Optimization Based Method for Fault Section Estimation on Distribution Systems

RODRIGO DE A. COELHO1, JAMILE P. N. AMOAH1, KARCIUS DANTAS1, KÉZIA DANTAS2, AND RAQUEL ZACARIAS3

1Department of Electrical Engineering, Federal University of Campina Grande (UFCG), Campina Grande, Paraíba 58429-900, Brazil
2Department of Computer Science, State University of Paraíba (UEPB), Campina Grande, Paraíba 58429-500, Brazil
3Light SA, Rio de Janeiro, Rio de Janeiro 20080-002, Brazil

Corresponding author: Rodrigo de A. Coelho (rodrigo.almeida@ee.ufcg.edu.br)

This work was supported by the Aneel Research and Development Program through Light SA/State University of Paraíba (UEPB)/Federal University of Campina Grande (UFCG)/Foundation Paraíba Technological Park (PaqTe-PB) under Grant PD-00382-0132/2020.

ABSTRACT Faults are inevitable in power systems and the accurate fault location is essential for system restoration and prompt response to customers demands. An alternative to identify the fault section in power distribution systems is to monitor the alarms and status of the protective devices. This paper presents a novel approach for fault section estimation in power distribution systems. The fault section location is treated as a 0-1 integer programming problem. The fault hypothesis is based on the actual and expected status of protective relays, circuit breakers, reclosers and fault indicators. Aiming to solve the programming problem, a new objective function is proposed and the genetic algorithm is used. The proposed method is applied to a typical 33 bus distribution system. The performance and effectiveness of the proposed method are assessed in challenging scenarios, including spurious data and operating failures of protective devices. The results show the feasibility of the proposed method for fault section estimation on power distribution systems.

INDEX TERMS Fault section estimation, analytic optimization model, distribution systems, genetic algorithm.

I. INTRODUCTION

Electrical power systems are susceptible to faults and power supply interruptions, specially power distribution systems [1]. Power interruptions may result in increased customers demands, as well as financial losses to utilities caused by onerous fines imposed by regulatory agencies. Therefore, accurate fault detection and location is essential for system restoration and prompt response to customers and regulatory agencies demands.

Typical approaches to fault detection in power systems make use of signal processing techniques to analyze voltage and/or current signals [2], [3], [4]. However, power distribution systems often do not provide sufficient equipment for voltage/current monitoring. In this scenario, monitoring the alarms and status of the protective devices (PD) can ensure the fault detection. For this purpose, the power system can be divided into sections, according to its topology. In this paper, a section is a part of the system (e.g: line, bus, etc) delimited by PD, such as circuit breakers (CB), protective relays (PR), etc. In general, the fault section estimation problem is straightforward when the PD operate correctly. However, in the cases of failure and/or malfunctioning of PD, the fault diagnosis is not always trivial [5].

The fault section estimation was initially proposed by [6]. In that paper, an expert system (ES) was presented and data from PR and CB were used. Other ES-based methods for fault diagnosis are presented in [7], [8], and [9]. In general, ES-based methods use a rule-based database and apply a reasoning system to locate the faulted section. However, the design and maintenance of the database are laborious tasks. In addition to ES, several techniques have been applied to the fault section estimation problem, such as neural networks (NN) [10], [11], [12], Petri nets (PN) [13], [14], [15], and Fuzzy logic (FL) [16], [17], [18]. Despite their good performance, NN-based methods inevitably require a lot of data for
Analytic optimization models are alternatives to the aforementioned techniques [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31]. In general, the analytic model-based methods establish criteria to identify the true and the false fault hypothesis (FH) and the fault section estimation problem can be formulated as an unconstrained 0-1 integer programming problem [32], which is solved using optimization algorithms. The optimization-based methods were first applied to the fault estimation problem in [19].

In that paper, the genetic algorithm (GA) was used to locate the fault based on the actual and expected status of PR. In [20], the AG was used to estimate the fault section based on the actual and expected status of CB. Other approaches have been proposed to locate the fault section using both PR and CB status. Those approaches are based on different techniques: Ant system (AS) [22], Tabu search (TS) [23], [24], [27], GA [30], TS and GA [25] and brain storm optimization (BSO) [29]. However, the above-mentioned approaches have been proposed for fault location on transmission systems, which are generally widely monitored and have complete information on the status of PD. Regarding power distribution systems, most of them have a less comprehensive monitoring level, in addition to a more complex topology, representing a challenge for fault section estimation.

In [21], a GA-based method evaluated the status of PD to locate faults in ring distribution networks. In that paper, radial networks were not analyzed, which are predominant in distribution systems. In [26], another GA-based method has been proposed to locate faults based on PD alarms acquired at the substations. However, as monitoring is based on substation data, the fault section identification may be unfeasible for faults located in remote areas. Also, the GA has been used in [28] for fault location using alarms from feeder terminal units (FTU). Nevertheless, a large number of FTU may be needed to ensure the fault location. In [31], a method using an oppositional BSO and data from FTU has been proposed for fault location in distribution networks. However, each bus of the network must be monitored by an FTU, making the fault location difficult for networks with low monitoring level.

In this paper, a fault section location method suitable for distribution networks is proposed. The method uses the GA as an optimization technique, which is a typical metaheuristic technique with promising performance for different power system problems [33], [34], [35]. The proposed method combines the status of different types of PR, CB, reclosers and fault indicators (FI) to describe the fault hypothesis and accurately locate the fault section. The main contributions of this work are:

- A new objective function (OF) based on the status of PR, CB, reclosers and FI is derived to locate the fault section by applying GA. In addition, the OF considers failure indexes that improve the fault section estimation even in cases with spurious data (PD operating logic errors or communication errors).
- A simple procedure is derived to attribute the weight factors to each element of the OF, including the PD and the corresponding sections. This procedure highlights the importance level of each PD and each corresponding section for the fault diagnosis.
- The proposed method has been successfully tested in several challenging cases, including spurious status of PD. Unlike the existing methods, the proposed one distinguishes true FH from false, showing superior performance and demonstrating its applicability to cases with abnormal or missing PD status, in addition to spurious data.

II. PROPOSED PROBLEM FORMULATION

The fault section estimation problem refers to the identification of the most probable fault hypothesis that explains the information taken from the protective devices operations [19]. Thus, the goal is to model a mathematical function that reflects the logical relationship between the status of power system protective devices and the possible fault sections.

A. THE FAULT HYPOTHESIS (FH)

The FH describes how the reported alarms can be logically explained as a function of the status of the sections and the PD. If a FH is consistent with the reported alarms, the expected status of PD should correspond to the alarms as closely as possible. Therefore, the FH can be expressed as follows

$$H = [S, R_m, R_b, R_c, C, E]$$

where:

- $S = \{s_1, s_2, \ldots, s_n\}$ is the set of possible fault sections and $s_k$ represents the status of the $k$-th element of $S$, with $s_k = 1$ and $s_k = 0$ equivalent to its faulted and normal status, respectively. $S$ is a vector to be determined;
- $R_m = \{r_{1m}, r_{2m}, \ldots, r_{nm}\}$ is the set of main PR related to $S$ and $r_{km}$ denotes the status of the $k$-th element of $R_m$. If it operates, $r_{km} = 1$, otherwise $r_{km} = 0$;
- $R_b = \{r_{1b}, r_{2b}, \ldots, r_{nb}\}$ is the set of backup PR related to $S$ and $r_{kb}$ corresponds to the status of the $k$-th element of $R_b$, with $r_{kb} = 1$ and $r_{kb} = 0$ equivalent to its operating and non-operating status, respectively;
- $R_c = \{r_{1c}, r_{2c}, \ldots, r_{nc}\}$ is the set of CB failure relays related to $S$ and $r_{kc}$ denotes the $k$-th element of $R_c$. If $r_{kc}$ operates, then $r_{kc} = 1$, otherwise $r_{kc} = 0$;
- $C = \{c_1, c_2, \ldots, c_n\}$ is the set of CB related to $S$ and $c_k$ represents the status of the $k$-th element of $C$. If it is tripped, $c_k = 1$, otherwise $c_k = 0$;
- $E = \{e_1, e_2, \ldots, e_n\}$ is the set of FI related to $S$ and $e_k$ corresponds to the status of the $k$-th element of $E$. 

R. D. A. Coelho et al.: Optimization Based Method for Fault Section Estimation on Distribution Systems

VOLUME 10, 2022

96129
If \( e_k \) identifies the occurrence of a fault, then \( e_k = 1 \), otherwise \( e_k = 0 \).

Reclosers are also typical PD in distribution systems. It basically comprises a circuit breaker with associated protection relay. In this work, the reclosers status are evaluated only after the last reclosing attempt. If this attempt is successful, there will be no fault section to be estimated. Otherwise, if the fault persists, the recloser trips without any additional reclosing attempt. In this way, the reclosers are included in the proposed FH as simple CB with the corresponding PR.

B. THE OBJECTIVE FUNCTION (OF)

The OF has two main parts: the first, \( F_1(\mathbf{H}) \), reflects the discrepancy between the actual and the expected status of power system devices; the second, \( F_2(\mathbf{H}) \), indicates the number of fault sections and malfunctioning devices. Thus,

\[
\min \{ F(\mathbf{H}) \} = F_1(\mathbf{H}) + F_2(\mathbf{H}).
\]

The function \( F_1(\mathbf{H}) \), derived from [25], depends on actual and expected status of power system devices, namely: main PR, backup PR, CB failure relay, CB, and FI. Hence, \( F_1(\mathbf{H}) \) can be formulated as follows:

\[
F_1(\mathbf{H}) = w_{rm} \sum_{k=1}^{n_r} |r_{km} - r_{km}^*| \left[ 1 - v_{kr} r_{kr}^* \right]
\]

\[+ w_{rb} \sum_{k=1}^{n_r} |r_{kb} - r_{kb}^*| \]

\[+ w_{rc} \sum_{k=1}^{n_r} |r_{kc} - r_{kc}^*| \]

\[+ w_c \sum_{k=1}^{n_r} |c_k - c_k^*| \left[ 1 - v_r c_k r_{kc}^* \right] \]

\[+ w_e \sum_{k=1}^{n_r} |e_k - e_k^*| \]

where: \( r_{km} \) and \( r_{km}^* \) denote the actual and expected status of the \( k \)-th PR with a \( \mu \) characteristic – \( \mu \in \{ m, b, c \} \) where “m”, “b”, and “c” denote the main PR, backup PR, and CB failure relay, respectively; \( c_k \) and \( c_k^* \) represent the actual and expected status of the \( k \)-th CB, respectively; \( e_k \) and \( e_k^* \) denote the actual and expected status of the \( k \)-th FI; \( v_{rm}, v_{rb}, v_{rc} \), and \( v_e \) are the weight factors for the PR with a \( \mu \) characteristic, CB, and FI, respectively; \( n_r, n_c \) and \( n_e \) are the number of PR, CB, and FI, power system sections, respectively.

The second term of the OF, \( F_2(\mathbf{H}) \), is an improvement of the formulation proposed by [24]:

\[
F_2(\mathbf{H}) = \sum_{k=1}^{n_c} w_{r_c} s_k + w_{rm} \sum_{k=1}^{n_r} |x_{r_{km}} + y_{r_{km}}| \\
+ w_{rb} \sum_{k=1}^{n_r} |x_{r_{kb}} + y_{r_{kb}}| \\
+ w_{rc} \sum_{k=1}^{n_r} |x_{r_{kc}} + y_{r_{kc}}|
\]

\[+ w_{c} \sum_{k=1}^{n_r} |x_{c_k} + y_{c_k}| \]

\[+ w_{e} \sum_{k=1}^{n_r} |x_{e_k} + y_{e_k}| \]

where: \( s_k \) represents the status of the \( k \)-th section; \( x_k \) denotes the misoperation index of equipment \( \xi \) \((\xi \in \{ r_{km}, c_k, e_k \})\); \( y_k \) represents the operating failure index of equipment \( \xi \); \( w_{r_{km}} \) is the weight factor of the \( k \)-th section; \( w_{r_{km}}, w_{c_k} \) and \( w_{e} \) denotes the weight factors for failure or misoperation of PR with a \( \mu \) characteristic, CB, and FI, respectively; \( n_s \) is the number of power system sections.

C. EXPECTED STATUS

The expected status of main PR is defined as

\[
r_{km}^* = \sum_{s_{n} \in S(r_{km})} s_{n},
\]

where: \( \sum^{\oplus} \) denotes the continuous XOR operator, which results in 0 only if all elements of the summation are equal to zero, otherwise the result is 1; \( S(r_{km}) \) is the set of sections protected by \( r_{km} \).

The expected status of backup PR corresponds to

\[
r_{kb}^* = r_{km} \otimes \sum_{s_{n} \in S(r_{km})} s_{n},
\]

where \( \otimes \) and \( \oplus \) represent the logical NOT and AND operators, respectively.

The expected status of a CB failure relay can be formulated as follows

\[
r_{kc}^* = c_k \otimes \sum_{r_{n} \in R(c_k)} r_{n} \otimes r_{n}^*,
\]

where \( R(c_k) \) is the set of PR that can trip \( c_k \), and \( r_{n} \in \{ R_m, R_b \} \).

The expected status of a FI is given by

\[
e_k^* = s_n, \quad s_n \in S(e_k),
\]

where \( S(e_k) \) is the set containing the sections supervised by \( e_k \).

The expected status of a CB can be determined as

\[
c_k^* = \sum_{r_{n} \in R(c_k)} r_{n} \otimes r_{n}^*.
\]

D. MISOPERATING AND OPERATING FAILURE INDEXES

The misoperation index points to an inappropriate operation of a certain equipment. This index will be 1 when the device operates and its expected status indicates otherwise. Hence, its value can be obtained as

\[
x_k = \xi \otimes \tilde{\xi}^*.
\]
The operating failure index represents a failure in the operation of a certain equipment. This index will be 1 when the equipment has not operated and its expected status indicates otherwise. Therefore, its value is formulated as follows
\[ y_{\xi} = \bar{\xi} \otimes \xi^*. \] (11)

E. WEIGHT FACTORS

Since circuit breakers trips depend on relays command, the information on relays is considered more relevant at the OF. Thus, it is reasonable to assume that the weight factors for main PR must be greater than the weight factors for CB, i.e., \( w_{rm} > w_c \). In the same way, as the status of backup PR depend on the status of main PR, it follows that \( w_{rb} > w_{rb}. \) Once the CB failure relays are associated with CB, it is also righteous that \( w_c > w_{rc}. \) Furthermore, as FI have similar purposes to main PR in the OF, it is assumed that \( w_{rm} \approx w_c. \)

A given section of a distribution system may have a greater number of PD than other sections, which reflects in a section with a higher monitoring level. To include this aspect in the OF, a criterion was established to assign the weight factors associated to each section, \( w_{sk}. \) Hence, considering that \( y_{sk} \) represents the number of monitoring devices in a given section \( sk, \) the criterion to attribute the weight factors \( w_{sk} \) can be formulated as follows:
\[
\begin{align*}
    w_{sk} &> w_{sb}, \quad \text{if } y_{sk} > y_{sb}, \\
    w_{sk} &= w_{sb}, \quad \text{if } y_{sk} = y_{sb}, \\
\end{align*}
\] (12)

where \( x_{sk} \in S \) and \( s_{sb} \in S. \)

III. GENETIC ALGORITHM

A genetic algorithm (GA) is an optimization method introduced by Holland in 1975 [36] and later popularized by Goldberg [37]. Based on the concepts of genetics and Charles Darwin’s theory of natural selection, Holland developed a method that emulates the process of evolution through an iterative process, which involves creating a population of individuals, evaluating their fitness, and generating a new population through genetic changes [36]. The study of GA requires the concept of some terms, which are listed in Table 1, and briefly, the method can be described as follows.

| Term       | Meaning in GA                                      |
|------------|----------------------------------------------------|
| Solution   | Chromosome or individual                           |
| The elementary part of a solution | Gene                                                 |
| Solution set | Population                                           |
| Iteration  | Generation                                          |
| Crossover  | An operation that forms new solutions from two random solutions |
| Mutation   | Random modification in the chromosome to prevent the population from becoming homogeneous |

The GA flowchart is shown in Fig. 1, it starts with a random population \((n_{pop})\) representing a set of possible solutions, evolving through successive generations. In each generation, a new population is formed, derived from the original one through crossover and mutation operations. In the generation loop, all individuals in the population are evaluated by a survival criteria, which consists of the value of the objective function (fitness) and a previously established selection mechanism, which determines which individuals should survive and participate in the next generation. This process is repeated until a complete evolution of the population to the ideal solution occurs [38]. Despite criticisms regarding processing time, GA is still one of the most robust methods found in the literature, mainly because GA is simple, flexible, and capable of finding the optimal solution.

IV. FAULT SECTION ESTIMATION

A. TEST SYSTEM

A widely used arrangement to study distribution systems is the IEEE 33 bus distribution system, originally proposed by [39]. This system comprises 33 buses, 32 lines, and no reactive power compensation unit. The grid is supplied by a feeder connected to the first bus, without additional power generating units. Over years, this test system has been used to study several problems in conventional distribution systems.

Recently, a modification to the IEEE 33 bus distribution system was proposed in [40], which inserted PD along the system. The test system adopted here is based on [40], which is depicted in Fig. 2. The protective scheme consists of CB, PR, and FI.

From a PD point of view, despite having 33 buses, the test system has only eight monitorable sections, as illustrated in Fig. 3.
Thereby, for the test system adopted, the FH is defined as
\[ H = \begin{bmatrix} s_1, \ldots, s_8, r_{1m}, \ldots, r_{4m}, r_{1b}, \ldots, r_{4b} \\ r_{1c}, \ldots, r_{4c}, c_1, \ldots, c_4, e_1, \ldots, e_7 \end{bmatrix}. \] (13)

### 1) Parameters Settings

The weights for the proposed OF are presented in Table 2, which were determined after a detailed sensitivity analysis. The used GA parameters are:
- Population size = 25;
- Number of bits / parameter = 8 (number of sections);
- Crossover rate = 0.8 (80%);
- Mutation rate = 0.02 (2%).

| Scenario | Faulted section | Activated PD | Spurious status |
|----------|-----------------|--------------|-----------------|
| 1.1      | s_1             | r_{1m}, c_1  | -               |
| 1.2      | s_1             | r_{1m}       | -               |
| 1.3      | s_1             | r_{1m}, c_1  | c_3             |
| 2.1      | s_2             | r_{1m}, c_1  | -               |
| 2.2      | s_2             | r_{1m}       | -               |
| 2.3      | s_2             | e_1, r_{1b}, r_{1c} | - |
| 3.1      | s_3             | r_{1m}, c_1  | -               |
| 3.2      | s_3             | r_{1m}, c_3  | -               |
| 3.3      | s_3             | r_{1m}, c_3  | e_6, r_{4m}, c_1 |
| 4.1      | s_4             | r_{2m}, c_2  | -               |
| 4.2      | s_4             | r_{2m}, c_2  | r_{4b}, c_7    |
| 4.3      | s_4             | c_2          | -               |
| 5.1      | s_5             | r_{4m}, c_4  | -               |
| 5.2      | s_5             | r_{4m}, c_4, c_5 | c_3          |
| 5.3      | s_5             | r_{4m}, e_5  | r_{3m}         |
| 6.1      | s_6             | c_4, e_5, e_7 | -               |
| 6.2      | s_6             | r_{4m}, c_4, e_7 | r_{3m}         |
| 6.3      | s_6             | r_{4m}, c_7  | -               |
| 7.1      | s_7             | r_{3m}, c_3, c_4 | -               |
| 7.2      | s_7             | r_{3m}, c_3, c_4, e_4 | - |
| 7.3      | s_7             | r_{3m}, c_3, c_4, e_4 | r_{3m}, c_3 |
| 8.1      | s_8             | r_{3m}, c_3, c_4, e_6 | -               |
| 8.2      | s_8             | r_{3m}, c_4  | -               |
| 8.3      | s_8             | r_{3m}, c_6  | r_{4b}, c_7, c_3, c_4 |

As shown in Table 4, the fault scenarios comprise spurious data from PD related to the faulted sections, spurious status from PD related to sound sections and operational failures of PD. Besides evaluating the feasibility and effectiveness of the proposed method, for comparison purposes, the fault scenarios were also applied to two well-established methods in the literature, termed here as methods M1 [24] and M2 [29]. Additionally, since the aforementioned methods do not include FI status on their problem formulation, the test
system must be adjusted to cover the features of M1 and M2, enabling its application. Once slight modifications were accomplished for the sake of comparison purposes, some particularities of each method must be mentioned before their application:

- Sections: since M1 and M2 do not consider FI, sections $s_2$, $s_3$, $s_7$, and $s_8$ do not exist in their formulation. Based on this, the test system shown in Fig. 2 should contain only four sections:
  - Section A, which includes buses 1-2, 19-25, i.e., $s_A = s_1 \cup s_2 \cup s_3$;
  - Section B, covering buses 3-6, thus $s_B = s_4$;
  - Section C, which covers buses 26-33, that is, $s_C = s_5 \cup s_6$;
  - Section D, comprising buses 7-18, i.e., $s_D = s_5 \cup s_6$.

- PD: The implemented M1 and M2 methods have taken into account the main protection, the backup protection and the breaker failure protection.

The results for the evaluated fault scenarios are shown in Table 5. It can be seen that M1 and M2 failed for many cases. In contrast, the proposed method correctly identified the fault sections for most of the case studies, including the ones with missing and spurious status of PD. The proposed method could not diagnose the faulted section in only three scenarios:

- Scenarios 4.3 and 7.3: these cases contain only the status of CB corresponding to the faulted section. Since the status of CB reverberates only at the expected status of the CB failure relay, (7), this status is not sufficient to sensitize the diagnostic method. In these scenarios, the methods M1 and M2 also did not locate the faulted section.

- Scenario 8.2: in this case, the spurious normal status of $e_6$ caused the method to indicate the fault section underlying the correct one. As $e_6$ is the only PD in Section 7, its normal status made the fault diagnosis unfeasible. However, even so, the proposed method presented a reasonable estimate for the fault section.

In another prominent case study (scenario 1.2) only the main PR status is activated, which was sufficient to locate the fault section using the proposed method. For the hypothesis of failure of the main PR and the CB (scenario 2.3), both the proposed method and M2 correctly located the fault section.

Table 5. Test results from故障 scenarios.

| Scenario | Activated PDs | Faulted section diagnostic result |
|----------|---------------|----------------------------------|
| 1.1      | $r_{1m}$, $c_1$ | $s_A$ | $s_A$ | $s_1$ |
| 1.2      | $r_{1m}$       | none  | none  | $s_1$ |
| 1.3      | $r_{1m}$, $c_1$, $c_3$ | $s_A$ | $s_A$ | $s_1$ |
| 2.1      | $r_{1m}$, $c_1$, $c_1$ | $s_A$ | $s_A$ | $s_2$ |
| 2.2      | $r_{1m}$, $c_1$ | none  | none  | $s_2$ |
| 2.3      | $c_1$, $r_{1b}$, $r_{1c}$ | none  | none  | $s_2$ |
| 3.1      | $r_{1m}$, $c_1$, $c_3$ | $s_A$ | $s_A$ | $s_3$ |
| 3.2      | $r_{1m}$, $c_3$ | none  | none  | $s_3$ |
| 3.3      | $r_{1m}$, $c_3$, $c_4$, $r_{4m}$ | none  | none  | $s_4$ |
| 4.1      | $r_{2m}$, $c_2$, $c_2$ | $s_B$ | $s_B$ | $s_4$ |
| 4.2      | $r_{2m}$, $c_2$, $r_{2b}$, $c_7$ | none  | none  | $s_4$ |
| 4.3      | $c_2$ | none  | none  | $s_4$ |
| 5.1      | $r_{4m}$, $c_4$, $c_3$ | $s_C$ | $s_C$ | $s_5$ |
| 5.2      | $r_{4m}$, $c_4$, $c_3$, $c_3$ | $s_C$ | $s_C$ | $s_5$ |
| 5.3      | $r_{4m}$, $c_4$, $r_{3m}$ | none  | none  | $s_5$ |
| 6.1      | $c_4$, $c_4$, $c_7$ | none  | none  | $s_6$ |
| 6.2      | $r_{4m}$, $c_4$, $r_{3m}$ | $s_C$ | $s_C$ | $s_6$ |
| 6.3      | $r_{4m}$, $c_4$, $c_7$ | none  | none  | $s_6$ |
| 7.1      | $r_{3m}$, $c_3$, $c_4$ | $s_D$ | $s_D$ | $s_7$ |
| 7.2      | $r_{3m}$, $c_4$, $c_5$, $r_{4m}$ | none  | none  | $s_7$ |
| 7.3      | $c_3$ | none  | none  | $s_7$ |
| 8.1      | $r_{3m}$, $c_3$, $c_4$, $c_6$ | $s_D$ | $s_D$ | $s_8$ |
| 8.2      | $r_{3m}$, $c_4$ | none  | none  | $s_8$ |
| 8.3      | $r_{3m}$, $c_4$, $c_6$, $r_{4m}$ | none  | none  | $s_8$ |

Generally, M1 and M2 performed well for scenarios where there were information from both CB and main PR related to the fault section. However, those methods failed when only the status of the main PR was available (e.g: scenario 1.2), besides other cases with spurious or missing data.

V. CONCLUSION

A new genetic algorithm based method for fault location in distribution systems was presented in this paper. Here, the fault hypothesis was defined according to the protective devices status, such as protective relays, circuit breakers and fault indicators status. The proposed objective function is based on the actual and expected status of those protective devices, taking into account their malfunctioning. Moreover, a simple procedure to attribute the weight factors to each element of the objective function, including the protective devices and the corresponding sections, was proposed. Thus, an analytic model to accurately determine the faulted sections in distribution networks was presented.

A typical distribution system were used for case studies and the proposed method presented a good performance to locate the faulted section in most of them. The results show that the proposed method is appropriate even for challenging scenarios with spurious status and operational failure of PD. Additionally, the proposed method was compared to two well-established methods in the literature, demonstrating its effectiveness and suitability to locate the faulted sections in distribution networks. As the proposed method is based only on PD status, it is also suitable for distribution systems with distributed generation. In this case, bi-directional PD should be taken into account.
REFERENCES

[1] M.-S. Choi, S.-J. Lee, D.-S. Lee, and B.-G. Jin, “A new fault location algorithm using direct circuit analysis for distribution systems,” IEEE Trans. Power Del., vol. 19, no. 1, pp. 35–41, Jan. 2004.

[2] F. B. Costa, A. Monti, and S. C. Paiva, “Overcurrent protection in distribution systems with distributed generation based on the real-time boundary waveform transform,” IEEE Trans. Power Del., vol. 32, no. 1, pp. 462–473, Feb. 2017.

[3] Z. Wei, Y. Mao, Z. Yin, G. Sun, and H. Zhang, “Fault detection based on the generalized S-transform with a variable factor for resonant grounding distribution networks,” IEEE Access, vol. 8, pp. 93151–93167, 2020.

[4] É. M. Lima, R. D. A. Coelho, N. S. D. Brito, and B. A. D. Souza, “High impedance fault detection method for distribution networks under non-linear conditions,” Int. J. Electr. Power Energy Syst., vol. 131, Oct. 2021, Art. no. 107041.

[5] Y. Sekine, Y. Akimoto, M. Kunugi, C. Fukui, and S. Fukui, “Fault diagnosis of power systems,” Proc. IEEE, vol. 80, no. 5, pp. 673–683, May 1992.

[6] C. Fukui and J. Kawakami, “An expert system for fault section estimation using information from protective relays and circuit breakers,” IEEE Trans. Power Del., vol. PWDR-1, no. 4, pp. 83–90, Oct. 1986.

[7] C. Yang, H. Okamoto, A. Yoyogami, and Y. Sekine, “Expert system for fault section estimation of power systems using time-sequence information,” Int. J. Electr. Power Energy Syst., vol. 14, nos. 2–3, pp. 225–232, Apr. 1992.

[8] T. S. Sidhu, O. Cruder, and G. J. Huff, “An abductive inference technique for fault diagnosis in electrical power transmission networks,” IEEE Trans. Power Del., vol. 12, no. 1, pp. 515–522, Jan. 1997.

[9] Y.-C. Huang, “Fault section estimation in power systems using a novel decision support system,” IEEE Trans. Power Syst., vol. 17, no. 2, pp. 439–444, May 2002.

[10] T. Bi, F. Wen, Y. Ni, and F. F. Wu, “Distributed fault section estimation system using radial basis function neural network and its companion fuzzy system,” Int. J. Electr. Power Energy Syst., vol. 25, no. 5, pp. 377–386, Jun. 2003.

[11] G. Xiong, D. Shi, J. Chen, L. Zhu, and X. Duan, “Divisional fault diagnosis of large-scale power systems based on radial basis function neural network and fuzzy integral,” Electr. Power Syst. Res., vol. 105, pp. 9–19, Dec. 2013.

[12] J. Liang, T. Jing, H. Niu, and J. Wang, “Two-terminal fault location method of distribution network based on adaptive convolution neural network,” IEEE Access, vol. 8, pp. 54035–54043, 2020.

[13] K. L. Lo, H. S. Ng, and J. Treac, “Power systems fault diagnosis using Petri nets,” IET Proc.-Gener. Transmiss. Distrib., vol. 14, no. 3, pp. 231–236, May 1997.

[14] V. Calderaro, C. N. Hadjicostis, A. Piccolo, and P. Siano, “Failure identification in smart grids based on Petri net modeling,” IEEE Trans. Ind. Electron., vol. 58, no. 10, pp. 4613–4623, Oct. 2011.

[15] B. Xu, X. Yin, X. Yin, Y. Wang, and S. Pang, “Fault diagnosis of power systems based on temporal constrained fuzzy Petri nets,” IEEE Access, vol. 7, pp. 101895–101904, 2019.

[16] C. S. Chang, J. M. Chen, D. Srinivasan, F. S. Wen, and A. C. Lieu, “Fuzzy logic approach in power system fault section identification,” IEE Proc. Gen. Transmiss. Distrib., vol. 144, no. 5, pp. 406–411, 1997.

[17] W.-H. Chen, “Online fault diagnosis for power transmission networks using fuzzy digraph models,” IEEE Trans. Power Del., vol. 27, no. 2, pp. 688–698, Apr. 2012.

[18] H. Peng, J. Wang, J. Ming, P. Shi, M. J. Perez-Jimenez, W. Yu, and C. Tao, “Fault diagnosis of power systems using intuitionistic fuzzy spiking neural P systems,” IEEE Trans. Smart Grid, vol. 9, no. 5, pp. 4777–4784, Sep. 2018.

[19] F. Wen and Z. Han, “Fault section estimation in power systems using a genetic algorithm,” Electr. Power Syst. Res., vol. 34, no. 3, pp. 165–172, Sep. 1995.

[20] F. Wen and Z. Han, “A refined genetic algorithm for fault section estimation in power systems using the time sequence information of circuit breakers,” Electr. Mach. Power Syst., vol. 24, no. 8, pp. 801–815, Dec. 1996.

[21] F. Wen and C. S. Chang, “A new approach to fault diagnosis in electrical distribution networks using a genetic algorithm,” Artif. Intell. Eng., vol. 12, nos. 1–2, pp. 69–80, Jan. 1998.

[22] C. S. Chang, L. Tian, and F. S. Wen, “A new approach to fault section estimation in power systems using ant system,” Electr. Power Syst. Res., vol. 49, no. 1, pp. 63–70, Feb. 1999.

[23] L. T. F. S. WenC. S. Chang, “A modified abductive inference model for fault section estimation in power systems using the Tabu search approach,” Electr. Mach. Power Syst., vol. 28, no. 5, pp. 399–414, May 2000.
JAMILE P. N. AMOAH received the B.Sc., M.Sc., and D.Sc. degrees in electrical engineering from the Federal University of Campina Grande, in 2012, 2014, and 2020, respectively. She is currently an Assistant Professor at the Federal University of Alagoas. She has experience in electrical engineering, with emphasis on electric power systems, working mainly on the following topics, such as protection of electrical systems, distribution systems, distributed generation, optimization, and fault section estimation in distribution systems.

KARCUS DANTAS was born in Brazil, in 1982. He received the B.Sc., M.Sc., and D.Sc. degrees in electrical engineering from the Federal University of Campina Grande (UFCG), Brazil, in 2005, 2007, and 2012, respectively. Since 2010, he has been with the Department of Electrical Engineering, UFCG. His research interests include electromagnetic transients in power systems, power quality, and power system protection.

KÉZIA DANTAS received the B.Sc., M.Sc., and D.Sc. degrees in computer science from the Federal University of Campina Grande, Brazil, in 2007, 2009, and 2014, respectively. Since 2014, she has been with the Department of Computer Science, State University of Paraiba. Her research interests include software engineering and artificial intelligence with focus on machine learning and deep learning.

RAQUEL ZACARIAS received the B.Sc. degree in administration from the Federal Rural University of Rio de Janeiro, Brazil, in 2011, and the degree in business management from Estácio University, Brazil, in 2017, where she is currently pursuing the bachelor’s degree in electrical engineering. Since 2009, she has been with the Light SA, Rio de Janeiro, Brazil. Her research interests include business management based on resource optimization, crisis management and decision making, especially in power distribution systems.