A New Heuristic Algorithm for Service Restoration in Unbalanced Distribution Networks

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***Abstract*— This paper presents a new heuristic algorithm for solving fast service restoration problem based on analytically index in un-balanced distribution networks. A suitable assignment of switch indices to all tie switches (ts) in networks are used to find best solution and decrease number of switching operation. Customer's priority, load variation and minimum out-of-service loads have been considered in this paper. Three levels for load demand have been considered to load variation. The validity of this approach has been tested on the one un-balanced three phase distribution networks. Results have been presented for modified IEEE 37-node test case. The fastness and effectiveness convergence of this approach helps finding best solution for service restoration problem.**

Keywords - Service Restoration; Smart Grid; Un-balanced Distribution Network; Three Phase Load Flow.

I. INTRODUCTION

Customer's satisfaction and service reliability are the important topic where most of the paper localizes in this issue. Revenue earned by the Power Distribution Companies and customer's satisfaction is closely depending on reliability in distribution networks. In order to satisfy users demand and maintain profit of power Supply Company, it is necessary to restoring power service as soon as possible [1]. How to arriving a fast and effective service restoration in power distribution networks (PDNs), considering un-balanced distribution network and load variation is of major concern in this paper. Protection devices in network detect the fault location, when a fault is occurred in the PDN. After isolating the fault by operation line switches, the PDN is divided to three sections: First, the upstream section that is supplied from same feeder, second, the downstream un-faulted section that are transferred to neighboring feeders according to presented approach in this paper, and finally, damage buses and lines that are isolated from network. In this paper several issues have been considered that are described in resumption. Service restoration plan must be restored maximum safe out-of-service loads. Service restoration plan is implemented by changing switches state in PDNs; therefore, the time taken by the service restoration depends on the number of switching operation. Therefore, the number of switching operation should be kept to minimum as possible. This issue must be considered in service restoration plan that the supply must be restored to highest priority customers. Radial structure of distribution network, buses voltage limit, branches current limit and equipment loading limit must be observed. In past years, many methods have been proposed to find solution for restoration problem from different perspective. Heuristic search method [2]-[4] or expert system approach [5] have been adopted. In [6] fuzzy cause-effect networks are used to model the heuristic knowledge inference involved in the restoration plan. In [7] a fuzzy decision-making approach has been applied to determine the most desirable restoration plan with consideration different practical factors, but fuzzy method doesn't guarantee the optimal solution. In [8] non-dominated sorting genetic algorithm-II (NSGA-II) for solving the service restoration problem is presented and to reduce the software runtime, a faster version of NSGA-II has been implemented. In [9], [10], restoration problem in distribution network with dispersed generation is implemented. In [11], service restoration with Load curtailment of in-service customers via direct load control has been implemented.

The rest of this paper is organized as follows: Section II describes the problem formulation of a typical restoration problem. In section III, indices for ranking the networks' switch are described. Section IV reviews a new heuristic algorithm for service restoration. Section V briefly describes three-phase load flow program for fast response to the network change inducted by system reconfiguration. Section VI shows a numerical example to demonstrate the fastness and effectiveness of the proposed methods and the conclusion are drawn in section VII finally.

II. PROBLEM FORMULATION

Service restoration in un-balanced distribution networks considering customer's priority are formulated as multi-constraint and multi-objective optimization problem. In this paper, three different objective functions are presented. Maximizing total load to be restored, minimizing the number of the switching operations and maximizing priority load restored are these objective functions. Besides, important constraints consists of network radial structure, buses voltage, lines current, equipments loading have also been considered in this paper. Objective function briefly:

$$\max \sum_{k \in N_t} L_k \tag{1}$$

$$\max \sum_{k \in N_{HP}} L_k \tag{2}$$

$$\min \ N_{op} \tag{3}$$

Where

L_k Energized loads in network;

N_t Total buses are restorable;

N_{HP} Buses with high priority those are restorable;

N_{op} Number of switching operations;

Constraints:

1) Radial network structure should be maintained.
2) Bus voltage limits (for all buses):

$$V_k^{\min} < \left|V_k^p\right| < V_k^{\max} \tag{4}$$

Where

$V_k^{\min}$ Minimum acceptable bus voltage;

V_k^p Voltage at bus k, phase p;

$V_k^{\max}$ Maximum acceptable bus voltage.

3) Line current limits (for all lines):

$$I_j^{\min} < \left|I_j^p\right| < I_j^{\max} \tag{5}$$

Where

$I_j^{\min}$ Minimum acceptable line current;

I_j^p Current in line j, phase p;

$I_j^{\max}$ Maximum acceptable line current.

4) Equipment loading limits (for transformers):

$$\left|tr_i\right| < tr_i^{\max} \tag{6}$$

Where

tr_i Loading for i transformer;

$tr_i^{\max}$ Rated loading for i transformer.

Operational constraint can be obtained from three phase load flow calculation.

III. SWITCH SELECTION INDICES

Two switch's indices have been used in this paper for finding best tie switches to implement service restoration. A first and most important index is VD that is proportionate with voltage drop between substation bus and primary side of each tie switch (ts). For each ts, VD is defined as follow:

$$VD = \frac{P_i^p R_i + Q_i^p X_i}{V} \qquad p = a, b, c \tag{7}$$

Where

P_i^p Sum of active loads (per-unit) between substation bus and primary side of tie switch i, for each three phase;

Q_i^p Sum of reactive loads (per-unit) between substation bus and primary side of tie switch i, for each three phase;

R_i Sum of real segment of positive impedance sequence (per-unit) of lines between substation bus and primary side of i tie switch;

X_i Sum of imaginary segment of positive impedance sequence (per-unit) of lines between substation bus and primary side of i tie switch;

and V is substation voltage.

This index is shown in Fig.1. Suppose that one fault took place at point A. Therefore, area1 is downstream un-faulted area and ts3 is one candidate switch for service restoration implementation. For ts3, VD is obtained from node number 10, 12 and 13 that is proportionate with direction2 (dir2). Thereupon:

$$VD(ts3) = \frac{(P_{10}^p + P_{12}^p + P_{13}^p)(R_{(F3-10)} + R_{(10-12)} + R_{(12-13)})}{V} + \frac{(Q_{10}^p + Q_{12}^p + Q_{13}^p)(X_{(F3-10)} + X_{(10-12)} X_{(12-13)})}{V} \qquad p = a,b,c$$

A second index (Z_{path}) is direction impedance (per-unit) for lines lying in the path between the secondary side of each ts and end buses in network. For each ts, this index is defined as follow:

$$Z_{path} = \sum_{b \in N_{br}} Z_b \tag{8}$$

Where Z_b is positive impedance sequence (per-unit) of branch b and N_{br} is lines lying in the path between the

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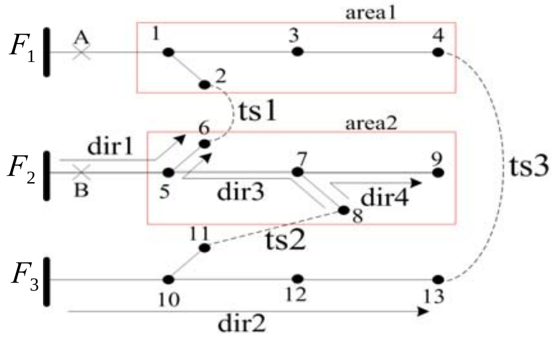

Figure 1. A 16-bus distribution network.

secondary side of each ts and end buses in network. This index is shown in Fig.1. Suppose that one fault took place at point B. Therefore, area2 is downstream un-faulted area and ts2 is one candidate switch for service restoration implementation. For ts2, Z_{path} is impedance of direction3 and direction4 (dir3 and dir4). Thereupon:

$$Z_{path1}(ts2) = Z(8-7) + Z(7-5) + Z(5-6) \quad or \quad dir3$$

$$Z_{path\,2}(ts\,2) = Z(8-7) + Z(7-9) \quad or \quad dir\,4$$

IV. Service Restoration Algorithm

A short-circuit's fault is occurred on the feeder, circuit breaker at the outset of feeder is operated to clear the fault. All boundary line switches are operating to isolate the faulted area. The feeder's circuit breaker is then closing to restore the upstream customers. For the downstream area, best switch indices for best switches selection based on a heuristic approach is implemented. The proposed approach is calculated fast and implemented using remotely controlled switches in un-balanced distribution networks. Proposed algorithm considering five steps are described in follow.

Step 1) isolation the fault;

Step 2) creation the candidate ts and ss list;

Step 3) selection one ts due to proposed algorithm, three phase un-balanced load flow implementation, and network constraints survey. If no constraints violation exists, go to step 5;

Step 4) selection next ts due to proposed algorithm, selection respective sectionalize switch (ss) for keeping radial structure of network, three phase un-balanced load flow implementation and network constraints survey. If no constraints violation exists go to step 5, else repeat this step;

Step 5) return best service restoration plan.

When a failure occurs in each PDN, fault's line, sending and receiving bus sides for this line are detected. The adjacent buses and lines are wended in each direction sequentially and to clear the fault, first circuit breaker in these directions is founded and operated. Therefore, feeder that fault has been occurred on it and feeder's circuit breaker is detected. For fault isolation, the adjacent buses and lines are wended in each direction sequentially. The first switches in each direction is found and operated. Therefore three areas are formed in network: First, the upstream out-of-service area that is first restored by closing the feeder's circuit breaker, second, the damage area that must been repaired, and finally, the downstream un-faulted area then is transferred to the neighboring feeders according to the proposed algorithms. Candidate tie switches are identified from energized feeder that can connect directly into the out-of-service area. Candidate sectionalizes switches (ss) that are located in the out-of-service area and identified from this section. For each candidate ts, VD and Z_{path} are obtained. In this section, new weighting factor is utilized to converts of these two indices into an equivalent single index. Final index has been described as follow:

$$FI = \alpha VD + \beta \max(Z_{path}) \tag{9}$$

Where α and β are two weight factors, that have two continues amounts between 0 and 1 ($0< \alpha$ and $\beta <1$ and $\alpha = 1-\beta$). First and most important index has been greater weighting than second index in this paper. Weighting factors amount can be initialized with PDN operators. In tis paper, α is 0.7 PU and β is 0.3 PU. FI list is sorted in increasing order amount of FI and ts lists are formed.

One ts due to least member of FI (first part of ts list) operation and three phase unbalance load flow calculation are attempted and network constraints are checked. If all network constraints are satisfied, restoration plan and amount of N_{op} are identified; else, next ts from ts list is selected and operated. Therefore, one direction in distribution network is being existed that making one loop in network. For removing this loop, one ss in this direction must be opened to maintain radial structure.

ss is opened, ts is closed, three phase un-balance load flow calculation is attempted and network constraints are checked. If all network constraints are satisfied, restoration plan and amount of N_{op} are identified; else, next (ts, ss) are operated for implementing service restoration.

V. Three-Phase Load Flow Technique

After network restoration, the three phase unbalanced distribution load flow has to be calculated to examine the voltage, current and capacity constraints for feeders, lines and elements with additional of new load points. In this paper, we are used fast load flow technique for fast service restoration. For receipt more information about this technique, please refers to [12]. In this section, summary of this technique [12] is described. The fundamental idea discussed here is how to obtain the power flow solution by using the elements of a unique quasi-symmetric matrix called TRX in the iterative process. The proposed TRX

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matrix constitutes a complete database by including information of network topology structure as well as branch impedances of the distribution feeder. The method is described in six steps: data preparation, initialization, current and voltage calculations, quasi-symmetric matrix calculation, and convergence process. This formulation is given including three phase line shunt-admittances and loads are modeled as constant power. The input data is given by three-phase per-unit node-branch oriented information. The basic data required is: three-phase injected powers and sending and receiving nodes of a given line impedance. The branch impedances are given as a rectangular 3nx3 phase impedance matrix Z_{abc}.

$$Z_{abc} = [Z_{abc}^{01} \cdots Z_{abc}^{ij} \cdots Z_{abc}^{(n-1)n}] \tag{10}$$

Where, Z_{abc}^{ij} is the 3-phase matrix impedance corresponding to ij line section:

$$Z_{abc}^{ij} = \begin{bmatrix} \overline{Z}_{aa}^{ij} & \overline{Z}_{ab}^{ij} & \overline{Z}_{ac}^{ij} \\ \overline{Z}_{ba}^{ij} & \overline{Z}_{bb}^{ij} & \overline{Z}_{bc}^{ij} \\ \overline{Z}_{ca}^{ij} & \overline{Z}_{cb}^{ij} & \overline{Z}_{cc}^{ij} \end{bmatrix} \tag{11}$$

Shunt admittances modeled by a rectangular 3nx3 matrix Y_{abc}:

$$Y_{abc} = [Y_{abc}^{01} \cdots Y_{abc}^{ij} \cdots Y_{abc}^{(n-1)n}] \tag{12}$$

Fig.2 shows a radial distribution network with n+1 nodes, and n branches and a single voltage source at the root node 0. Under the unbalanced approach, nodal power injection vector S is given per node and per phase.

$$S = \begin{bmatrix} \overline{S}_{p-1} \\ \vdots \\ \overline{S}_{P-i} \\ \vdots \\ \overline{S}_{p-n} \end{bmatrix}^T = \begin{bmatrix} P_{p-1} + jQ_{p-1} \\ \vdots \\ P_{p-i} + jQ_{p-i} \\ \vdots \\ P_{p-n} + jQ_{p-n} \end{bmatrix}^T \qquad p = a, b, c \tag{13}$$

At given iteration k, the relationship between injected currents I^k and branch currents J^k is set through an upper triangular matrix T accomplishing the Kirchhoff Current Laws (KCL) as follows:

$$J_{abc}^{k} = -T . I_{abc}^{k} \tag{14}$$

$$\overline{I}_{p-i}^{k} = \left(\frac{\overline{S}_{p-i}}{V_{p-i}^{k}} \right)^{*} - \sum_{p=a,b,c} \overline{Y}_{pp}^{ij} \, \overline{V}_{p-i}^{k} \tag{15}$$

Update voltage:

$$V_{abc}^{k+1} = V_{abc-0} + T_{abc}^{T} . Z_{abc} . T_{abc} . I_{abc}^{k} \tag{16}$$

Where, V_{abc-0} is initial voltage vector.

Convergence check-in and final calculations:

$$\left| \overline{V}_{p-i}^{k+1} - \overline{V}_{p-i}^{k} \right| \le \varepsilon \qquad i = 1, \ldots, n \qquad p = a, b, c \tag{17}$$

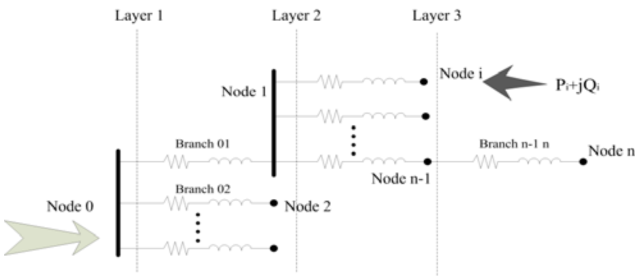

Figure2. The branch and node numbering of a radial distribution network.

VI. NUMERICAL EXAMPLE

To illustrate effectiveness of proposed algorithms, IEEE 37-node un-balanced distribution network has been considered. This method has been coded in MATLAB software. This section is demonstrated performance of method. When a failure occurs in network, protection devices are operated immediately for detecting and isolating the fault. In this paper, network's load patterns are considered based on three levels. First base is low level that demonstrator of hours in day that load's demand is minimum. Second base is median level that demonstrator of hours in day that load's demand is median state and third base is peak level that demonstrator of hours in day that load's demand is maximum. This issue is shown in Fig.3. In this paper, total numbers of switching operations for isolating the fault and service restoration are obtained. The impedance of lines, phase impedance matrix and phase admittance matrix are calculated from data of this network (IEEE 37-node) in [13].

After network restoration, the three phase un-balanced distribution load flow has to be calculated to examine the voltage, current and capacity constraints for feeders, lines and elements with additional of new load points. In this paper, we are used fast load flow technique for fast service restoration. For receipt more information about this technique, please refers to [12]. In this test case, one, two, or three phase loads with wye or delta connections can exist. In this paper some assumptions for un-balanced distribution networks have been considered that are described as follow:

1) All load are modeled based on constant power model;
2) The Regulator and Capacitors components is removed from networks;
3) For all branches in networks, one switch in send side of branch has been considered;
4) Some tie switches are introduced in the networks for illustrating restoration plan.
5) Amount of loads are modified in order to performance restoration plane and regard networks constraints.

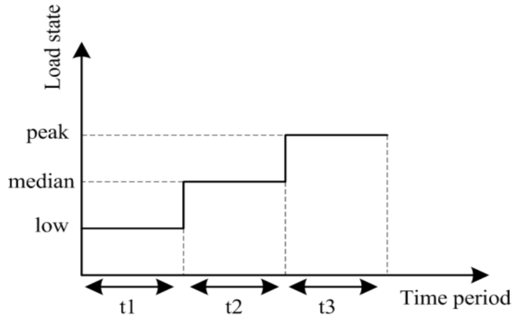

Figure 3. load state.

TABLE I. RESTORATION RESULTS FOR MODIFIED IEEE 37-NODE NETWORK WITHOUT LOAD VARIATION

Case	fault location	switch operation to fault isolation	switches operation to SR	Load state	runtime (S)
1	2-26	2-26, 26-27	2-35	mid	0.5
2	2-23	2-23, 23-24, 23-25	20-25	mid	0.35
3	4-5	4-5, 5-6, 5-13, 5-36	27-36, 4-6, 22-16, 7-8	mid	0.74
4	3-4	3-4, 4-5	27-36, 22-16, 7-8	mid	1.12
5	5-6	5-6, 6-14, 6-7	22-16	mid	0.66

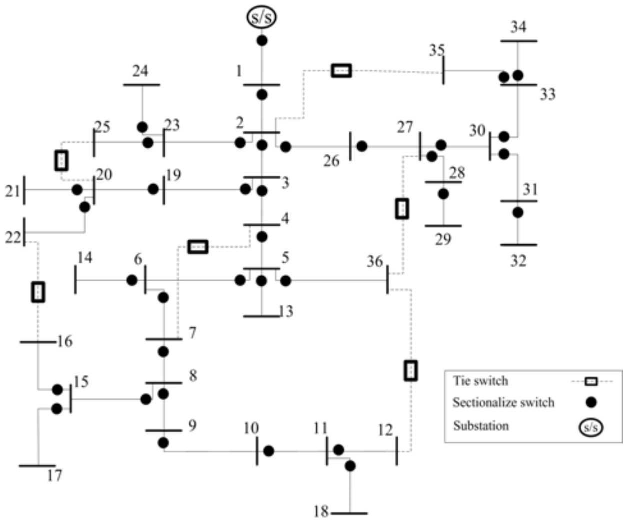

Figure 4. modified IEEE 37-node network.

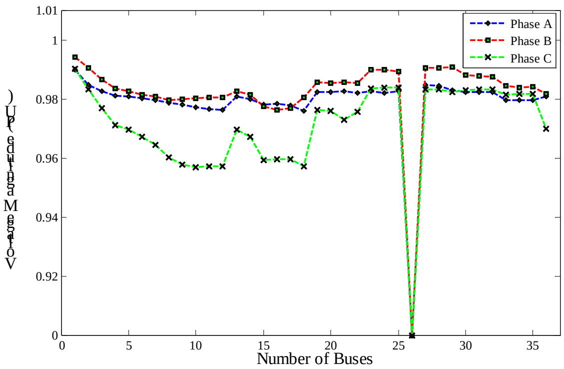

Figure 5: voltage after restoration for modified IEEE 37-node network.

Fig.4 shows the one-line diagram of modified IEEE 37-node test case. Introduced tie lines (or tie switches) for service restoration, actual and with loss are considered. Voltage magnitude range must be within limits of 0.95 and 1.05 per-unit.

A. Service restoration results without load variation

Table I displays the restoration algorithm results for IEEE 37-node un-balanced distribution network without load variation. In this table, numbers of switching operations for isolating the fault and implementing service restoration have been demonstrated. For example, when network load is in median level and failure is occurred in line 2-26 (case 1) two switching operations have been required to isolating the fault (ss2-26 and ss26-27), and one switch operation has been required to implement service restoration (ss36-27). Software runtime for this case is 0.5 second that shows fastness of service restoration plan. Voltage magnitude per-unit for fault on this branch is shown in Fig.5. This Figure shows that voltage for all buses are in definition limits.

B. Service restoration results considering load variation

Table II displays the restoration algorithm results for IEEE 37-node un-balanced distribution network considering load variation. For example, when network load is in peak level and failure is occurred in line 2-26, three switch operations have been required to implement service restoration. Due to voltage magnitude per-unit in this level, voltage limit is observed. Whereas, when network load is in low level and failure is occurred in line 3-4 (case4), number of switching operation is decreased and one switch operation has been required to implement service restoration. In this section, considering software runtime and another results, fastness and effectiveness of proposed algorithm has been demonstrated.

Consideration comparison the results (software runtime and number of switching operations) of this article and the results of [14], the fastness and effectiveness of proposed algorithm have been shown.

TABLE II. RESTORATION RESULTS FOR MODIFIED IEEE 37 NODE NETWORK WITH LOAD VARIATION

case	fault location	switch operation to fault isolation	switches operation to SR	Load state	runtime (S)
1	2-26	2-26, 26-27	2-35, 36-27, 30-33	peak	0.85
2	2-23	2-23, 23-24, 23-25	20-25	peak	0.47
3	4-5	4-5, 5-6, 5-13, 5-36	27-36, 4-6	low	0.57
4	3-4	3-4, 4-5	27-36	low	0.67
5	5-6	5-6, 6-14, 6-7	22-16, 36-12, 10-11	peak	1.04

VII. CONCLUSIONS

In this paper, fast service restoration in un-balanced PDNs, considering costumer's priority with to as multiple objective functions consist of: 1) maximizing the amount of total load to be restored, 2) minimizing the number of switching operation, 3) customer's priority consideration have been implemented. For this work, we are used a new heuristic algorithm based on two important indices. The core of the proposed algorithm is loads between candidate ts and substation's bus or voltage drop between candidate ts and substation's bus. Fast load flow technique based on a real quasi-matrix [13] has been utilized. Finally, the proposed algorithm has been implemented and tested on IEEE 37-node un-balanced distribution network. Results show that fastness and effectiveness restoration plan has been implemented.

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