Fault Location in Distribution Networks Through Graph Marking

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***Abstract*—This paper presents an automatic method for locating faults based on the statuses of fault indicators that are telemetered to the distribution control center. The method constructs an undirected subgraph of the the part of the network that is relevant to the fault event; the vertices of this graph are areas that comprise the possibly faulted electrical equipment, and its edges are the fault indicators. Two graph marking approaches for fault location are discussed: a conventional marking approach that is adopted by the industry and an improved version of it, the downstream marking approach. This paper demonstrates that the downstream marking approach is superior to the conventional one, particularly in terms of immunity to fault indicators that fail to be set. Numerical results and comparisons are presented for unsymmetrical faults and on several networks.**

***Index Terms*—Distribution networks, fault indicators, fault location.**

I. Introduction

THE FAST location of faults in distribution systems leads to a reduction in customer outage times, which utilities regard as a main power quality metric in today's deregulated electrical markets. Power distribution outages cause supply interruptions with associated economic loss. An effective fault management system requires rapid fault location (FLOC) and fault isolation and service restoration for the faulted network part. With the increased complexity and size of distribution networks, FLOC can no longer be reliably carried out by sole reliance on human operators. This research addresses the problem of automatic fault location by making use of the statuses of fault indicators (FIs) that are telemetered to the distribution control center.

The methods for fault location can be generally classified into two categories: impedance-based methods and traveling wave methods [1]. Traveling wave techniques have been proposed for distribution systems in [2], where fault location is achieved by comparing the time of arrival of the initial transients in double ended methods or through cross-correlating the reflected and the incident wave amplitudes in single ended methods. While traveling wave methods are accurate on transmission systems, the presence of numerous laterals in distribution systems introduce additional reflections that compromise accuracy. A traveling wave approach employing a wavelet transform [3] has been proposed to identify the faulted lateral, after which fault location is performed using impedance-based methods [4]. A continuous-wavelet transform was used to determine specific frequencies based on which a distribution network fault could be located, assuming a known network topology and line geometry [5].

Despite the advancements in traveling wave methods, impedance-based methods remain more popular amongst utilities due to their ease of implementation [6]. The classical impedance-based method that uses one-terminal voltage and current data is the simple reactance approach [7]. The reactance approach estimates the distance to the fault location on a line by computing the ratio of the measured reactance to the total reactance of the line; notable improvements in accuracy are through the well-known methods of Takagi *et al.* [8] and Eriksson *et al.* [9]. However, the main applicability of these approaches remains for transmission lines [10] and their reliable use in distribution networks requires additional telemetered data [6]. Distribution system faults are in fact more challenging to locate because of changing conductor sizes, multiple feeder taps, multiphase laterals and unbalanced operation; faults at different locations can therefore give rise to the same voltages and currents observed at the substation. To circumvent this challenge, [11] proposed a novel approach for automated fault location in distribution networks. The approach in [11] employs an iterative fault distance determination algorithm based on the steady-state analysis of a faulted distribution feeder, combined with a fault location search algorithm using a depth-first search strategy applied to the network tree structure. There have been several reported advances that build on the circuit analysis approach, for instance [12]–[14]; however, the possibility of multiple fault locations remains a disadvantage that may give rise to maintenance crews being sent to multiple suspected locations. Fault location methods in distribution networks can be enhanced when combined with additional information such as voltage sag characteristics reported by intelligent electronic devices [15], or data collected from fault indicators [6], [16]–[18].

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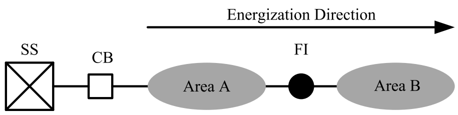

Fig. 1. Radial network configuration (energization A → B).

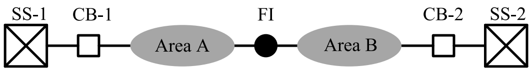

Fig. 2. Radial network configuration with energization from two sources.

Fault indicators are designed to simply indicate the occurrence of a fault [19], [20]. Although FIs have been in use in distribution systems for the past two decades, they were not equipped with communication capabilities [21] and thus relied on visual inspection by maintenance personnel. Today, FIs with communication capability are important components in smart grids as they lead to faster identification of fault locations and thus improve system reliability. The importance of FIs in smart distribution networks has been reflected in several recent studies addressing the optimal location of FIs on a network [16], [22], [23].

This paper considers the problem of automatically locating highly probable fault areas using the statuses of FIs that are telemetered to the energy control center. Locating fault areas based on information from FIs was studied in [17] and is the subject of a U.S. patent [24]; this conventional graph marking approach has been already implemented in actual distribution management systems. The current paper proposes the downstream graph marking approach for locating fault areas for unsymmetrical faults, and demonstrates that it possesses a significant advantage as compared to the conventional graph marking approach in the presence of non-active FIs; this improved method, which is referred to in the paper as the downstream marking approach, practically replaced the conventional approach in the new and upgraded distribution fault management systems that are currently in operational use. The simplicity of the proposed downstream marking approach is good for practical application; it is used in the field on both radial and meshed networks.

The rest of this paper is organized as follows. Section II introduces the three types of fault indicators and the marks that they assign to the adjacent areas, based on their statuses. Section III reviews the conventional marking approach and introduces the downstream approach. Numerical results are reported in Section IV, where the success rate of the two approaches in Section III is discussed under erroneous fault indicator settings. The paper is concluded in Section V.

II. Fault Indicators and Area Marking

Fault location can make use of several types of fault indicators: non-directional, uni-directional, and bi-directional. The distinction between the FI types and the marks they assign is explained with reference to Fig. 1 and Fig. 2; in this context, an area can comprise a subnetwork potentially having several lines.

TABLE I
Non-Directional FI in a Radial Network Configuration (Energization A → B)

FI Status	Area A	Area B
Set	-1	+1
Not Set	0	-1

A. Non-Directional Fault Indicators

The simplest type of fault indicator is the non-directional FI; it is designed to indicate the flow of a fault current through it. Consider Fig. 1 which shows one substation (SS), one circuit breaker (CB), and one non-directional FI between two areas A and B. If a fault occurs in area B, the fault current has to flow from the SS through area A and then to the fault location in area B. The FI can sense a fault current from area A to area B, and this is denoted by stating that the FI is Set. Note that if the fault had occurred in area A, then the fault current would flow from the SS to the fault location in area A. In this case the FI cannot see the fault in area A, because the fault current does not pass through it; this is explained by stating that the energization direction is from A to B, i.e., the non-directional FI can be Set only when the fault current flows from area A to area B.

If the FI Status in Fig. 1 is Set, then a fault has occurred in area B; the FI contributes a mark of +1 to area B to signal that it has seen a fault in this area, and a mark of -1 to area A indicating that there is no fault in area A. If the FI Status is Not Set, then the FI has not seen a fault in area B and therefore gives it a mark of -1, while area A gets a mark of 0 indicating that the FI cannot see if a fault has occurred upstream the energization direction. These observations are summarized in Table I.

Now consider Fig. 2, which has two substations SS-1 and SS-2. The non-directional FI can now detect a fault current flowing from area A to area B (contributed by SS-1), and a fault current flowing from area B to area A (contributed by SS-2). The FI is said to be energized in both directions (A to B and B to A), because it can see the fault current flowing in these two directions. The non-directional FI is however not useful in this setup: although the FI will be Set when a fault occurs either in area A or B, it cannot tell in which area the fault has occurred. This motivates the need for FIs that are Set only when the fault current flows in a predetermined direction (called the protection direction in uni-directional FIs - see Section II-B), and FIs that can be Set in both directions but indicate as an output the direction of the fault current (called the protection direction in bi-directional FIs - see Section II-C).

B. Uni-Directional Fault Indicators

A uni-directional FI is characterized by a specific protection direction; the protection direction denotes the direction of the fault current that makes the FI Set, i.e., the FI can detect a fault only if the FI is energized in its protection direction. Consider Fig. 1 with a uni-directional FI having a protection direction from area A to area B; because the protection direction is the same as the energization direction, the marks would

TABLE II
UNI-DIRECTIONAL FI IN A RADIAL NETWORK CONFIGURATION (ENERGIZATION A → B)

FI Status	Protection Direction A → B		Protection Direction B → A	
	Area A	Area B	Area A	Area B
Set	-1	+1	0 (Error)	0 (Error)
Not Set	0	-1	0	0

TABLE III
UNI-DIRECTIONAL FI IN A RADIAL NETWORK CONFIGURATION WITH TWO POWER SOURCES

FI Status	Protection Direction A → B		Protection Direction B → A	
	Area A	Area B	Area A	Area B
Set	-1	+1	+1	-1
Not Set	0	-1	-1	0

TABLE IV
BI-DIRECTIONAL FI IN A RADIAL NETWORK CONFIGURATION (ENERGIZATION A → B)

FI Status	Area A	Area B
Set A → B	-1	+1
Set B → A	0 (Error)	0 (Error)
Not Set	0	-1

be as given in the third and fourth columns of Table II. However, if the protection direction of the uni-directional FI in Fig. 1 is from area B to area A, then it cannot detect any fault occurrence and will always contribute a mark of 0.

In the case of Fig. 2 which has two power sources, the FI will always be energized; assume that its protection direction is from A to B. If the fault occurs in area B, there will be a fault current flowing from area A to area B (contributed by SS-1); because the fault current flows in the protection direction of the FI (A to B), the FI will be Set. Now consider the event of a fault in area A. The fault current will flow from area B to area A (contributed by SS-2); because the fault current flows in opposite sense to the protection direction, the FI will not be Set. The corresponding marks are given in Table III.

C. Bi-Directional Fault Indicators

A bi-directional fault indicator has three states: Not Set, Set in the protection direction A to B, and Set in the protection direction B to A; the protection direction denotes the output of the FI which indicates the direction of the fault current flow that made it Set. In the case of Fig. 1 where the energization direction is from area A to area B, the FI cannot be Set in the direction B to A, i.e., the bidirectional FIs do not have an advantage over the uni-directional FIs when the network configuration is with one power source; the corresponding marks are given in Table IV.

Now assume that the FI in Fig. 2 is bi-directional. If the fault occurs in area B, there will be a fault current flowing from area A to area B (contributed by SS-1); the FI will be Set in the protection direction A to B. Now consider the event of a fault in area A. The fault current will flow from area B to area A (contributed by SS-2); the FI will be Set in the protection direction B to A. Table V shows the marks corresponding to Fig. 2 that has two power sources; note that when the bi-directional FI is Not Set, it signals that both areas A and B are not faulted.

TABLE V
BI-DIRECTIONAL FI IN A RADIAL NETWORK CONFIGURATION WITH TWO POWER SOURCES

FI Status	Area A	Area B
Set A → B	-1	+1
Set B → A	+1	-1
Not Set	-1	-1

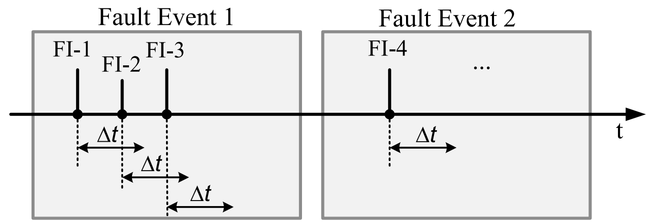

Fig. 3. Fault events.

III. GRAPH-BASED APPROACH

The statuses of FIs are telemetered to the distribution control center. A Fault Event starts as soon as an FI changes its status to Set or a CB trips. The fault location algorithm waits for a pre-specified period of time Δt for another notification of an FI status change or a CB tripping; if it receives such a notification, then it waits for another Δt. All the occurring events are collected together until no further events are recorded within Δt. An example is shown in Fig. 3: the fault event starts by the FI-1 status being Set; before the first Δt has elapsed, a notification from FI-2 arrives. After the third Δt has elapsed, there is no further change in any FI status and therefore these three events build Fault Event 1. The next change in the status of FI-4 signals the start of a new Fault Event, because FI-4 took more than Δt to be received by the fault management system. The statuses of the FIs in each Fault Event are used as inputs to the fault location program. The pre-specified period of time Δt is a parameter that is used to define a Fault Event; it is specified because the telemetered values are obtained from SCADA via different remote terminal units (RTUs). The value of Δt is system dependent; it is practically set by the operator based on the delays in the available measurement and transmission equipment.

After the Fault Event is identified, the fault location algorithm builds an undirected graph from all equipment in the part of the network that is relevant to the Fault Event:

- For an outage fault, the relevant part of the network is the part that has been de-energized by the fault due to CB tripping; the equipment to be considered is confined by open switches.
- For a non-outage fault, the relevant part of the network is the island which contains the FIs that have been Set; the equipment to be considered is confined by the delta sides of the three-phase transformers. Non-outage faults refer to phase-to-ground faults on isolated networks. There are special fault indicators for detecting non-outage faults by measuring capacitive fault currents; such types of fault indicators are installed in isolated networks.

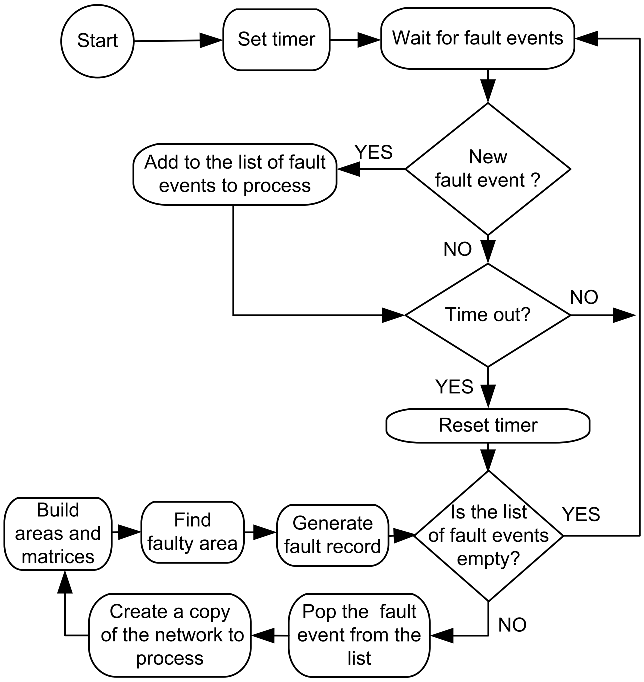

Fig. 4. Dynamic creation of areas and matrices for FLOC.

The undirected graph created by the FLOC algorithm consists of areas as nodes and edges defined by tripped CBs or FIs. The information provided in areas and edges is stored in the so called FLOC matrices. The graph and matrices used for identifying the final faulty area are built up dynamically, i.e., in the presence of a fault event as shown in Fig. 4. If no other fault event occurs during a specified time period before the timer has been started or the last fault event has occurred, the topology associated with the fault indicator or tripped switch is evaluated and FLOC areas are created, and the corresponding matrices are built up; the matrices represent the marks contributed by the FIs in tabular format, which are used to locate the fault (examples are given in Tables VII, VIII, IX, X, XIII, and XIV). Since the processing time of the fault event is different than the time of fault occurrence, it may happen that the previously faulted network part is already restored, fault indicators are cleared and no fault record is generated. Otherwise, if the fault still persists, the corresponding areas are created. For area creation, the copy of the network including the telemetered data (status of switching devices and fault indicators) is processed starting at the fault indicator or tripped switch. The copy of the network has already a form of an undirected graph (micro model) with branches and switching devices as edges and the connected components as nodes. The connected components can include additional injections (loads, generators or capacitors). Using the standard Depth First Search (DFS) algorithm an undirected graph is created on the base of the network copy; see Section III-A for details. The edges of this graph are fault indicators or tripped switches and the graph nodes contain all equipment in between.

A. Depth First Search Algorithm

The Depth First Search algorithm [25], [26] is explained using the state chart in Fig. 5. DFS starts with a start node

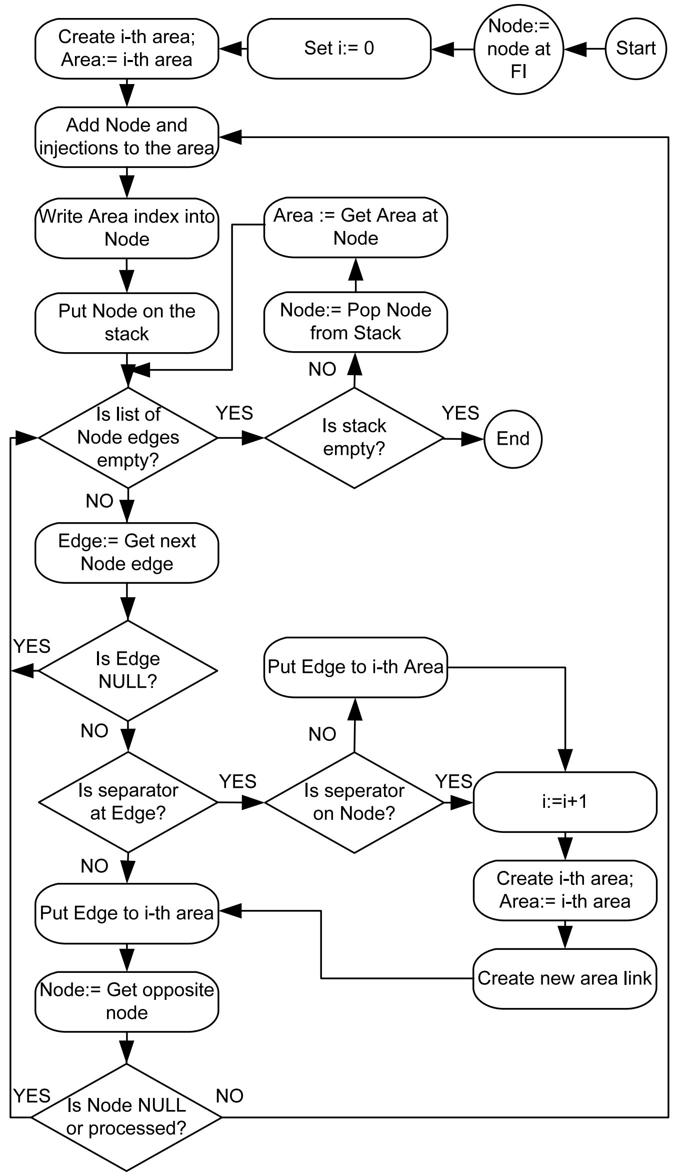

Fig. 5. State chart of the DFS for area creation.

at the fault indicator and creates an area with the index 0. The node with all connected injections is added to the area and the area index is written into the node. Subsequently, the node is stored on the stack. The algorithm moves down the graph along the edges to the next not processed (i.e., not already stored on the stack) child node. If some edges shall be excluded from the search (for example because of the wrong phase information), then for such edges the algorithm will return NULL and the next edge gets checked. If the edge fulfills the search criteria, the child node is picked. If there is no separator (like fault indicator or protective switch) at the edge between the parent and child nodes, then it is stored inclusive of the edge in the area of its parent node. Otherwise, the procedure depends on the placement of the separator. If it is located opposite to the parent node, the edge is inserted into the parent area and afterwards a new area and a new area link get created. Otherwise, first the child area together with a new

TABLE VI
TIME REQUIRED FOR TRACING AND AREA CREATION

Network	Topology Tracing [ms]	Number of Areas	Area Creation [ms]
IEEE-123	5.32	5	0.60
IEEE-8000	120.87	10	1.02
		20	1.82
		40	3.07

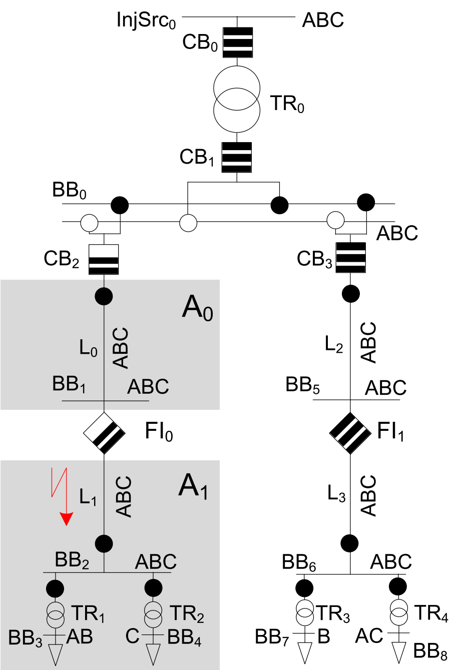

Fig. 6. Simple network after area creation.

link are created, and the edge is inserted into the child area. The trace stops at the end of the feeder or at a normally open switching device. The algorithm terminates when the stack is empty.

Table VI shows the execution time required by topology tracing and area creation for the IEEE-123 and 8000-node distribution networks, when the DFS algorithm is executed on an i5-4670K, 3.4/3.8 GHz PC with 16 GB RAM. Note that the time needed for the area creation part of the algorithm is independent of the network size.

Example: The DFS algorithm for area creation is demonstrated using the example network shown in Fig. 6; this network has two fault indicators FI-0 and FI-1 installed, which observe each phase separately. Also four non-ganged circuit breakers are in service. A fault occurs on phase-A of the network part that is observed by FI-0. The circuit breaker CB-2 trips on phase-A. A notification (fault event) is sent to the FLOC processor containing the information about the activated fault indicator FI-0 and the tripped circuit breaker. After Δt time has elapsed, the processing is started to localize the faulted area. First areas are created. The starting node is BB-1, because FI-0 is located at this node. Since the fault indicator is set only for phase-A, the network is traced for this phase only. First an area A-0 is created. BB-1 is put both into area A-0 and on the stack. The list of edges at BB-1 is given in this order: L-1 and L-0. BB-2 is identified as the opposite node. Since there is a separator located between BB-1 and BB-2, a new area A-1 and a link between areas A-0 and A-1 are created. L-1 and BB-2 are put into area A-1 and BB-1 is additionally stored on the stack. The list of edges at BB-2 is available in this order: TR-1 and TR-2. Thus, after TR-1 has been assigned to area A-1, BB-3 is identified as the next opposite node and stored both in the area A-1 and on the stack. From BB-3, no non-processed node can be reached. BB-3 gets removed from the stack and BB-2 is processed again. Since BB-3 has been already treated, the edge TR-2 is checked. It is connected only at phase-C, this is why BB-4 does not get processed. BB-2 is popped from the stack and the algorithm returns back to BB-1. At the start of the algorithm BB-1 has been assigned to area A-0. Now L-0 is moved into this area as well. BB-0 is neither put on the stack nor added to area A-0, because it is already energized. The border of the faulty area has been reached. Finally BB-1 is removed from the stack and the algorithm terminates. As a result, two areas and an edge at the set fault indicator FI-0 are created.

FLOC assigns marks to each created area. The assignment is based on the evaluation of the FIs in use. These marks and graph topology are stored in FLOC matrices. Two approaches for assigning marks are discussed below: the conventional approach in Section III-B and the downstream marking approach in Section III-C.

B. Conventional Marking Approach

The conventional marking approach is the subject of a 2012 United States Patent [24] and has been also discussed in [17]. The approach is based on assigning marks to the areas as presented in Tables I–V, while taking into account the status and type of each FI and the network energization. For illustration, consider the network in Fig. 7 with two injection sources, two loops, and having bi-directional fault indicators. The fault has occurred on phase-A in area A-5. FI-0, FI-3, FI-4, FI-5 and FI-6 are set for phase-A along the flow direction. CB-4 and CB-7 have tripped for phase-A. This time the network gets subdivided into six areas due to the larger network size and multiple injections. Table VII shows the marks contributed to the areas by the FIs. The area with the highest probability of a fault is the one with highest *Fault Index*, which is given by the sum of marks (M_j) assigned to the area divided by the number of nonzero marks (n):

$$\textit{Fault Index} = \frac{\sum_{j \in A-i} M_j}{n} \tag{1}$$

It is evident from Table VII that A-5 has the highest fault index, which truly corresponds to the faulted area.

FLOC using the conventional marking approach can be summarized by the following procedure; it is applicable to both radial and meshed networks.

Step 1: Use DFS to find the areas in the part of the network that is relevant to the Fault Event and such that the links between these areas are the FIs.

Step 2: Apply the marks to each of the areas based on the rules in Tables I–V.

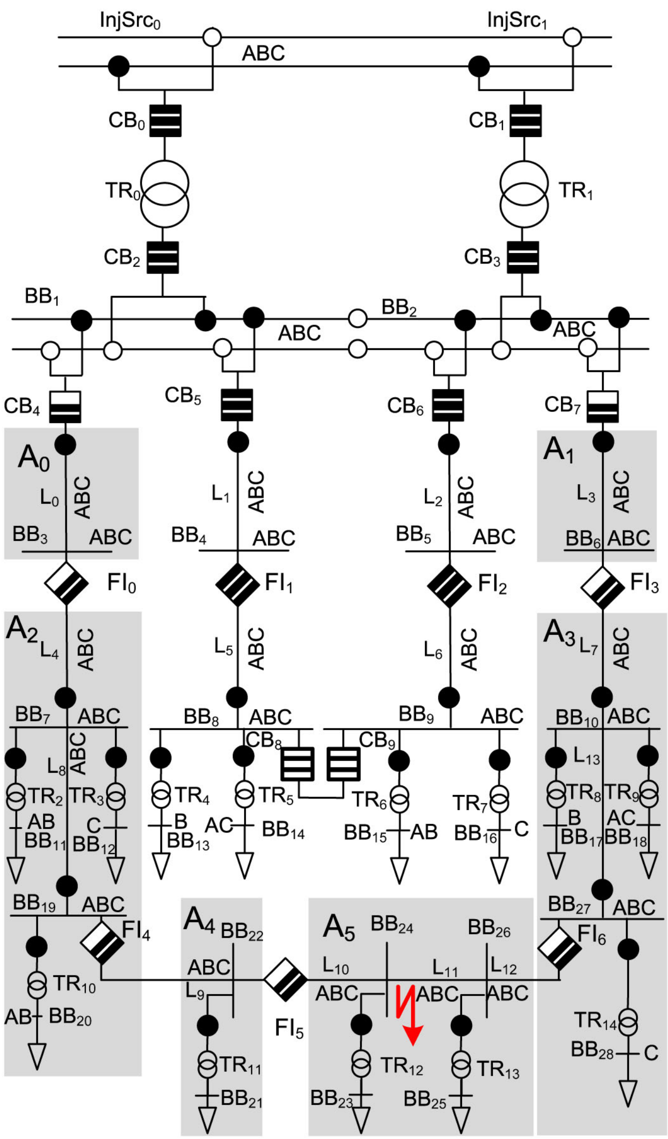

Fig. 7. Network with parallel injection.

TABLE VII
CONVENTIONAL MARKING APPROACH FOR THE NETWORK IN FIG. 7

FIs	FI-0	FI-3	FI-4	FI-5	FI-6	Fault Index
Status	S	S	S	S	S	
Flow	A0↦A2	A1↦A3	A2↦A4	A4↦A5	A3↦A5	
A-0	-1					-1
A-1		-1				-1
A-2	+1		-1			0
A-3		+1			-1	0
A-4			+1	-1		0
A-5				+1	+1	1

Step 3: Compute the fault index (1) for each area, and identify the area with the highest index as the one in which there is the highest probability of a fault.

C. Downstream Marking Approach

The downstream marking approach is a variation of the conventional approach described above; this approach is designed to minimize the impact of FIs that are wrongly set. It can be easily introduced with reference to the meshed network in Fig. 7: each bidirectional FI whose status is Set contributes a mark of +1 to all the areas downstream the FI (following the protection directions of the Set FIs) and a mark of -1 to all areas upstream the FI, and each bidirectional FI whose status is Not Set contributes a mark of -1 to all the areas upstream and downstream the FI. The result is shown in Table VIII, where the *Downstream Fault Index* for an area is simply the sum of all marks (M_j) assigned to it:

$$Downstream\,Fault\,Index(i) = \sum_{j \in A-i} M_j \tag{2}$$

TABLE VIII
DOWNSTREAM MARKING APPROACH FOR THE NETWORK IN FIG. 7

FIs	FI-0	FI-3	FI-4	FI-5	FI-6	Fault Index
Status	S	S	S	S	S	
Flow	A0↦A2	A1↦A3	A2↦A4	A4↦A5	A3↦A5	
A-0	-1		-1	-1		-3
A-1		-1			-1	-2
A-2	+1		-1	-1		-1
A-3		+1			-1	0
A-4	+1		+1	-1		+1
A-5	+1	+1	+1	+1	+1	+5

The area with the highest probability of containing the fault is the one with the highest index, correctly identified as A-5.

FLOC using the downstream marking approach can be summarized by the following procedure.

Step 1: Use DFS to find the areas in the part of the network that is relevant to the Fault Event and such that the links between these areas are the FIs.

Step 2: Apply the marks to these areas based on the following rules:

1) For meshed networks having bidirectional FIs (see Table V):
   - The FI status is Set in a specified direction: assign a mark of +1/-1 to all the areas downstream/upstream the FI in the specified direction. Each area that receives a +1 mark (downstream the Set FI) should be adjacent to another bidirectional FI that is Set and has its protection direction also pointing to this area.
   - The FI status is Not Set: assign a mark of -1 to all the areas downstream and upstream the FI.
2) For non-meshed networks having either non-directional or uni-directional FIs:
   a) Radial network with one power source, having non-directional FIs (see Table I) or uni-directional FIs whose protection directions are aligned with the energization direction (see Table II).
      - The FI status is Set: assign a mark of +1 to all the areas downstream the FI in the energization direction.
      - The FI status is Not Set: assign a mark of -1 to all the areas downstream the FI in the energization direction.
   b) Radial network with multiple power sources, having uni-directional FIs (see Table III) that are always energized.

TABLE IX
CONVENTIONAL MARKING APPROACH FOR THE NETWORK IN FIG. 7 - FI-5 STATUS IS FAULTY

FIs	FI-0	FI-3	FI-4	FI-5	FI-6	Fault Index
Status	S	S	S	NS	S	
Flow	A0↦A2	A1↦A3	A2↦A4	-	A3↦A5	
A-0	-1					-1
A-1		-1				-1
A-2	+1		-1			0
A-3		+1			-1	0
A-4			+1	-1		0
A-5				-1	+1	0

TABLE X
DOWNSTREAM MARKING APPROACH FOR THE NETWORK IN FIG. 7 - FI-5 STATUS IS FAULTY

FIs	FI-0	FI-3	FI-4	FI-5	FI-6	Fault Index
Status	S	S	S	NS	S	
Flow	A0↦A2	A1↦A3	A2↦A4	-	A3↦A5	
A-0	-1		-1	-1		-3
A-1		-1		-1	-1	-3
A-2	+1		-1	-1		-1
A-3		+1		-1	-1	-1
A-4	+1		+1	-1		+1
A-5		+1		-1	+1	+1

- The FI status is Set: assign a mark of +1 to all the areas downstream the FI in the protection direction.
- The FI status is Not Set: assign a mark of -1 to all the areas downstream the FI in the protection direction.

Step 3: Compute the downstream fault index (2) for each area, and identify the area with the highest index as the one in which there is the highest probability of a fault.

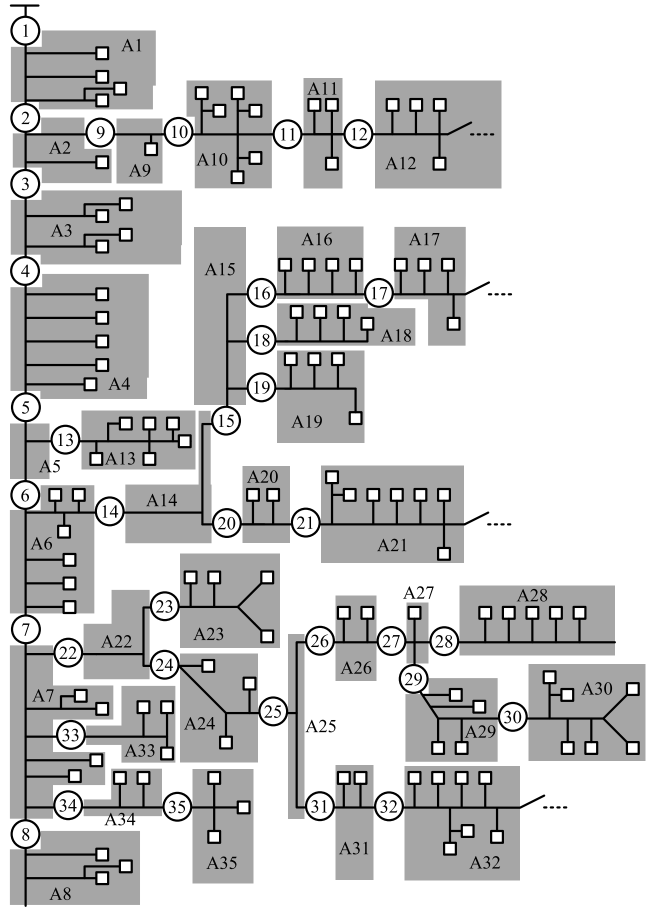

Fig. 8. Distribution network from the Taiwan Power Company.

D. Comparison of Marking Approaches

While both the conventional and the downstream marking approaches correctly identify the faulty area in the example of Fig. 7, the downstream marking approach is more immune to some FIs failing to be Set. Consider for illustration the same example in Fig. 7, but with FI-5 having a faulty status of Not Set. Tables IX and X show the identification of the fault location via the conventional and downstream marking approaches, respectively. It is evident from the results that the conventional approach identifies A-2, A-3, A-4, and A-5 as highly probable faulted areas, whereas the downstream approach marks only A-4 and A-5 as possibly faulted areas (they have the highest downstream fault index of +1). The downstream marking approach is superior in this case as it confines the overall possibly faulted area to a smaller geographical region. It should be noted here that FIs with a faulty status present a major challenge in meshed networks; as the next section demonstrates, the downstream marking approach has better immunity to faulty FIs in radial networks.

IV. ILLUSTRATIVE EXAMPLES

This section compares the performance of the Conventional Marking (Section III-B) and the Downstream Marking (Section III-C) approaches on a distribution system from the Taiwan Power Company serving 123 loads; this system is shown Fig. 8 where the locations of 35 non-directional FIs obtained from [22] are indicated.

The first example in Table XI considers a fault in area A17 in the network of Fig. 8; this fault causes the following 10 FIs to be Set: 1, 2, 3, 4, 5, 6, 14, 15, 16, and 17. With all FIs correctly activated, the two approaches (Conventional and Downstream) correctly identify A17 as the fault area; this is indicated in row 3 of Table XI. The remaining rows in Table XI show the results of the two approaches when one of the 10 FIs that should have been Set fail to be activated. The complete set of results demonstrates that the downstream marking approach is successful in isolating the fault area in 8 out of the 10 cases with non-active FIs. The second example in Table XII considers a fault in area A30 causing the following 14 FIs to be Set: 1, 2, 3, 4, 5, 6, 7, 22, 24, 25, 26, 27, 29, and 30; in this example, the downstream approach is successful in 12 out of the 14 non-active FI cases, and the conventional approach correctly identifies only A30 in one out of the 14 cases. For illustration on how these results were obtained, an electronic companion [27] shows the matrices for both the conventional and downstream marking approaches in two sample cases corresponding to a fault in A30: when there are no non-active FIs, and when FI-7 is non-active.

The downstream marking approach is also more advantageous in some cases of FI placement. Consider for illustration

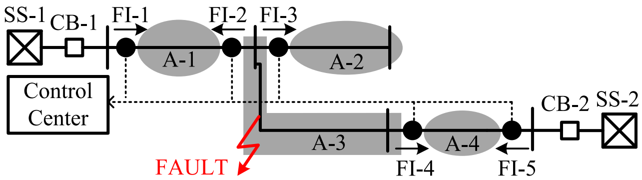

Fig. 9. Network with Uni-directional FIs.

TABLE XI
FLOC WITH FAULT IN A17 AND A NON-ACTIVE FI - NETWORK IN FIG. 8

Non-active FI	Result - Fault in Area	
	Conventional	Downstream
-	A17	A17
17	A16	A16
16	A15 & A17	A15 & A17
15	A14 & A17	A17
14	A6 & A17	A17
6	A5 & A17	A17
5	A4 & A17	A17
4	A3 & A17	A17
3	A2 & A17	A17
2	A1 & A17	A17
1	A17	A17

TABLE XII
FLOC WITH FAULT IN A30 AND A NON-ACTIVE FI - NETWORK IN FIG. 8

Non-active FI	Result - Fault in Area	
	Conventional	Downstream
-	A30	A30
30	A29	A29
29	A27 & A30	A27 & A30
27	A26 & A30	A30
26	A25 & A30	A30
25	A24 & A30	A30
24	A22 & A30	A30
22	A7 & A30	A30
7	A6 & A30	A30
6	A5 & A30	A30
5	A4 & A30	A30
4	A3 & A30	A30
3	A2 & A30	A30
2	A1 & A30	A30
1	A30	A30

the network in Fig. 9 that has two power sources, five uni-directional FIs with their protection direction indicated by the arrow sign, and four areas. The fault is assumed to be in A-3 resulting in FI-1 and FI-5 being Set (both CBs are tripped), while FI-2, FI-3, and FI-4 remain Not Set. The results for the conventional and the downstream approaches are shown in Tables XIII and XIV, respectively; note that in the downstream marking approach, the Set/Not Set FI contributes a mark of +1/-1 downstream the FI in the protection direction. Based on Eq. (1), the conventional approach cannot calculate a fault index for A-2 because none of the FIs contribute a non-zero mark to it; on the other hand, the computations of the downstream marking approach in Table XIV show that A-3 is correctly identified as the faulted area.

In summary, the proposed downstream marking approach applies to both radial and meshed networks. For radial networks, the method exhibits bad data detection of FI statuses. The method is applicable to meshed networks when bidirectional FIs are installed. According to the golden rule of

TABLE XIII
CONVENTIONAL MARKING APPROACH FOR THE NETWORK IN FIG. 9

FIs	FI-1	FI-2	FI-3	FI-4	FI-5	Fault
Status	S	NS	NS	NS	S	Index
A-1	+1	-1				0
A-2		0	0	0		?
A-3			-1			-1
A-4				-1	+1	0

TABLE XIV
DOWNSTREAM MARKING APPROACH FOR THE NETWORK IN FIG. 9

FIs	FI-1	FI-2	FI-3	FI-4	FI-5	Downstream
Status	S	NS	NS	NS	S	Fault Index
A-1	+1	-1			+1	+1
A-2	+1				+1	+2
A-3	+1		-1		+1	+1
A-4	+1			-1	+1	+1

protection, loops in distribution networks are allowed only if a fault causes not more than two circuit breakers to trip, i.e., the fault will be only on one loop. In practice, distribution networks are either radial or weakly meshed and the downstream marking approach applies to them. The approach also applies to reconfigured networks, provided that the resulting protection scheme remains properly coordinated and inline with good protection practices. Distribution system operators give special attention to the impact of the reconfiguration solution on the protective scheme [28], as this will influence the reliability of the network in terms of serving customer loads. To enable practicable network reconfiguration, Broadwater *et al.* [29] have proposed a method for protection system design that is adequate for all envisioned configurations of a circuit. In a related approach, Hsu and Yi [30] design protection schemes in which protective devices remain properly coordinated when switching is limited to certain switchable regions of the network.

V. CONCLUSION

Fault indicators with communication capabilities are deployed in smart grids and play an essential role in locating fault areas and consequently improving system reliability. The conventional graph marking approach [24] for automatically locating the fault area based on the fault indicator statuses is already employed in the industry. This paper presents a downstream graph marking approach that is shown to be superior to the conventional method in terms of (i) robustness in the presence of non-active fault indicators and (ii) performance under some directional FI placement schemes. Both the conventional and downstream marking approaches are very simple to implement and are used in real-life systems. The success of the downstream marking approach has been already proven in the field, on both unsymmetrical U.S. and balanced European distribution networks.

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