Advanced Fault Location Algorithm and Impact on Optimized Repair Crew Dispatch

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Abstract—**Fault management in distribution systems lacks effective solution because of the unavailability of sufficient measurement data and comprehensive tools for fault analysis. To improve fault management, a systematic approach that takes advantage of distribution-level Smart Grid technologies is proposed. The new approach executes very accurate fault locating first, and then advices system operators on optimized repair crew dispatch next. The benefits in implementing this approach is assessed by reduction in costs associated with fault management activities.**

Keywords-fault management, fault location, crew dispatch, distribution systems, outage management, risk analysis

I. INTRODUCTION

A typical distribution system accounts for 40% of the cost to deliver power and 80% of customer reliability problems [1]. Aging of electric equipment, vegetation and animal intrusion and other causes makes faults in distribution systems more frequently than transmission and generation systems [2]. Fault detection and location in distribution systems are more difficult because of the complex topology and variety of properties of transmission feeders [3]. Cost associated with the faults and power not delivered varies depending on the type of the customer served.

Fault management is one of the major functions in a distribution utility and the major responsibility of an Outage Management System (OMS), which includes fault detection, location and repair. Typically fault management is initiated by the call center receiving trouble calls, which report loss of power at customer site; protection engineers then start fault analysis, which yields an approximate estimation of the location (an area) and cause of the fault; and, system operators issuing work order to repair crew to disconnect faulted area and find the faulted spot, which is based on the result of fault analysis. System is at last restored after any necessary repair/replacement.

A major obstacle for improving the distribution fault management is the lack of monitoring devices installed along the feeders leading to an inability to monitor the system closely in real-time as the faults occur. Consequently, fault management is quite often slow and heuristic. When a fault occurs, it may go unnoticed for some time unless customers report it to the trouble call center. The locating of fault may take long time because repair crew must search along the feeders without a clear instruction where the fault location is and it may be delayed significantly until they visually identify the fault [3].

Current studies are focusing on improving individual steps of fault management. Studies on the linkage between tasks and the impact on the overall performance of system reliability are missing. For example, the approach for crew dispatching in [4] is based on the assumption that fault analysis provides precise location and cause of fault, which does not stand for many fault location approaches; service restoration approaches in [5] produces switching schemes that recovers as much load as possible, but does not differentiate whether the reduced load loss is worth the trouble of switching and interrupting customers connected to healthy feeders.

This paper provides a solution for improving individual tasks as well as the overall performance of fault management. The benefit is the reduction in the duration and scale of the outage. Reliability indices which are defined to represent different features of outages such as duration, frequency and scale [6], are used to quantify the cost of outages and assess the benefits.

After an introduction, Section II reviews s related studies in fault location and crew dispatch; Section III proposes a fault management including new fault location algorithm and crew dispatch method based on improved fault location results and risk analysis approach. Case study is provided in Section IV, followed by conclusions (Section V).

II. REVIEW OF PREVIOUS STUDIES

A. Distribution Fault Location

Based on the type of data and models that the fault location techniques use, the current algorithms can be grouped into following categories [8]:

- Non-electric quantities
- Apparent impedance measurement
- Direct three-phase circuit analysis
- Superimposed components
- Traveling waves

- Sparse voltage magnitudes

The first category refers to staff expertise that relies on information from trouble calls, metering system and other information that is believed to be related to the type and location of faults. Such methods help narrow down the fault area but cannot provide accurate location.

The apparent impedance methods calculate the distance of fault based on the ratio of selected voltage to selected current based on the assumption about fault type and faulted phases. Such methods are simple but not accurate when applied to non-transposed and unbalanced systems, and yield more than one results (multiple "candidate" locations with no preference). Three-phase circuit analysis and methods using superimposed component are suitable for unbalanced systems, but the problem of multiple results remains. Traveling wave based methods are suitable for underground cable networks, but requires high frequency sampling and increased accuracy of data, which increases implementation cost. When implemented in an over head system these methods suffer from undesired reflection and loss of signal strength from load taps and laterals.

As a part of Smart Grid deployment projects, IEDs for monitoring, protection, and other purposes including the smart metering systems, power quality monitoring, and distribution system automation have emerged in distribution systems. These smart sensors are being installed all over the system, from substation down to the customer location. The latest fault location methods that use sparse voltage dip measurements from Power Quality Monitors (PQM). The location of fault is identified by comparing calculated values of V from various fault scenarios with the field-recorded value. However having a complete and correct system model (topology and parameters) is a key to producing accurate results.

B. Optimized Repair Crew Dispatch

Current study of optimal distribution crew dispatch is focused around system restoration after large scale outages, system-wide blackouts and multi-location fault inspection [9], [10]. On top of the subject of minimum losses (which is the subject for optimization of switching operation), maintenance crew dispatch considers the risk of human error and complexity of fault management work. Assessment of the crew dispatch takes care of the following issues:

- Total restored MVA;
- Number of crew and vehicles;
- Steps of restoration (switching operation) and time taken.

Heuristic search, among other methods such as generic algorithm and fuzzy network, is the most common algorithm for solving the restoration and crew dispatch optimization, For most of the methods, crew dispatch is optimized after the sequence of switching is scheduled; for others, switching operation and crew dispatch is optimized simultaneously.

No reference of crew dispatch for field inspection and fault isolation has been studied yet based on the literature search. The research is based on the assumption that location and cause

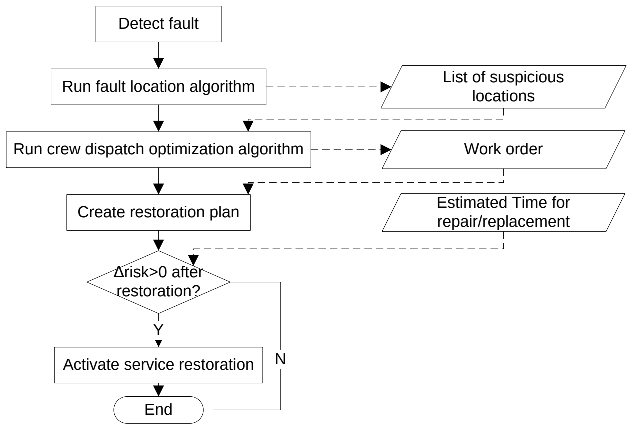

Figure 1. Proposed fault management steps.

of outages are known before maintenance crew is dispatched. This may true for planned outages or the ones caused by major equipment failure but doesn't apply to faults caused by insulator defect, plant and animal intrusion and fuse blowing. How to create the work order to minimize the cost associated with feeder inspection and repair prior understanding of where the fault may be located is the focus of the crew dispatch approach described in this paper.

III. OPTIMIZED FAULT MANAGEMENT

A. Overview of Fault Management Tasks

Flow chart for the proposed fault management is shown in Fig. 1. The solid lines indicate sequence of procedures; dashed lines indicate flow of information and knowledge. After a fault is reported, the Outage Management (OM) system first executes fault locating algorithm using field recorded data and system model and identify suspect locations; the output is then fed to crew dispatch optimization program to create work order and service restoration plan based on the minimum-risk principle. Restoration plan is then generated and when the cause of fault and estimated time for repair/replacement work has been reported by the crew, the benefit of restoration is evaluated to decide whether it is worthwhile or necessary to switch some of the disconnected load to the "healthy" part of the system during the time of repair/replacement.

B. Formulation of Risk

Reliability Indices from [11] are used in formulating costs associated with interruption events. Using these reliability indices, we can build the function that represents the outage cost that considers the duration, range and affected customers comprehensively. This formulation makes it possible to analyze the benefit of the individual OM tasks in terms of associated cost of the impact.

Cost brought by an interruption event i is defined as follows [12]:

$$Cost(i) = \beta_1 \cdot SAIDI(i) + \beta_2 \cdot ASIDI(i) + \beta_3 \cdot MAIFI'(i) + \beta_4 \cdot MED(i) \quad (1)$$

where:

SAIDI: System Average Interruption Duration Index;

ASIDI: Average System Interruption Duration Index;

MAIFI': Momentary Average Interruption Frequency Index where only customers with special requirement for power quality are accounted for;

MED: SAIDI of a Major Event Day;

β1~β4: weight factor for unit coordination and for customer differentiation.

Risk associated with a dispatch schedule is defined as:

$$Risk = \sum P_i \cdot Cost_i \qquad (2)$$

where P_i is the probability that an event may happen (e.g. outage is caused by failure of a certain component, or fault occurs to the downstream of a certain switch), and $\Sigma P_i=1$; $Cost_i$ is the cost of outage given that the event does happen.

C. New Fault Location Algorithm

A model-based fault location algorithm for radial distribution systems is proposed in [13]. The algorithm uses voltage magnitudes from the sparse voltage measurement devices installed in distribution systems. The flow chart is shown in Fig. 2. The algorithm consists of four steps: Pre-fault load flow calculation, estimation of applicability, fault simulation and faulted node selection. The algorithm is capable of assessing the measurement applicability, detecting bad data and adjusting the contribution of field-recorded data from different measurements according to the accuracy of measurements. Stochastic analysis is introduced in the algorithm to reduce the impact of data error on the output.

The likely fault location is selected taking into account all analyzed nodes during the fault location process. Weighted-voltage deviation is used for locating the fault.

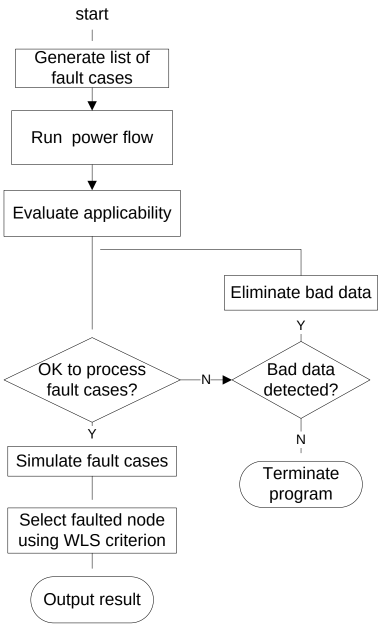

Figure 2. Flow chart for proposed fault location algorithm.

For each analyzed node, the during-fault magnitude deviation between measured and calculated voltage sags is computed:

$$\delta_k^j = \left\| \Delta V_k^{j,cal} - \Delta V_k^{meas} \right\|, k = 1, \ldots m, j = 1, \ldots np \qquad (3)$$

where

$\Delta V_k^{j,cal}$ is the difference in three-phase pre-fault and during-fault voltage magnitudes (voltage sags) calculated at node k considering node j as the faulted node;

ΔV_k^{meas} is the three-phase voltage sags measured at node k;

m is the total number of voltage measurements;

np is the total number of fault cases simulated.

The weighted-deviation is calculated as

$$\gamma_j = \sum_{k=1}^{m} (\delta_k^j / \sigma_k)^2 \qquad (4)$$

The faulted node is the one with the smallest value of γ_j.

$$n_f = j \mid \gamma_j = \min\{\gamma_s\}, s = 1, \ldots np \qquad (5)$$

The output of this algorithm is a list of node number arranged by the closeness of calculated and simulated value of the voltage magnitudes. The algorithm has been tested on a 130-node system [13].

D. The Crew Dispatch Optimization

The proposed fault location method produces a list of nodes starting with the most suspected node based on the calculated fault location index. When data condition is not satisfactory, the calculated value of the index of the actual faulted node may not be the largest, but will not fall out of the top few nodes. In such cases if work order is generated based solely on the selected node (the first one), the crew may not find the faulted spot in the proposed area and then it will take a much longer time for field inspection. This creates the necessity of optimization.

Although the "true" faulted node may not be the first one on the list, it is easy to form the inspection areas based on the first M nodes on the list (M=4 in case study). Using (1) and (2) the risk associated with a crew dispatch schedule can easily be calculated:

- The probability of fault being in one area is associated with the number of nodes in this area and their ranking on the list;
- Time for crew to get to the inspection area is in proportion with the distance of the inspection area from the crew station; time for searching one area is associated with the size of the area and the number of dispatched crews;
- Forced temporary interruptions are considered for critical customers only and are associated with number and time of switching operations;

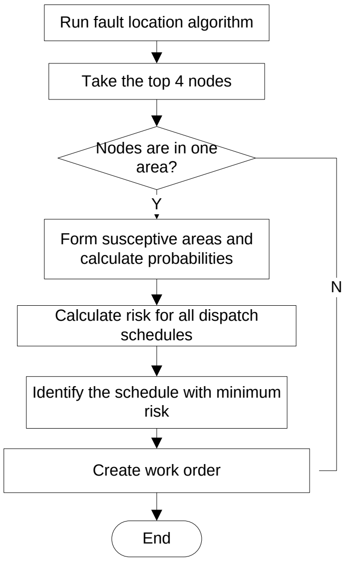

Figure 3. Crew Dispatch Optimization

- The steps for searching one area are: the crew goes to the nearest upstream switch and disconnects the area. if the fault goes away then search for faulted spot begins; if the fault remains then fault is not in this area and the crew returns to station;
- One can choose to search the areas one by one, or to split crew into groups to search the areas in parallel and there is a cost associated with each of the plans,
- The result of optimization includes number and sequence of areas for inspection, number of crew dispatched to each area, and sequence of switching operation.

The optimal schedule is selected by the following optimization:

$$\textit{Min Risk(node 1,…node M; } N_{labor1}, \ldots N_{labor.i})$$

$$s.t. \quad \sum_{1}^{i} N_{labor.j} = N_{labor.\max} \qquad (6)$$

where

node 1~ node M: top M likely faulted nodes;

i: number of areas;

$N_{labor.j}$: number of dispatched crews to area j;

$N_{labor.max}$: total number of available crews.

Flow chart for crew dispatch optimization with M=10 is shown in Fig. 3.

E. Service Restoration Plan

Risk associated with service restoration plans can be calculated using similar method, with additional constraints of three-phase load balance, voltage limitations and transformer capacities. Reduction in risk ΔRisk caused by restoration is calculated. If ΔRisk exceeds the threshold, restoration is considered "helpful" and should be executed. Otherwise restoration is considered "meaningless" or "harmful" and will not be executed. Flow chart is shown in Fig. 4.

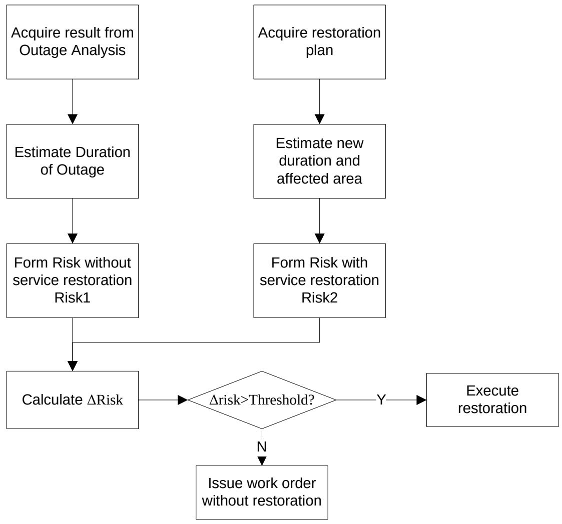

Figure 4. Assessment of Service Restoration

IV. Case Studies

A. Model-Based Fault Location

A 13.8 kV, 134-node, overhead three-phase primary distribution feeder is used as the test system. Fig. 5 shows the topology of the feeder.

Root voltage and current are recorded at node 1. Four voltage measurements are placed in the system, at node 30, 48, 103 and 118 respectively. Cases of both perfect data condition and bad condition have been generated by adding randomly created error to the recorded voltage values. Test scenarios with different location, fault type and fault resistance are recorded in Table I. Fig. 6 shows the node numbers (X-axis) with smallest value of γ_j (Y-axis) calculated for fault occurring at node 36 with fault resistance of 1Ω.

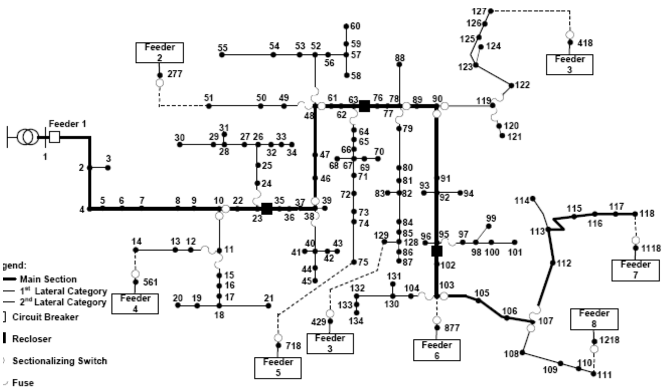

Figure 5. Test system

TABLE I. TEST SCENARIOS

Faulted node	*Fault type*	*Fault resistance (Ω)*
17, 36, 42, 107	A-G	1
63, 90	A-G	10
5, 77	A-B-C	5
86	A-B	1

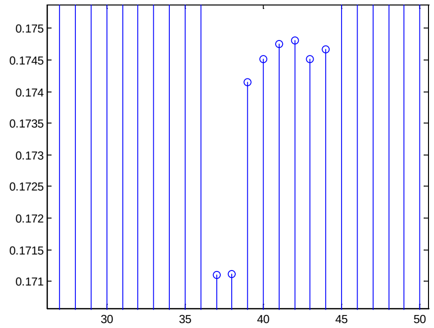

Figure 6. Nodes with smallest γ_j

The impact of number of measurements and data accuracy has also been tested. More results are recorded in [13].

B. Crew Dispatch

The extended distribution system connected to bus 4 of IEEE reliability test system (RBTS4) is used as a test model (Fig. 7). System topology, parameters of feeders and reliability indices are recorded in [14]. Following are the assumptions of the study:

- A circuit breaker (CB) is installed at the root of each feeder;
- Manually operated switches (SW) are installed at the beginning of the laterals;
- Average load (MW) is taken in the calculation of connected load;
- ASIDI is calculated from ENS (Energy Not Served) using (7):

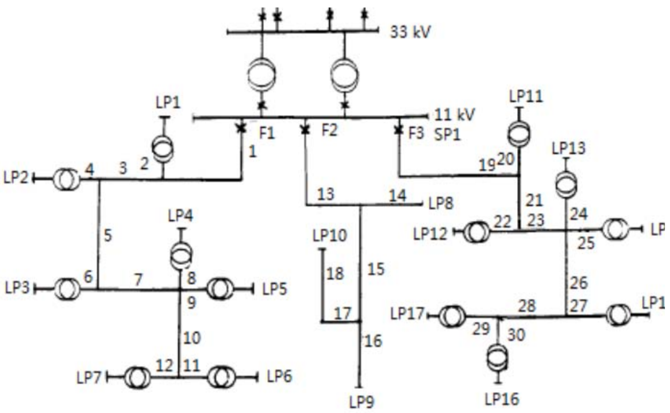

Fig. 7. RBTS4 Test System [14]

$$ASIDI = \frac{\sum ENS_i}{L_T} \qquad (7)$$

where

ENSi is the value of ENS of feeder i from [14];

LT is the total connected MW.

- For critical loads the weight factors from (1) is higher than ordinary loads.

Four cases are generated to demonstrate the procedures:

1) All suspected nodes/sections (section 2, 3, 5, 6) are from one area.

2) Suspected nodes/sections (section 3, 5, 21, 23) are from two areas without ranking (results from a circuit analysis-based fault location method);

3) Suspected nodes/sections (section 3, 5, 21, 23) with ranking are from two areas;

4) Suspected nodes/sections (section 3, 5, 21, 23) with ranking are from two areas, and customers are with different degree of importance (government/institution at LP 12).

The total number of crews is 4 (N_{labor}=4), and four suspected nodes/sections are selected (M=4) because of the relatively small size of the system. Heuristic Search is used in solving the optimization problem. The optimized field inspection plan and associated risks are recorded in Table II.

The case studies show how the optimization result changes

TABLE II
OPTIMIZED INSPECTION PLAN AND ASSOCIATED RISKS

Case NO.	Work Order	Associated Risk
1	Dispatch all to F1. Open CB on F1 and search along the line from the beginning of section 2 and 3 until fault is found.	N/A
2	Split crew into two groups and inspect F1 and F3 simultaneously. Group 1: - Open CB on F1; - If fault disappears, open SW on section 3; If not close CB and terminate inspection; - Close CB on F1; - Start inspection from beginning of section 3. Group 2: - Open CB on F3; - If fault disappears, open SW on section 21; If not close CB and terminate inspection; - Close CB on F3; - Start inspection from beginning of section 21.	0.4131
3	Dispatch all to feeder 1; if fault is not found, inspect feeder 3. Steps for inspection of each feeder are the same as in Case 2.	0.3267
4	Dispatch three crew to F1 and one to F3; Inspect simultaneously. Steps for inspection of each feeder are the same as in Case 2.	0.3316

with different situation: fault location method, fault location results, load information, etc. When generating work order, such factors should be considered.

V. CONCLUSION

The paper proposes a new fault management method. The following are main contributions:

- A model-based fault location algorithm using sparse voltage measurement data is proposed and proven to yield accurate results under bad data condition;
- Outage cost affected by OM activities is formulated using reliability indices;
- Risk function is proposed and risk analysis to optimize maintenance crew dispatch is introduced;
- Optimization problem of crew dispatch given results from fault location and formulation of risk is proposed and solved using heuristic-search algorithm.

The examples show how: a) fault location method could be significantly improved by using new data, b) crew dispatch using results from fault analysis could be optimized, and c) the improvement results in reduced costs.

Future work includes: a) solve optimization problem using non-heuristic method, b) include service restoration through more case studies and c) implement proposed fault management in a real distribution system.

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