Electric Power Systems Research 179 (2020) 106060

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Allocation of fault indicators in distribution feeders containing distributed generation

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ARTICLE INFO

Keywords:
Distributed generation
Fault indicator
Fault location

ABSTRACT

As distribution systems are typically radial and branched, different branches have the same accumulated impedance from substation. Consequently, the impedance-based distance estimation techniques may identify multiple suspected locations for the same fault. The allocation of fault indicators reduces this problem. However, with distributed generation in distribution systems, the fault current, previously fed only by the substation, is now also fed by distributed generators. This may cause an incorrect operation of conventional fault indicators, requiring directional ones. In this context, an approach for allocation of conventional and directional fault indicators in distribution feeders, taking into account the distributed generation, is proposed in this paper. To represent the distance traveled by the maintenance teams during faults location, the proposed approach uses actual paths between the suspected fault locations, making the method realistic. Furthermore, using a NSGA-II algorithm, the best set of conventional and directional fault indicators required is determined. Results show that conventional fault indicators work accurately in the presence of low power distributed generators (less than 20% of the substation power) and, in the presence of high power generators, few directional fault indicators are needed.

1. Introduction

Electrical distributions systems are very susceptible to faults, especially the overhead ones. These faults are caused by equipment failure, animals, trees, lightning, etc. [1,2], and the incapability of quickly locate and eliminate them leads to social and economic problems. Moreover, bad reliability indexes blacken the utilities' image and may cause legal and contractual penalties. In order to solve this issue, researchers have been developing improvements in fault location techniques [3].

Depending on the available monitoring devices, different fault location approaches can be applied. The most recent ones use neural networks [4], wavelets [5] and S-transform [6], but the impedance-based methods are better adapted for current distribution systems [7], being the main class of approaches adopted by utilities. To obtain the fault location, these methods estimate the fault impedance from substation using voltage e current measurements. Based on that estimate, the fault location can be determined. However, as the distribution feeders are typically radial with many laterals, more than one suspected fault location for the same impedance estimated at substation may exist. This problem is known as the multiple fault location problem [8]. In order to reduce or even eliminate it, utilities frequently use Fault Indicators (FIs).

FIs are installed along the feeder to help the maintenance teams on identifying fault locations, providing visual and remote indications [9]. They have an acceptable level of reliability, greater than 98% correct indication [10]. In conventional feeders, where there is no distributed generation (DG), FIs trip only for downstream faults since there is only one source contribution, the substation. For instance, given a feeder containing one lateral, installing one FI at the beginning of the lateral is enough to eliminate the multiple fault location problem. If the fault is on the lateral, the FI trips; otherwise, if the fault is on the main feeder, the FI does not trip. In this example, choosing the adequate location for the FI is trivial. However, this is not the case for feeders containing several laterals.

Literature presents different approaches to allocate FIs. For instance, in Ref. [11] the Fuzzy logic is used to identify the best branches for FIs allocation to reduce the fault location time. Other approaches assume the availability of impedance-based methods providing the impedance (or the distance) from substation up to the fault, while FIs are allocated in order to reduce or eliminate the multiple fault location problem. In Ref. [12], the optimal allocation of the FIs is obtained by a genetic

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https://doi.org/10.1016/j.epsr.2019.106060
Received 1 April 2019; Received in revised form 4 September 2019; Accepted 6 October 2019
Available online 22 October 2019
0378-7796/

algorithm (GA) using an objective function that considers the loads, the number of customers and the distance between FIs. In Ref. [13] a study of fault location based on the distance estimation with and without FIs is presented; the results show that the use of FIs associated with distance estimation reduces the SAIDI (System Average Interruption Duration Index) when compared with the distance estimation sole. In Ref. [14] it is shown the importance of considering the patrolling speed in FIs allocation procedure. Some different patrolling speeds along lines were used to calculate their impact on the FIs allocation. The Ref. [15] describes the application of FIs associated with fault analyzers for distance estimation in compensated networks. The number and the location of the FIs were chosen by an agreement between the manufacturer and the utility; that is, based on their experience.

When admitting the availability of fault distance estimation, the distance between the suspected fault locations is a very important information and, instead of the actual distances, approximated distances (simplified calculations) are commonly adopted. In Ref. [8], the FIs allocation is obtained by a Chu–Beasley based GA with two possible objective functions. The first one uses the number of suspected fault locations, while the second one provides an approximated distance between them. The adoption of a simplified approach to estimate the distances to be run by maintenance teams may mask the effort to find the faults. Thus, one contribution of this paper is the use of the actual distances between the suspect fault locations. These directions through streets are calculated using Dijkstra algorithm [16]. For that, the actual map (streets, corners, etc.) of the feeder is modelled as a graph and constraints, such as one-way streets and closed streets for vehicles, may be considered, which makes the method realistic.

Furthermore, traditionally the methods used for the FIs allocation do not consider DG. In this case, power flows are unidirectional, from substation to loads or faults. However, depending on the fault location, DGs may unwantedly trip the FIs, which makes the FIs innocuous for the fault location purpose [17]. In order to solve this problem, there are some developments to adapt FIs, such as the directional FIs for systems with high grounding impedance [18], but this functionality is not available for solidly grounded systems. Also, despite relays being more expensive than conventional FIs, devices already installed along the feeder may provide the directional function, as reclosers with ANSI 67 relays.

The second contribution of the proposed approach uses the availability of directional FIs. A new objective function considering the costs of conventional and directional FIs is proposed. Therefore, for feeders with DG, there are two objective functions, one based on the distance between suspected fault locations and another based on the cost of conventional and directional FIs. To solve the multi-objective problem, the NSGA-II (Non-dominated Sorting Genetic Algorithm II) [19] is used, which is one of the most popular multi-objective optimization algorithms [20]. It provides a Pareto optimal front by sorting individuals based on every objective function. The generations are chosen by dominance and crowding-distance criteria.

In summary, this paper proposes an approach to allocate conventional and directional FIs, in the presence of DG or not, admitting that the fault distances from substation are given by impedance-based fault location methods. According to literature, these methods have easy implementation and low deployment costs, however they are not adequate to deal with high impedance faults and their performance depend on the system operation state as well as the faults conditions. A study including a detailed discussion of the pros and cons of the main impedance-based fault location methods are found in Ref. [21].

The paper is organized as follows: in Section 2 the multiple suspected fault location problem is presented. The FIs allocation problem in distribution feeders without DG is then discussed. In Section 4, the impact of DG on the FIs allocation is shown and, in Section 5, the proposed method including DG influence is presented. Complementary studies are in Section 6 and the conclusion in Section 7.

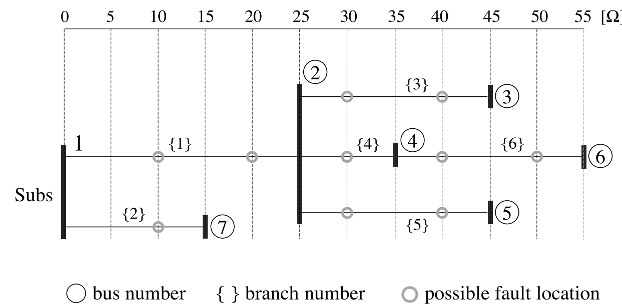

Fig. 1. Feeder containing accumulated impedances and possible fault locations.

2. The multiple suspected fault location problem

Admitting that when there is a fault, an impedance-based method gives its distance from substation, multiple suspected fault locations may exist, since distribution feeders usually have many laterals. The proper allocation of FIs reduces or even eliminates the multiple suspected fault locations. The following example, based on the feeder shown in Fig. 1, clarifies how FIs can be applied. The impedances measured from the substation are indicated by dashed vertical lines. For instance, bus 6 is 55 Ω way from substation. Assuming a 10 Ω impedance step, all possible fault locations are indicated by gray circles. For a fault 30 Ω way from the substation, there are three suspected fault location, on branches {3}, {4} and {5}, and the maintenance team needs to patrol these three branches to find the fault. However, by allocating one FI at the beginning of branch {3}, one suspected fault location is eliminated, once the FI trips for faults on branch {3}. Therefore, by reducing the number of suspect locations, the distance to be traveled by the maintenance team also reduces. Note that, for instance, the allocation of FIs at the beginning of branches {3} and {5} completely eliminates the multiple fault location problem for the 30 Ω fault. Ultimately, for instance, the allocation of FIs at the beginning of branches {2}, {3} and {5} completely eliminates the multiple fault location problem for any fault on this feeder, which means that all faults would be uniquely identified. On the other hand, given less than three FIs, there are many possible allocation proposals, each one associated with a distance to be travelled by the maintenance teams during faults location, and these distances can be used to qualify the proposals. In summary, the best allocation proposal results in the shortest distance to be travelled by maintenance teams.

The quantity of possible allocation proposals $P_{C,FI}$, given by (1), depends on the number of candidate branches, n_C, and the amount of available FIs, n_{FI}. Given a number of FIs, the objective is to define the branches where FIs are allocated resulting in the shortest distance to be travelled during faults location. Assuming no investment limitation, the trivial solution is to allocate FIs on every lateral branch.

$$P_{C,FI} = \frac{n_C!}{n_{FI}!(n_C - n_{FI})!} \quad (1)$$

3. Optimal FIs allocation without DG

In order to model the proposed method, a matrix containing the possible fault locations and the FIs statuses is adopted, as proposed in Ref. [8]. The amount of FIs and the impedance step are given parameters. The number of rows in the matrix is equal to the possible combinations of the FIs statuses (p), given by $p = 2^{n_{FI}}$, where n_{FI} is the number of FIs to be allocated. The number of columns (m) is equal to the highest accumulated impedance divided by the given step. For instance, in Fig. 1, the highest accumulated impedance is 55 Ω (on bus 6). Assuming an impedance step of 10 Ω, m = 5 columns. In general, the impedance step should be lower than the shortest branch impedance, ensuring that every branch has at least one possible fault location.

Table 1
Matrix representing one allocation solution for two FI in the feeder of Fig. 1.

FIs statuses		Impedance step (Ω)				
FI_2	FI_5	10	20	30	40	50
0	0	/1/	/3/	/4/, /5/	/7/, /8/	/10/
1	0	/2/	NP	NP	NP	NP
0	1	NP	NP	/6/	/9/	NP
1	1	NP	NP	NP	NP	NP

NP = Not Possible.

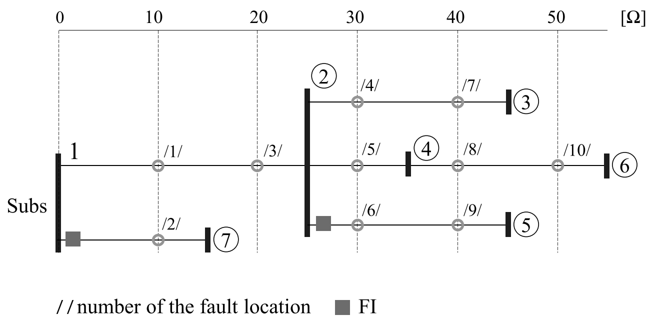

Fig. 2. Possible fault locations for the FIs allocation of Table 1.

Assuming two FIs on branches {2} (FI_2) and {5} (FI_5), the Table 1 presents the resulting matrix, while Fig. 2 shows the possible fault locations for this allocation proposal. The matrix elements contain the suspected fault location, according to Fig. 2, for every discrete impedance and FIs statuses combination. For instance, assuming a 40 Ω fault while FI_2 and FI_5 are not tripped, there are two suspected fault locations, namely, 7 and 8.

The proposed distance objective function F_d is defined by (2), where d_{ij} is the shortest distance between the suspected fault locations in row i and column j of the matrix. If there is only one possible fault location $d_{ij} = 0$. Assuming one FI on every lateral branch, all faults would be uniquely identified and F_d, zero. However, given a limited number of FIs, the distances calculated by the objective function depend on the allocation proposal and the best solution is associated with the shortest F_d. For the allocation illustrated in Table 1 and Fig. 2, F_d is the sum of the shortest distances between the suspected locations /4/ and /5/ due to the 30 Ω fault and, /7/ and /8/ due to the 40 Ω fault. Note that these are the faults with more than one suspect fault location.

$$F_d = \sum_{i=1}^{p} \sum_{j=1}^{m} d_{ij} \tag{2}$$

The proposed approach to obtain the shortest path between the suspected fault locations is presented in the following.

3.1. Obtaining the distance between the suspected fault locations

The allocation of FIs to improve impedance-based fault location is a feasible approach. Many criteria can be adopted in order to select a good allocation proposal. Literature has shown few ways for estimating this distance; simplified calculation, instead of the actual distances, are commonly adopted. As shown in Ref. [8], the distances between the suspected fault locations are probably the best practical criterion, which is estimated by the distance summation of each suspect fault location to their Geometrical Center (GC). Despite the simplicity, this distance estimation can be seriously affected, for example, by the presence of streets closed for vehicles, which cannot be modelled. The method proposed in this paper uses the actual map of the city, where the feeder is modelled as a graph. The distances are calculated using Dijkstra algorithm [16], since it can find the actual shortest path [22], making the proposed method realistic.

Based on the feeder shown in Fig. 3, it is possible to illustrate the benefits of using the actual distances instead of the simplified calculation proposed in Ref. [8]. DU is the distance measurement unit adopt in the figure. For instance, given a fault 8 Ω from the substation, if no FI is allocated, three suspected fault locations are indicated (A, B and C). Assuming the availability of one FI, based on the approach proposed in Ref. [8], the recommended solution is to allocate the FI on branch 3–11, which is enough to clear up suspicions about the location C. On the other hand, considering actual distances calculated over the map, as proposed in this paper, the recommended solution is to allocate the FI on branch 3–7, clearing up suspicions about the location A. In order to recommend this solution, the proposed approach takes into account the street 5–13, which provides a short path between locations B and C; the simplified approach does not consider the availability of actual paths.

Given the feeder of Fig. 3, Table 2 presents the values for the proposed objective function (F_d^{actual}), as well as the simplified objective function proposed in Ref. [8] (F_d^{GC}), assuming the allocation of up to 3 FIs and sorted by F_d^{actual}. The impedance step was set to 0.9 Ω. Due to the simplicity of the feeder, all the possible allocation proposals are shown and each column corresponds to a solution. For one FI, the best proposal for the proposed approach is to allocate the FI on branch 3–7 ($F_d^{actual} = 882$), while according to the simplified objective function, the best solution would be to allocate it on branch 3–11 ($F_d^{GC} = 150$). For two and three FIs, due to the reduced dimensions, simplicity and symmetries of the map, the best proposals are the same for both methods. However, even for this very simplified feeder and map, the proposed approach presents the advantage of recognizing the actual paths of the map, providing solutions where the distances to be run by

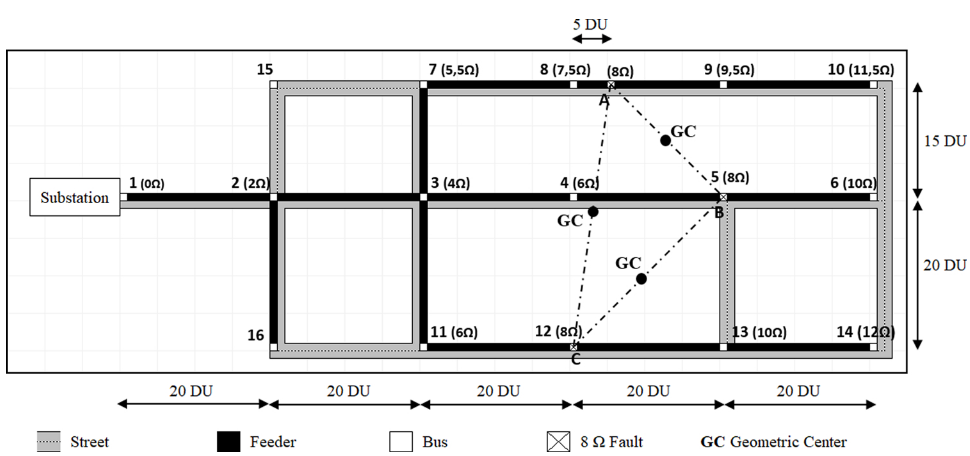

Fig. 3. Radial test feeder superimposed to a map.

Table 2
Evaluation of all allocation proposals for the feeder of Fig. 3.

Branch	1 FI					2 FIs										3 FIs									
2–3					●					●		●		●	●				●	●	●		●	●	●
2–16				●					●		●		●		●	●	●	●					●	●	●
3–4			●				●	●					●	●			●	●		●	●	●			●
3–7	●					●		●	●	●						●		●	●		●	●	●		
3–11		●				●	●				●	●				●	●		●	●		●		●	
F_d^{actual}	882	920	1177	1232	1232	111	111	111	771	771	809	809	1066	1066	1232	0	0	0	0	0	0	111	771	809	1066
F_d^{GC}	201	150	253	291	291	33	33	33	168	168	117	117	220	220	291	0	0	0	0	0	0	33	168	117	220

the maintenance team are reduced. Note also that as the number of FIs increases, the number of suspected fault locations reduces. For instance, given three FIs it is possible to find six solutions in which the objective functions are nulls and, therefore, the multiple fault location problem is completely eliminated. Providing multiple solutions is also an advantage, once some solutions may not be feasible due to practical limitations.

3.2. Feeder with actual maps

The actual distances between suspected fault locations are calculated using the feeder superimposed to its actual map. In our tests, the geographic data was obtained from Open Street Maps (OSM) [23], while the system parameters were taken from the IEEE 34-bus feeder. Therefore, the configurations, and consequently the impedances, are those from the IEEE standard feeder, but the lengths of the cables were calculated from the map. Fig. 5 shows this test feeder map, whose diagram is in Fig. 4.

In Fig. 4 it is proposed a more affordable way to visualize the feeder, with the length of the branches proportional to their impedances. Vertical lines, distant from each other of 2 Ω, correspond to the fault impedance steps. For instance, given a 20 Ω fault, there are two suspected fault locations, on branches 854–856 and 854–852. The proposed method calculates the shortest paths (according to the actual map) between these locations, for every impedance step and according to the FIs allocation proposal.

3.3. Using metaheuristics

In order to find the best locations to install the FIs, the so-called brute force (all possible allocation proposals are tested) can be very efficient for very small systems. For instance, considering the system of Fig. 3 and three FIs, there are only 10 possible solutions, as shown in Table 2. However, for large systems, the use of metaheuristics is more adequate.

A test was performed on the IEEE 34-bus feeder comparing the brute force and the GA [24]. For GA, a binary encoding is adopted, where the chromosomes containing FIs are set to 1, while the remaining is set to 0. The reproduction is based on roulette and the elitism is used. Additionally, the single point crossover and the mutation of one-bit at a time are also adopted. A population containing 200 individuals was specified. Fig. 6 shows the number of proposals tested by the GA and brute force according to the number of FIs. In summary, if the number

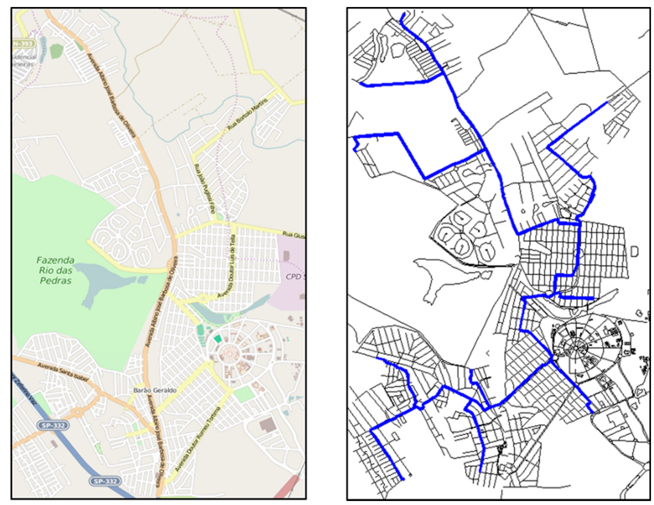

Fig. 5. Test feeder: left- OSM map, right IEEE 34-bus feeder over the map.

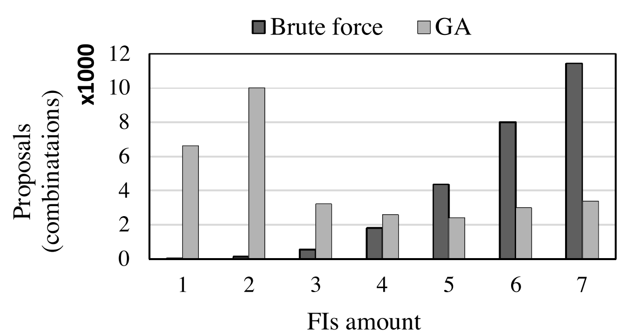

Fig. 6. Brute force vs GA according to the amount of FIs [IEEE 34-bus adapted feeder].

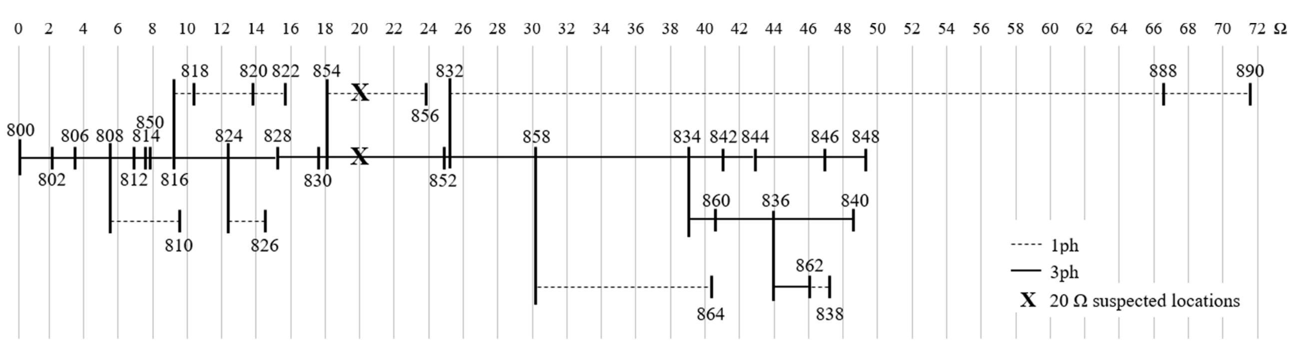

Fig. 4. IEEE 34-bus adapted feeder with the branch lengths proportional to their impedances.

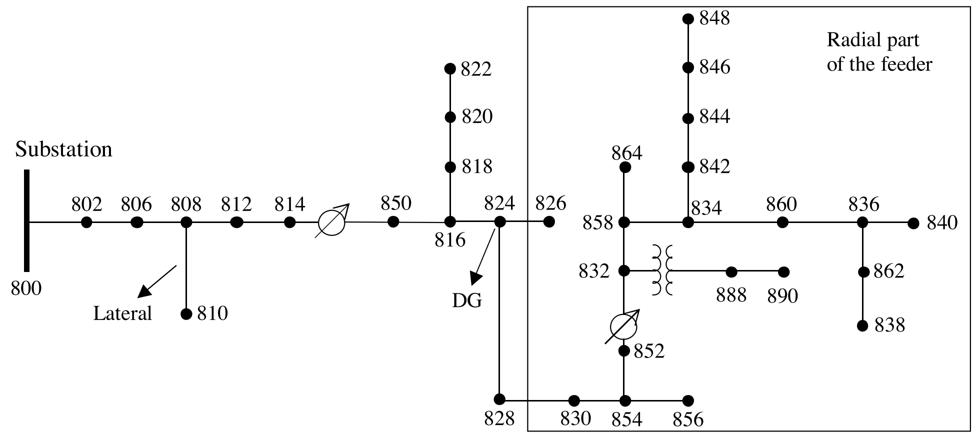

Fig. 7. IEEE 34-bus feeder with DG on bus 824.

of FI is small, the brute force is appealing. However, as the number of FIs increases, the GA based method becomes more interesting. In this example, the proposed GA reached the best solutions in all cases.

4. Impacts of distributed generation

In the last decade, the adoption of DG in distribution systems has significantly increased. Thus, power flows are not exclusively unidirectional, from substation to loads, under normal or during faults conditions. As a consequence, the basic principle that FIs trips only for downstream faults is no longer always true. It means that, when installed between the substation and a DG, FIs may trip by either contribution, depending on the fault location.

In order to verify the DG contribution impact, fault simulations were performed on the feeder of Fig. 7 using OpenDSS. The DG is a low voltage (LV) generator with 2 MVA and 9% reactance, connected by a 2 MVA transformer with 6% reactance on bus 824. The substation has a 2.5 MVA transformer with 8% reactance and infinity bus on high voltage (HV) side. The currents were measured on branches 800–802 (substation contribution) and 816–824 (DG contribution). Three-phase and single-phase short circuits were simulated. The fault resistances were set to 0.1 mΩ for the three-phase short circuit (I_{k3}), resulting in the highest current contributions, and 40 Ω for the single-phase fault (I_{k1}), resulting in the lowest contributions. In this condition, a typical range for the fault currents is obtained.

Fig. 8 shows the range for currents from the substation and from the DG for faults in different buses. As expected, while the fault moves from the substation in the direction of the DG, the substation contribution decreases and the DG contribution increases. The lowest contribution of the substation is 148 A.

When the contribution ranges overlap, it is not possible to set a pickup current ensuring that conventional FIs only trip for the substation contribution. For instance, according to Fig. 8, one FI allocated at 28.000 m with a 200 A pickup is tripped by the substation contribution for a fault at 30.006 m as well as by the DG contribution for a fault at 26.353 m, which makes the FI useless. Assuming a 250 A pickup current, only the substation contribution trips the FI; however, the FI does not trip for faults lower than 250 A, which makes it only partially useful. Finally, if a 40 A pickup is set, any fault trips the FI, making it useless again.

The DGs rated power, the types of faults and the connection of the transformers affect the operation of FIs. In the following, these aspects are discussed and the cases where conventional FIs properly work in the presence of DG are presented.

4.1. Type of faults and DG transformer connection

Depending on the transformer connection, the DG contribution to faults may be very low. Fig. 9 shows the fault currents for the same scenarios discussed in Fig. 8, considering two possible transformer connections linking the DG to the feeder, and two maximum short circuits scenarios (two-phase (I_{k2}) and three-phase (I_{k3})).

As seen in the right side of the figure (9-b and 9-d), with delta-wye (HV-LV) connection, the smallest DG contribution to faults is very low. As the transformer is delta connected, there is not a zero sequence impedance path for the fault current. During a grounded fault, there is only the load current and, therefore, FIs do not trip. By admitting I_{k2} as the highest contribution, the overlap is smaller, reducing the undesired behavior of FIs due to the DG. Thus, by not considering three-phase short circuits, which are less common, one can set FIs to trip only by the substation contribution.

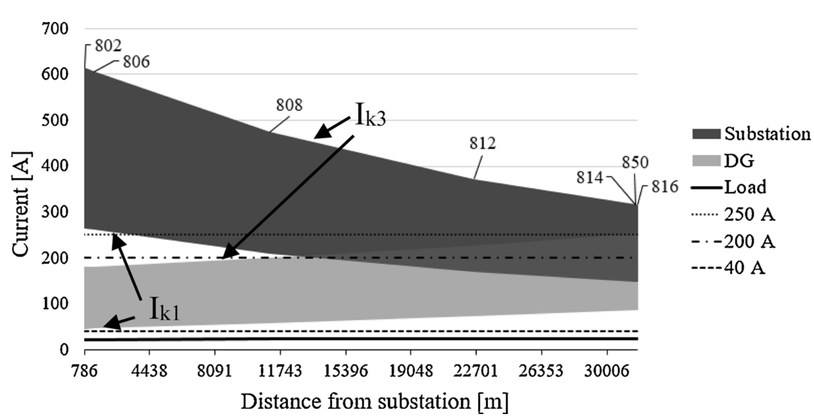

Fig. 8. Substation and DG contributions to short circuits between them.

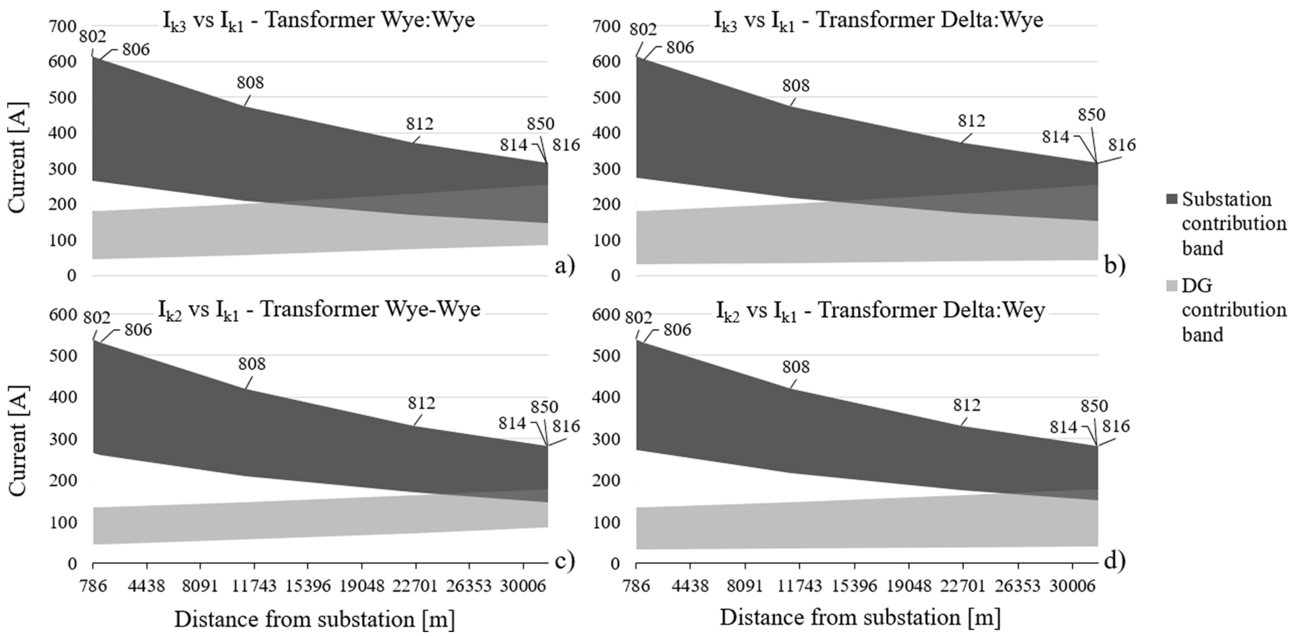

Fig. 9. Fault contributions depending on the fault type and transformer connection.

4.2. DG location

Another important aspect is the DG location. Fig. 10 shows the current ranges for the same DG on bus 816 (10-a), 828 (10-b), 832 (10-c) and 836 (10-d). For the sake of simplicity, two-phase and single-phase faults are considered. Only the part of the feeder where the contributions have different directions are shown. For faults after the DG, both contributions are added, which does not affect the operation of the FIs.

When the DG is close to substation (Fig. 10-a), the contribution overlap is negligible. However, as it moves away, the overlap increases, reducing the areas where conventional FIs can properly operate. Even so, depending on DG power it is yet possible to use conventional FIs properly. An example is shown in the next subsection.

4.3. Conventional FI applied in the presence of small DG

Despite DGs with significant rated power may affect the proper operation of conventional FIs, small DGs are more expected to be installed in most distribution feeders. In order to show that conventional FIs can properly operate in the presence of small DGs, two DGs were allocated on buses 848 and 840 (see Fig. 7). Both DGs were set to 0.5 MVA, connected by a delta-wye transformer of 0.5 MVA with 4% reactance and there is one FI on branch 834–842 (between the DGs). Depending on the fault location, the current on the FI is from the substation or the DGs. Therefore, the pickup current must be set in order to make the FI to trip only for faults on branches between buses 834 and 848, only with the substation contribution. If this condition is possible, the FIs is selective and can be useful. For instance, in this case, a 100 A pickup current meets this requirement, since the FI trips for the

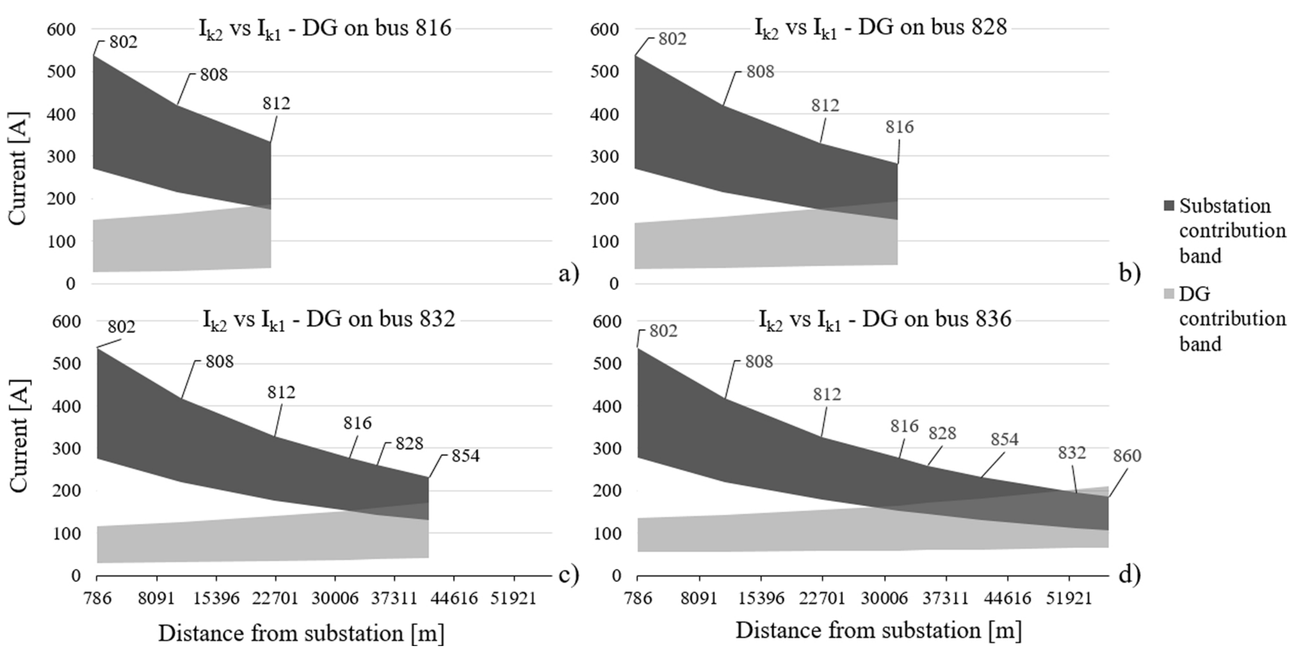

Fig. 10. Fault contributions with DG on different buses of the IEEE 34-bus feeder.

farthest ground fault (115 A at bus 848) and it does not trip for a three-phase short circuit at bus 834 (96 A). Therefore, the maximum DG power for which directional FIs are not required in this example is 0.5 MVA, which represents 20% of the substation rated power.

5. Allocation of conventional and directional FIs using NSGA-II

In this paper, it is assumed the availability of directional as well as conventional FIs in order to cope with the undesired operation of conventional FIs due to the presence of DG. Directional FIs can be set to trip due to substation or DG contributions. By assuming only the substation contribution, they operate as conventional FIs on radial feeders without DG. Thus, they must be allocated on branches where the DG contributions are higher than their pickup currents.

Henceforth, besides the distance objective function, given by (2), a cost objective function, given by (3), is used with the NSGA-II algorithm. For that, it is assumed that the cost of a directional FI (*DFI*) is three times the cost of a conventional FIs (*CFI*).

$$C_{FI} = DFI + CFI \mid DFI = 3 \cdot CFI \quad (3)$$

Considering the use of directional FIs, the objective functions (2) and (3) are tested simultaneously and, because of that, the NSGA-II was chosen. Instead of giving only one optimal solution, it provides a Pareto optimal front. This GA sorts individuals by every objective function and chooses the next generation by dominance and crowding-distance criteria. It is a process of search and decision. As a result, instead of providing only the best solution, this algorithm provides a set of good solutions.

Fig. 11 shows the result obtained by the brute force and NSGA-II, considering two FIs on IEEE 34-bus feeder. DGs were allocated on buses 840 and 848. Two best solutions provided by NSGA-II are highlighted in the figure. The first one with $C_{FI} = 4$ resulting in the shortest distances to be run by the maintenance team (FIs on branches 832–888 and 834–842) and the second with $C_{FI} = 2$ resulting in the smallest acquisition cost (FIs on branches 832–888 and 858–864). The solution with the shortest path has one directional indicator. All the 122 solutions evaluated by the exhaustive search are shown in the figure as well.

6. Complementary case studies

In this section, additional tests made on the adapted IEEE 34-bus feeder are presented, including the impact of the specified impedance step and tests with and without DGs.

6.1. Impedance step

The impedance step choice influences the algorithm. By reducing it, the matrix representing the possible solutions enlarges, resulting in

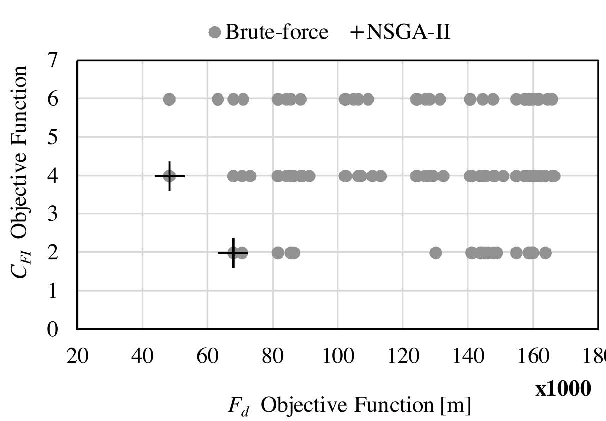

Fig. 11. Optimal allocation of two FIs on the IEEE 34-bus feeder containing two DGs.

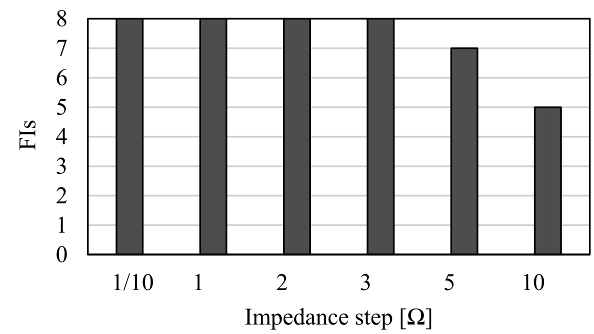

Fig. 12. Amount of FIs to eliminate all suspected fault locations vs. impedance step.

more computational burden. As a consequence, the solutions found by the proposed algorithm improve. On the other hand, as the step raises, the computational effort reduces and the solutions provided by the NSGA-II may deteriorate. Fig. 12 shows the required amount of FIs to ensure that the multiple fault location problem is eliminated according to the specified step size. From 0.1–3 Ω step, eight FIs are required, which is the number of forks of the feeder. For impedance steps higher than 5 Ω, the number of required FIs reduces. This is because, with larger impedances steps, short branches are neglected. Tests considering steps with less than 0.1 Ω present the same result obtained for 0.1 Ω, since all branches have at least one possible fault location. A good recommendation is to adopt a step that results in at least one possible fault location at every branch. The results presented are without DG, but they are also true in its presence.

6.2. FIs allocation with distributed generation

By definition, all branches connecting DGs or connecting DGs to the substation are candidates for directional FIs. In the remaining branches, conventional FIs can be adopted. In order to show the impact of adopting conventional and directional FIs, two case studies are shown in this section. In the first case, only conventional FIs are available, even in the presence of DGs. In the second case, conventional and directional FIs are available. For the first case, assuming the availability of conventional FIs, Table 3 shows the allocation solutions in the following scenarios: (a) without DG, (b) with one DG on bus 848, and (c) with two DGs on buses 848 and 840. As can be seen in the last row, with eight conventional FIs the multiple fault location problem is completely eliminated (F_d is null), even in the presence of one DG. In the presence of two DGs, the multiple fault location cannot be completely eliminated without directional FIs.

In the second case, conventional and directional FIs are available and a third DG was included on bus 862. Fig. 13 shows the values for F_d according to the number of directional FIs. The lines refer to the total amount of FIs. For instance, the squares indicate the solutions using two FIs. In this case, using one or two directional FIs, the objective function F_d is close to 50.000. However, without directional FIs the objective functions F_d is close to 70.000. Still according to the figure, using seven conventional FIs, by allocating one directional FI, the objective functions F_d significantly reduces, while by allocating new directional FIs the objective function F_d just slightly reduces. Nevertheless, in this case, allocating more than one directional FIs is not fruitful.

7. General conclusion

This paper presents a study on the allocation of conventional and directional FIs to improve fault location in distribution feeders containing DG. The FIs are allocated in order to reduce the multiple fault location problem inherent to the impedance-based fault location approaches. Two objective functions are used to qualify the solutions: the

Table 3
Allocation solutions considering only the availability of conventional FIs.

FIs	F_d without DG	FIs positions	F_d with 1 DG	FIs positions	F_d with 2 DGs	FIs positions
1	89,172	832–888	89,172	832–888	89,172	832–888
2	48,094	832–888, 834–842	48,179	832–888, 834–860	67,821	832–888, 858–864
3	26,742	832–858, 858–834, 834–860	26,742	832–888, 858–864, 834–860	49,150	854–856, 832–888, 858–864
4	19,009	854–856, 832–858, 858–834, 834–860	19,009	854–856, 832–888, 858–864, 834–860	41,417	824–826, 854–856, 832–888, 858–864
5	11,489	816–824, 854–856, 832–858, 858–834, 834–860	11,489	816–818, 854–856, 832–888, 858–864, 834–860	33,897	816–818, 824–826, 854–856, 832–888, 858–864
6	6,403	816–824, 854–856, 832–858, 858–834, 834–860, 836–862	6,403	816–818, 854–856, 832–888, 858–864, 834–860, 836–862	30,201	808–810, 816–818, 824–826, 854–856, 832–888, 858–864,
7	2,706	808–812, 816–824, 854–856, 832–858, 858–834, 834–860, 836–862	2,706	808–810, 816–818, 854–856, 832–888, 858–864, 834–860, 836–862	27,494	808–810, 816–818, 824–826, 854–856, 832–888, 858–864, 836–840
8	0	808–812, 816–824, 824–828, 854–856, 832–858, 858–834, 834–860, 836–862	0	808–810, 816–818, 824–826, 854–856, 832–888, 858–864, 834–860, 836–862		

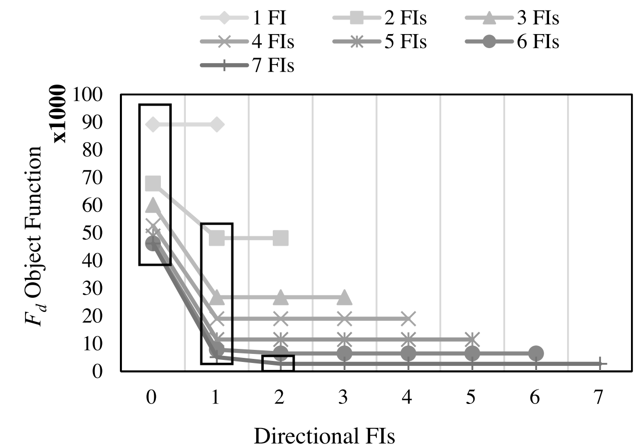

Fig. 13. *Fd* vs. the number of directional FIs. Solutions obtained with NSGA-II inside rectangles.

actual distances to be run by the maintenance teams and the costs of FIs. These distances are calculated using the Dijkstra algorithm, which assures the shortest path between the suspected fault locations and is computationally cost-effective. In order to provide good quality solutions, the NSGA-II algorithm is adopted. As there are two objective functions, a Pareto optimal front is calculated, instead of only one optimal solution.

As it was discussed, the integration of DGs may affect the expected operation of conventional FIs, especially, in the presence of large DGs. When there is only one large distributed generator, or all generators are on the main feeder, it is possible to find good solutions considering only conventional FIs; otherwise, directional FIs are required. As a simplified general rule, the maximum number of required directional FIs is equal the number of DGs less one.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank Conselho Nacional de Desenvolvimento Científico e Tecnológico CNPq and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior CAPES for the funding of this research.

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