Fast Fault Location for Fast Restoration of Smart Electrical Distribution Grids

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Abstract— **Distribution systems are evolving towards fault self-healing systems which can quickly identify and isolate faulted components and restore supply to the affected customers with little human intervention. A self-healing mechanism can considerably reduce the outage times and improve the continuity of supply; however, such an improvement requires a fast fault location method and also a communication and measurement infrastructure. In this paper the feasibility of fast service restoration through a fast fault location method is studied. A fast fault location method is proposed which is applicable to any distribution network with laterals, load taps and heterogeneous lines. The performance of the proposed method is evaluated by simulation tests on a real 13.8 kV, 134-node distribution system under different fault conditions. The results verify the applicability of the proposed architecture. We show that the communication delay plays a less important role in overall restoration time, and we stress the contribution of a fast fault location method in keeping the overall interruption time less than 1 minute.**

Keywords—Distribution systems; fault location; internet of things; self-healing; smart cities; smart grid

I. INTRODUCTION

Distribution network faults are one of the main factors threatening the reliability and quality of the supply system in future smart grids in smart cities. Distribution networks can be significantly affected by faults arising from different sources such as adverse weather conditions, construction work with digging the ground for pipelines and cables, bird contacts on overhead lines, and vegetation growth. Nowadays, on one hand, the society becomes more and more dependent on electrical power and on the other hand, as climate change increases the frequency and intensity of extreme weather events, the number of outages caused by severe weather is expected to rise [1].

In modern distribution networks of future cities with advanced communication and measurement infrastructure, an efficient outage management system can improve distribution system reliability through reducing the duration of outages by fast service restoration. Having a fast and accurate fault locator, remote switching devices and a communication system provides the possibility of fast service restoration. The final goal is a self-healing mechanism which will be able to identify and isolate faulted components and restore supply to the customers affected by the fault [2].

Fig. 1 shows the process of a conventional outage management system. Upon the occurrence of a fault and subsequent operation of the protection system, outage mapping is carried out. This is traditionally based on activities such as grouping of customer outage calls to determine the protective devices involved in fault clearing to find the outage area. Then, a repair crew has to be sent to patrol the area and walk along the power distribution lines, which can be kilometers, in order to find the fault evidences and to ensure safety prior to re-energizing the system. The whole restoration process may take from tens of minutes to hours.

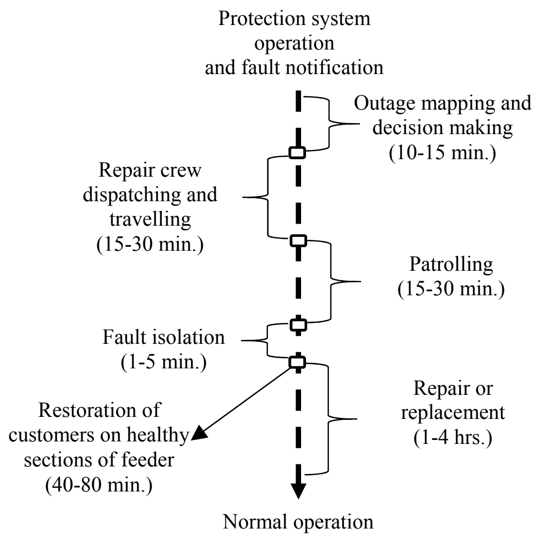

Fig. 1. Process of a conventional outage management system [2]

In modern distribution networks with advanced measurement and communication infrastructure, using an accurate fault location method will reduce outage times and enhance the reliability and quality of supply. Fault location helps utility personnel to quickly restore the maximum number of the interrupted customers located on the healthy sections as shown in Fig. 2 when compared with Fig. 1. Fault location not only provides the possibility of fast service restoration and hence reduction of the outage cost, but also narrows down the search area and minimizes the patrolling time.

Comparing Fig. 1 and Fig. 2 clearly indicates that fast fault location in an advanced outage management for fast service restoration can considerably reduce the outage times and improve the continuity of supply. However, such an improvement requires a fast fault location method and also a communication and measurement infrastructure. In this scenario, the rising concept of Internet-of-Things (IoT) can provide the information needed by fault location algorithms in (near-) real-time. Indeed, each smart meter in charge of monitoring a substation operation can be considered as an IoT device connected to the Internet that sends relevant data to remote algorithms and control policies. In this paper we discuss the possibility of implementation of such an advanced outage management system exploiting an IoT approach. Then, an optimized fast fault location method is proposed and tested by simulation studies on a 134-node, real distribution network. The simulation study verifies that the proposed method satisfies the attributes required to make an advanced fault management system feasible.

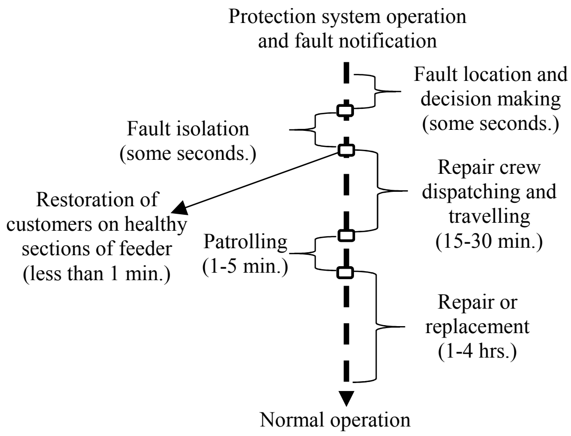

Fig. 2. The process of an advanced outage management system

The rest of the paper is organized as follows. Section II presents the state of the art. Section III discusses our IoT approach for sending information about the status of the power grid in (near) real-time. Section III introduces the proposed fast fault location method. Section IV presents the simulation results. Finally, Section V provides the concluding remarks.

II. State of the Art

For a smart-grid, the self-healing capability is recognized to be one of the key features [3], and in order to enable self-healing, one of the main steps is fault location. Thanks to the fault location and self-healing capabilities, it is possible to improve quality of the electricity supply for the customer.

Over the last two decades, several distribution fault location algorithms have been proposed. Impedance-based algorithms are designed to estimate the fault location using the voltage and current measurements at the head of the network main feeder [4]-[7]. Travelling wave-based methods are based on the correlation between fault location and some characteristic frequencies associated with specific paths which the fault originated travelling waves propagate [8], [9]. Methods based on artificial intelligent systems, such as neural networks are proposed as alternative methods that can have accurate results with less online computation [10], [11].

Inspired by emerging meters in electrical distribution systems [12], recently, another class of fault location methods has been proposed using sparse voltage sag measurements [13]-[17]. These methods assume the fault at each network node, one at a time, and calculate pre- and during fault voltages at nodes having measurements. Then, they identify the node with the smallest difference between the measured and calculated voltage sags as the fault location.

The problem of matching the available measurements data in the smart grid with the best fault location algorithms has been studied by M. Kezunovic [16]. However, despite various methods proposed for fault location, the feasibility of fast service restoration through a fast fault location method has not been well studied, to the authors' knowledge. In this work we aim to propose an optimized fast fault location method which can potentially speed up service restoration. Moreover, we study the effect of communication delays on overall restoration time to show the feasibility of an advanced outage management system through a fast fault location method.

III. An Internet of Things approach for Smart Grid

Nowadays, the Internet-of-Things (IoT) is a rising concept that consists on connecting "Things" on the Internet to exchange information and cooperate as a system of systems to achieve common goals [18]. Following this idea, next generation of smart meters will be IoT devices that will communicate relevant information about the status of the electrical distribution grid, also exploiting cloud solutions [19]. In this view, IoT will foster general purpose services in smart grids [20].

On this premises, the new smart meters have to send data in (near-) real-time to all the algorithms and control strategies that need such inputs to provide a service. To address this issue, the publish/subscribe communication paradigm is needed [21]. Indeed, with respect to the request/response approach, publish/subscribe provides an asynchronous communication allowing the development of loosely-coupled event-based systems. Hence in a smart metering system, each IoT device (i.e. smart meter) publishes information and generic algorithms subscribes to specific event notifications in order to receive the needed data. In addition, this approach increases the infrastructure scalability, by removing the dependencies between interacting entities.

In order to locate a fault along the distribution network, smart meters at primary and some of secondary substations publish recorded samples or phasor measurement of electricity current and voltage. The measurements are recorded when a fault occurred: a few cycles before and a few cycle after fault (and of course before protection reaction), samples or phasors are recorded to report. The fault location algorithm subscribes to the same values. When new data are received, the fast fault location algorithm starts processing them to find the location where the fault occurred [22].

IV. THE PROPOSED FAST FAULT LOCATION METHOD

The main idea of this work is to propose a fast fault location method that satisfies the key attributes required to make an advanced fault management system feasible. The proposed fault-location method utilizes voltage and current measurements at the head of main feeder and the magnitude of voltage sags recorded at some nodes equipped with voltage measurements, such as power quality meters or digital fault recorders. Synchronization or phasor-angle information is not required. The algorithm is based on the fact that each fault causes voltage sags with different characteristics at different nodes. Therefore, knowing the voltage sag magnitudes at certain measurement nodes, it would be possible to locate the faulted node. The method proposed in [13] assumes the fault at each node throughout the network and calculates voltage sags using a load flow algorithm during the fault. It then determines the faulted node by comparing how well the calculated values for each node (I_j) match the measured values. If the following index is calculated for each node, the node with the largest value of the index has the best match and would be one end of the faulted line:

$$I_j = \frac{1}{\sum_{i=1}^{m} \left| \Delta V_i^{meas} - \Delta V_{i,j}^{calc} \right| + \varepsilon} \quad (1)$$

Where ΔV_i^{meas} and $\Delta V_{i,j}^{calc}$ are the measured and calculated voltage sags at i^{th} measurement node for fault at j^{th} node, m is the number of measurements and ε is a small number to avoid deviation by zero.

For each node, after calculation of the pre- and during-fault voltage magnitudes using a power flow algorithm, the I value can be calculated. The surface in Fig. 3 shows the I values for different locations of a sample distribution network. As shown, the I takes its maximum around the faulted point and as the distance to fault increases, it gradually decreases. The method proposed in [13], examines all system nodes searching for the maximum of this surface. The main idea is to optimize this process. Therefore, instead of applying the algorithm to each node throughout the network, it is only applied to a limited number of nodes, significantly reducing the computational time.

Starting from any initial point, the trajectory to the maximum point of the surface is almost always upward. Therefore, a simple local search algorithm can be used to find the node with the maximum value of I (i.e. the nearest node to the fault).

As shown in Fig. 4, the proposed method starts at a random initial node and repeatedly moves to an improving neighboring node. At the final point of the search trajectory it reaches to a node which I is higher than its neighboring nodes. The last selected node is the fault location (i.e. the nearest node to the maximum of the surface in Fig. 3).

Following the occurrence of a fault, the proposed method investigates a limited number of nodes to find the nearest node to the fault location. The details of during fault load flow algorithm are described in [13].

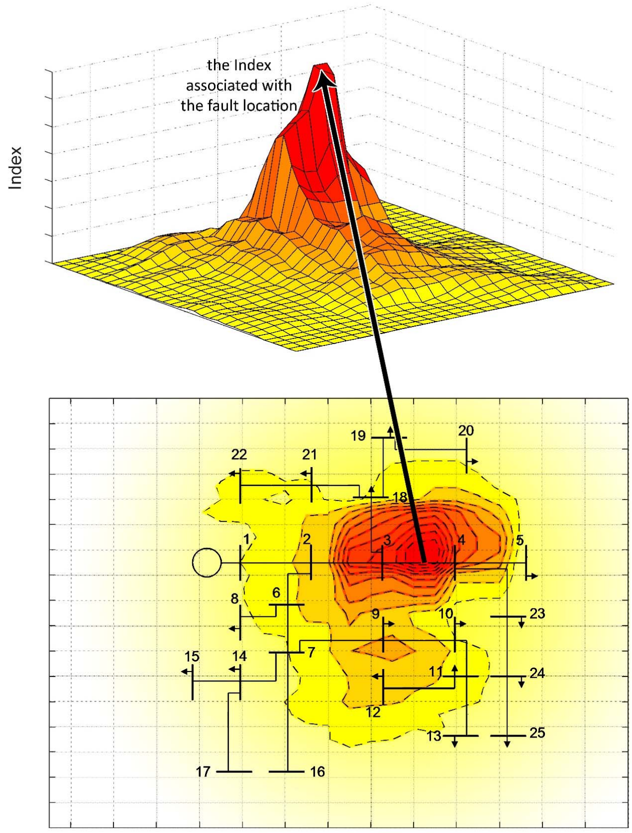

Fig. 3. Index values for different locations of a sample distribution network when there is a fault in the middle of line 3-4

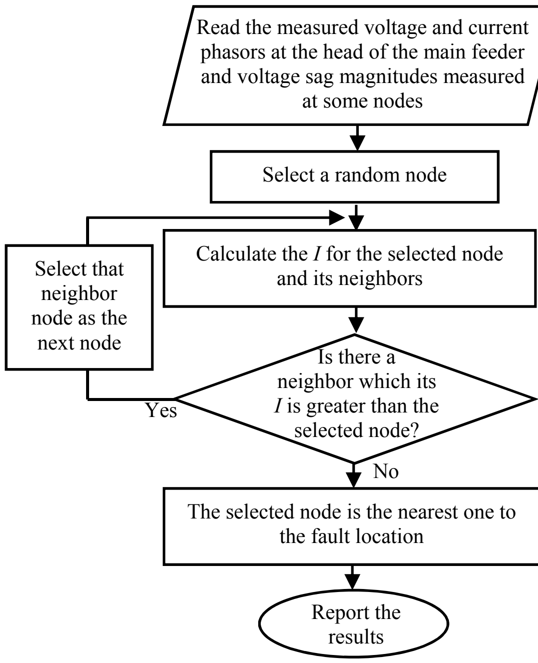

Fig. 4. Flowchart of the proposed fault location algorithm

V. SIMULATION STUDY

The simulation test is performed on an overhead, three-phase, 13.8 kV, 134-node real life distribution system shown in

Fig. 5 [13]. The test feeder is simulated in the Alternative Transient Program (ATP), and the loads are modelled as constant impedances. Five voltage measurements are arbitrarily placed in the system, at nodes 20, 51, 87, 118 and 127. Several fault scenarios are considered for different fault types, locations, and resistances.

TABLE I. shows the deviation between the actual and estimated fault locations in meter for different fault scenarios considering single phase to ground faults (AG). The results indicate that the proposed method provides satisfactory results for different fault locations. Moreover, it can be seen that the results are not affected by increasing the fault impedance. TABLE II. shows the difference for the same fault scenarios but different fault types. The comparison of the result shows that the proposed fault location algorithm has the same results for dissimilar fault types and its accuracy is acceptable.

TABLE I. DISTANCE BETWEEN THE ESTIMATED AND ACTUAL FAULT POINTS IN METER FOR SINGLE-LINE TO GROUND FAULTS (AG)

Scenarios	**Fault impedance**		
	1 Ω	**5 Ω**	**20 Ω**
Fault at line 74-75 55m from 74	55	55	55
Fault at line 90-119 44m from 90	44	44	44
Fault at line 109-110 15m from 109	15	15	15

TABLE II. DISTANCE BETWEEN THE ESTIMATED AND ACTUAL FAULT POINTS IN METER FOR DIFFERENT FAULT TYPES

Scenarios	**Fault type**		
	CA	**BCG**	**ABCG**
Fault at line 74-75 55m from 74	55	55	55
Fault at line 90-119 44m from 90	44	44	44
Fault at line 109-110 15m from 109	15	15	15

To test the robustness of the algorithm to the location of the meters, the five voltage measurements are placed in different nodes. TABLE III. reports the fault location estimation errors. The results indicate that as long as the meters are well distributed over the network, the algorithm is able to locate the faults. However, if a Distribution System Operator (DSO) decides to use the fault location results for automatic service restoration, more confidence can be placed in the results by verifying them through automatic pulling of downstream smart meters. The ability of modern smart meters to send “last gasp massages” following to an outage can also provide the required information to verify the fault location results.

As previously described, computational time is a factor that directly affects the restoration time and is hence a primary measure for assessing algorithmic efficiency. Here the computational time is defined as the CPU time that a fault location algorithm takes to perform its calculations and report the results. All the computations are performed on a personal computer with 2-GHz Intel Core 2 Duo processor and 2 GB of RAM.

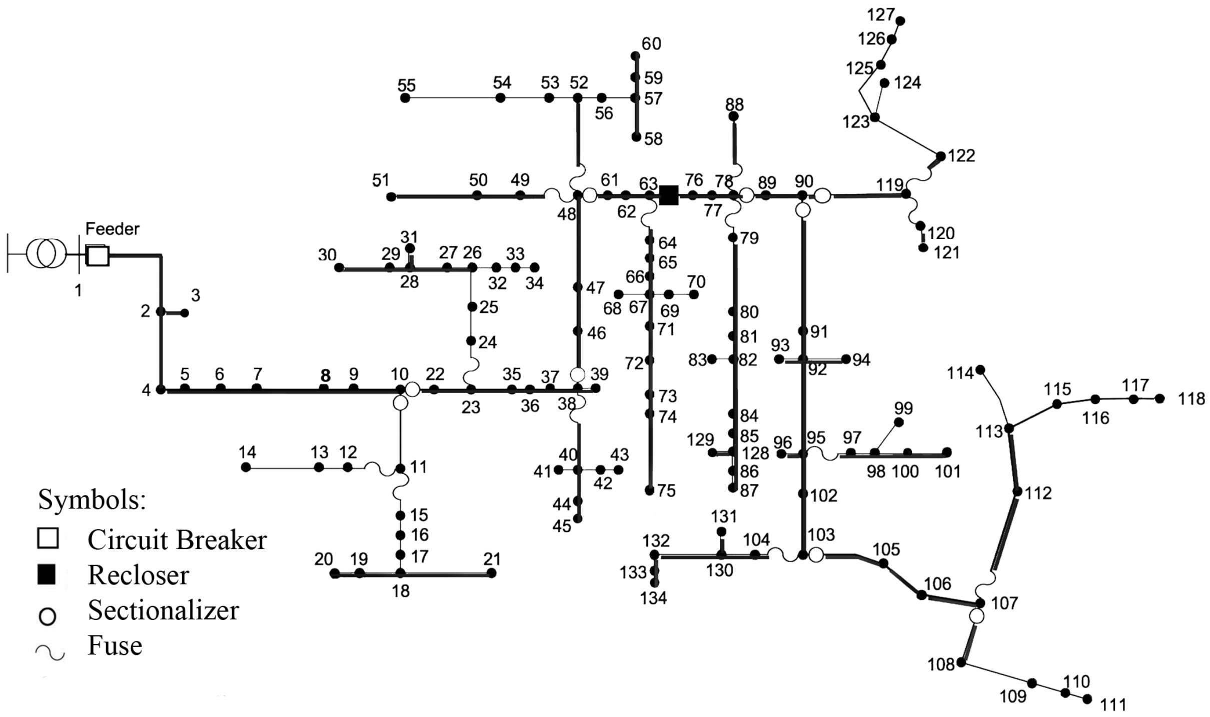

Fig. 5. Topology of the 134-node distribution network

TABLE III. THE EFFECT OF THE LOCATION OF THE METERS ON FAULT LOCATION RESULTS FOR SINGLE-LINE TO GROUND FAULTS (AG)

Scenarios	Nodes with meters		
	20, 51, 87, 118, 127	14, 55, 75, 111, 121	7, 26, 76, 114, 124
Fault at line 74-75 55m from 74	55	55	55
Fault at line 90-119 44m from 90	44	44	90
Fault at line 109-110 15m from 109	15	495	15

TABLE IV. presents the minimum, mean and maximum computational times of the proposed method and the algorithm proposed in [13] for all different fault scenarios considered.

As described in Section IV, the proposed method investigates a limited number of nodes to find the fault location. Therefore, as can be seen in TABLE IV. , it is much faster than the other algorithms and its mean computational time is less than 10 seconds. Such a fast fault location algorithm will enable the outage management system to take immediate corrective actions to restore the most possible number of customer in less than 1 minute and hence improve system reliability.

We also performed some tests to evaluate the transmission time to send data from the publisher (i.e. smart meter) to the subscriber (i.e. algorithm) as described in Section III. These tests have been done exploiting the MQTT protocol (an implementation of publish/subscribe) and repeated in Local Area Network (LAN) and Wide Area Network (WAN) environments. Such tests consist on emulating the behavior of the smart meter by publishing information about a fault in order to estimate the time (in seconds) needed to be delivered to the subscriber.

In LAN tests, publisher, subscriber and message broker are in the same local network, while in WAN tests, they are located in different location of the same city and communicate across the Internet. In order to stress these tests, the smart meter publishes data in a payload of about 18 Kbyte every second. As shown in TABLE V. in LAN communications the mean delivery time needed is 0.0355 s, the min and max are respectively 0.0162 s and 0.9928 s. While in WAN, the mean value is 0.3669 s, the minimum and maximum are respectively 0.2661 s and 4.7866 s.

TABLE IV. THE MINIMUM, MAXIMUM AND MEAN COMPUTATIONAL TIMES IN SECOND

method	min ΔT	mean ΔT	max ΔT
Proposed method	4.75	9.43	14.6
Method proposed in [13]	38.38	43.39	50.11

TABLE V. TIME IN SECOND TO DELIVER THE INFORMATION EXPLOITING THE PUBLISH/SUBSCRIBE

Scenarios	min ΔT (s)	mean ΔT (s)	max ΔT (s)
LAN	0.0162	0.0355	0.9928
WAN	0.2661	0.3669	4.7866

Comparing the maximum required time of communication with the maximum computation time of fault location algorithm, we see the communication delay has a small contribution in the overall delay. Therefore applying the fast algorithm which reduced the computation time from 50.11 s to 14.6 s (as maximum values shown in TABLE IV.) seems to be an approach which was worth to invest on, as it eventually reduced the overall maximum delay for more than 60% (from 54.81 s to 19.3 s).

VI. CONCLUSION

The capability of self-healing after a fault is one of the interesting subjects for DSOs, especially in emerging smart grids. It can largely reduce the electricity interruption time and guarantee a higher continuity of supply. In this paper, we propose a fast fault location method which can potentially speed up service restoration. Restoration time is already reduced when the DSO exploits fault location methods instead of traditional investigation, however faster restoration aiming at keeping interruption time less than some standard thresholds (e.g. 1 minute) is very beneficial for DSOs because the fault in this case is usually considered as transient fault and it is not reported [23], [24]. We showed communication delay plays a less important role in the overall delay, and applying a fast fault location algorithm can considerably reduce the overall restoration time. The proposed method is applicable to any distribution grid with laterals, load taps and heterogeneous lines.

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