0.6 hours. As a result, the average and maximum inspection times are very different for the two topologies, as shown in Fig. 4(b). Observe that the minimum investigation time is kept constant, as these events are related to short branches that have not been affected by the allocation of FIs. This claim is supported by the result illustrated in Fig. 4(c), which depicts the expected inspection time variations for each protection zone. It is important to stress that the most affected inspection time is related to the protection zone defined by the substation's relay. The search time for protection zone 1 was 1.6 hours originally and was reduced to less than 0.6 hours. The other affected protection zones were the ones defined by



(a) Histogram of the distribution network's inspection time.



(b) Inspection time considering the entire distribution network.



(c) Inspection time of each protection zone.

Fig. 4. Case study 1 – Impact of FI allocation on the expected inspection time.

the PDs located at branches 62, 80, and 106. Noteworthy, the protection zones defined by devices at nodes 1 and 62 are the largest and feature the longest inspection times. Thus justifying the allocation of more PDs in these regions. Finally, observe in Fig. 4(c) that the protection zones defined by the PDs allocated on branches 4, 25, 40, 41, 50, 89, 130, 95, and 100 always present the same (or very similar) inspection times due to their short lengths; thus, the benefits of allocating a FI in these protection zones would be minimum to none from a SAIDI perspective.

Since the maximum lengths within each protection zone have been reduced, which leads to a reduction in the worst-case inspection time, as shown in Figs. 4(b) and 4(c), the annual expected SAIDI[2] for the DS with and without the allocation of FIs are, respectively, 0.1128 h and 0.4858 h (a 76.78% reduction). It is fundamental to highlight that the original placement of PDs is the result of an optimization method that aims to enhance, among other features, the SAIDI. In this sense, the allocation of FIs is a valid strategy to further enhance the reliability indexes of an already planned power system.

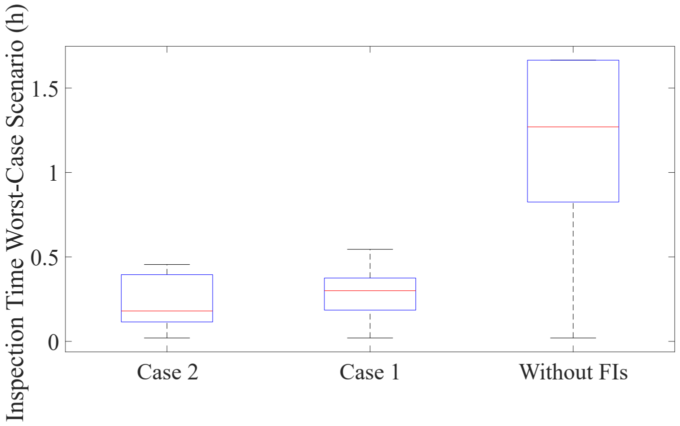


Fig. 5. Expected inspection times.

An additional study considering $Q = 1$ obtained the optimized allocation of FIs on the following branches: 3, 11, 24, 29, 48, 72, 77, 83, 86, 91, 96, 99, 104, 111, 114, 119, 120, 122, 124, and 131. As expected, more protection subzones are obtained by this solution due to the greater number of FIs available for allocation. Comparing the solutions obtained for considering $Q = 10$ (case study 1) and $Q = 20$ (case study 2), it is possible to observe that at least 7 out of the 10 FIs allocated by the CBGA in case study 1 are maintained at the same branch or a very close branch in case study 2. The FIs allocated at branches 3, 91, and 104 are maintained for both case studies and the ones at branches 9, 47, 82, and 114 are moved to branches 11, 48, 83, and 113, respectively, in case study 3. A direct comparison between the inspection times expected for the case without FIs, and case studies 1 and 2 is presented in Fig. 5. Observe that both the maximum and the average inspection times for the power system decreases as the number of FIs available for allocation increases. Such reduction in the inspection times causes a 18.26% reduction in the annual expected SAIDI for case 2 in comparison with case 1 (from 0.1128 h to 0.0922 h).

Given that the inspection time is affected by the number of FIs allocated in the DS, we provide a sensitivity analysis, illustrated in Fig. 6, regarding the effects of parameter Q on the network's expected SAIDI. It is possible to observe that as the number of FIs available for installation increases, the expected SAIDI decreases. Nonetheless, this is not a parameter that can be increased at will, as the utility must acquire the

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[2] It must be stressed that the SAIDI was calculated considering only the inspection time. The actual repairing time was not considered to avoid unrealistic values as this parameter changes depending on the fault nature and from one DS to another.

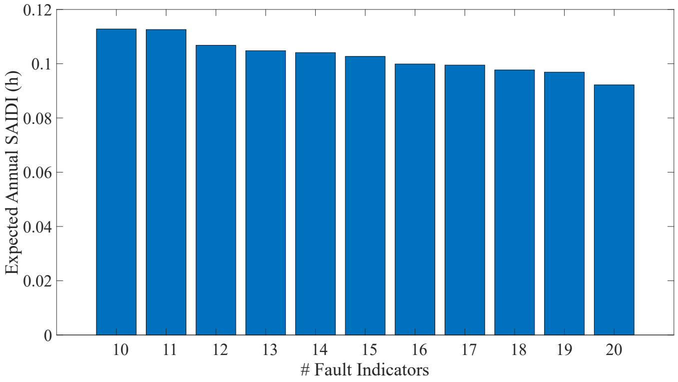

Fig. 6. Sensitivity analysis regarding the influence of FIs available for allocation.

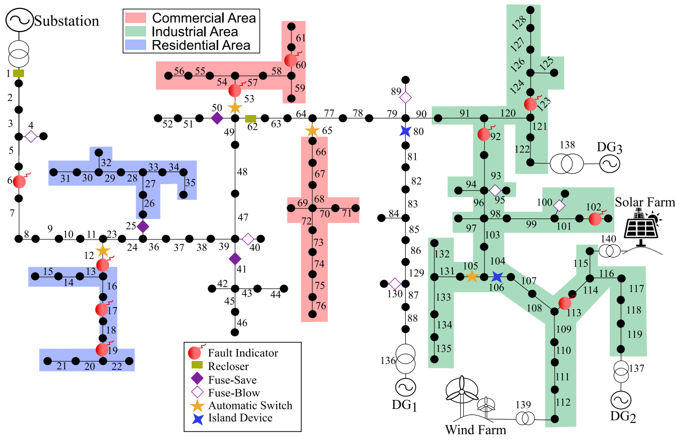

Fig. 7. Representation of the FIs installed for case study 3.

equipment, and the budget available for this goal is limited. In this sense, Q is meant to be used as input data that reflects the utility's budget rather than a tuning parameter.

B. Sensitivity analysis of parameter β

In this case studies presented in this subsection, 37 of the 4155 (0.89%) customers have priority over the others; the location and quantity of these customers can be found in [22]. Two case studies (3 and 4) are presented in this section to highlight the allocation changes caused by the variation of parameter β. Finally, a sensitivity analysis is presented considering the variation of parameter β, which is responsible for determining the impact of priority customers on the network's expected SAIDI.

Case study 3 adopts $\beta = 1$ and Q is set to 10. As a result, the proposed CBGA determines the placement of FIs on branches 6, 12, 17, 19, 53, 60, 92, 102, 113, and 123. It is possible to notice that the new allocation points are less spread throughout the DS, creating more cohesive protection subzones to provide additional attention to regions with priority customers. For example, in case study 1, which features the same number of FIs but disregards priority customers, the network section downstream of branch 53 was not selected to install FIs. However, the solution for case study 3 features the installation of two FIs in this region (branches 53 and 60) since 10 out of the total 37 priority customers are connected to this section. A similar situation is observed in other network sections, such as the section downstream of branch 12. For case study 1, only one FI was allocated in this section (branch 18), but in this scenario, three FIs are placed downstream of branch 12 (branches 12, 17, and 19) because this network section also serves 10 priority customers. While these actions benefit the service restoration to priority customers, they also lead to the lack of FIs in other network regions. For instance, in case study 1, a FI was positioned on branch 9 and the next on branch 47, having an inspection time of approximately 23 minutes for failures occurring between the branches connecting these two FIs, as indicated by the data available in [22]. However, for this case study there is a FI on branch 6, another on branch 12, and the next one is on branch 53, leaving a significant section of the network without an FI. This leads to an inspection time of approximately 37 minutes for failures occurring in the region between the FIs allocated on branches 12 and 53. As a result of the increment in the inspection time, the expected SAIDI for the network is 0.1649 h, which represents a 46.19% increase in comparison to the value obtained for case study 1 that features the same number of FIs. Therefore, utilities must carefully assess the level of attention they wish to provide to their priority customers as it could seriously affect the inspection time of network sections without FIs.

Case study 4 adopts $\beta = 0.5$ and $Q = 10$. The best allocation of FIs found by the CBGA features branches 5, 9, 13, 18, 48, 58, 91, 98, 118, and 123. By setting $\beta = 0.5$, the utility attributes lower importance to the support of priority customers than it did for case study 3, which mitigates the occurrence of extensive network segments without FIs. Consequently, it may be impossible to position FIs close to every priority client. For example, in this solution, priority customers downstream of branch 12 receive significant coverage given the installation of FIs on branches 13 and 18. In contrast, this solution does not assign an FI to assist priority customers downstream of branch 53. Instead, an FI is installed on branch 48 to prevent a substantial network segment from being without an FI. The expected SAIDI for this solution is 0.1198 h, which represents a 27.35% reduction in comparison to case study 3 and a 6.21% increase in comparison to case study 1.

As observed for case studies 3 and 4, changing the value of parameter β affects the placement of FIs, which in turn impacts the worst-case inspection time and consequently the SAIDI. Thus, the allocation problem was solved 10 times considering the variation of β, in steps of 0.1, from 0 to 1 to provide a sensitivity analysis regarding the relationship between β and the expected SAIDI. The SAIDI results are presented in Fig. 8.

As can be observed in Fig. 8, the increase of β worsens the feeder's expected SAIDI. In this sense, each utility must tune β to tailor the level of influence exerted by priority customers in the proposed method in a way that aligns the solution with their corporate and commercial policies.

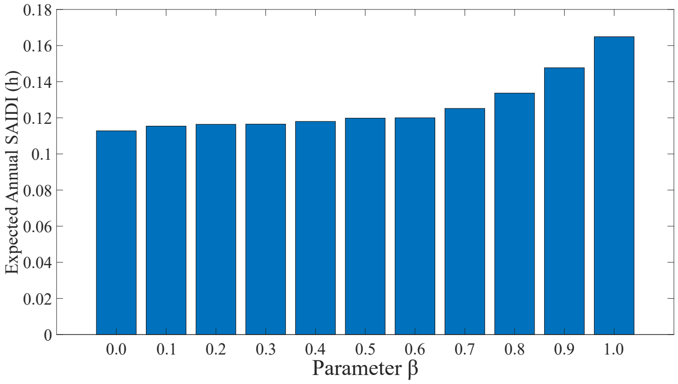

Fig. 8. Sensitivity analysis regarding the influence of priority customers.

V. CONCLUSIONS

This paper presents a methodology for optimizing the placement of FIs. It considers relevant criteria from the distribution utility standpoint, including service quality, maintenance crew inspection time, network topology, protection equipment location and operation schemes, load distribution, presence of priority customers, and the number of FIs available for allocation. The method is validated for a 135-node test system representing a real Brazilian DS considering multiple case studies and sensitivity assessments. The results are consistently satisfactory for every case study. The placement of FIs determined by this approach can enable utilities to respond to failures more promptly, resulting in shorter outage durations, which ultimately improve reliability indexes and customer satisfaction. Future works may address 1) the challenge of considering the integration of the FI with the SCADA system, 2) the effects of FI allocation on the service restoration problem as a quick fault location may allow for load transferring maneuvers that can further minimize the SAIDI, and 3) incorporate multi-period planning to address the planning and operational requirements of the utilities.

VI. ACKNOWLEDGMENT

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