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Research Article

A Simple Graphical Algorithm for Feeder Reconfiguration and Service Restoration of Distribution Networks

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Abstract

The present article proposes a simple method called kruskal's algorithm, to solve the distribution feeder reconfiguration problem for loss reduction and service restoration. The method is suggested for very simple feeder reconfiguration and does not involve any mathematical expressions. The test results reveal that the proposed method yields optimal configuration with reduced computation burden and a better restoration plan.

Keywords: Distribution networks; Feeder reconfiguration; Loss reduction; Service restoration.

Introduction

Alteration in the topology of a distribution network for efficient operation of the system results in reconfiguration. Feeder reconfiguration is performed by opening / closing two types of switches; tie and sectionalizing switches. As an effect of this, the power distribution network (PDN) system is divided into subsystems, wherein each contains a number of normally closed switches (sectional switches) and open switches (tie line switches), that are operated during the conditions of emergency for load restoration and normal conditions for loss reduction. Distribution feeder has a different combination of commercial, industrial, and residential loads. These loads tend to vary depending on the time of the day, weather, and season. Feeder reconfiguration would allow for the transfer of load from heavily loaded portion of the power distribution system to locations that are relatively lightly loaded. This would not only improve the operating conditions, but it would also enable the full utilization of system hardware capabilities. The reliability of PDN can be improved by changing the status of these switches, resulting in alteration of PDN configuration, bus voltage, line currents and line losses. Thus a whole feeder or part of a feeder may be served from another feeder by closing a tie switch linking the two while an appropriate sectionalizing switch must be opened to maintain radial structure. Besides, the requirements should be enforced during the reconfiguration process are minimum losses, voltage limits, current limits, feeder capacity and radial network [1].

The problem in question is now illustrated using the 3 feeder distribution system shown in figure 1. The dotted branches S5, S11and S16 represent tie switches connecting feeders. For notational convenience, the corresponding tie number will identify the tie switch. Without loss of generality and mindful of the practical situations, let us assume for ease of explanation that there are sectionalizing switches on every branch of the system. The corresponding branch numbers will also identify all 13 sectionalizing switches. For example the load at node 11 can be transferred to feeder–1 from feeder–2 by closing the tie switch S5 and opening the sectionalizing switch S9. The main drawback faced during the maintenance, dispatching and abnormal conditions is the difficulty in identifying all the distribution branches used for the power to flow, in PDN. In the perspective of loss reduction, the problem to be addressed in this article is to identify tie and sectionalizing switches that should be closed and opened, respectively, to achieve maximum reduction in losses and load balancing. Several methods are available in the literature to arrive at a switching strategy for network reconfiguration. Aoki et al. [2–6] used nonlinear programming technique to minimize power loss. An indicative formula and approximate power flow method were proposed in [2] and [7]. The method described in [8] achieves the optimal configuration by opening

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the branches with the lowest current derived in the optimal load flow with all switches closed.

Civanlar et al. [9] and Baran [10] proposed an approximate power flow method for loss reduction resulting from a switch operation on distribution systems. The combinatorial optimization techniques of genetic algorithms and simulated annealing were developed [11] in order to obtain the optimal solution for the switching problem. However, the optimal switching strategies proposed by most articles had to consider every candidate switch in order to evaluate the effectiveness of loss reduction. Extensive numerical computation is often required if the conventional load flow technique has to be used, considering the large solution space involved. An efficient search scheme is therefore desirable. In order to overcome this drawback graph theory based approach is tried.

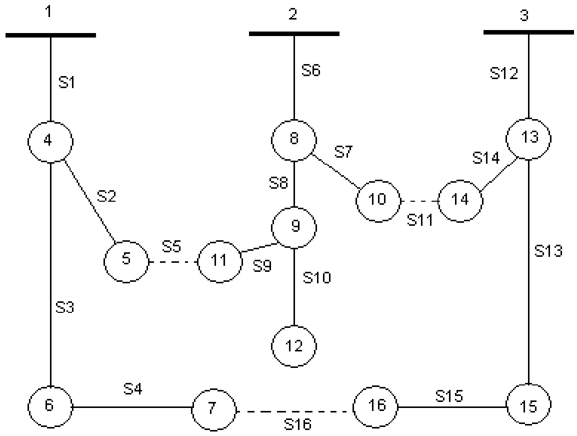

Figure 1. Single line diagram of IEEE 16–bus system

Graphs, the basic subject studied in graph theory are an abstract representation of a set of objects where some pairs of the objects are connected by links. The interconnected objects are represented by mathematical abstractions called vertices, and the links that connect some pairs of vertices are called edges. Typically, a graph is depicted in diagrammatic form as a set of dots for the vertices, joined by lines or curves for the edges. Vertices are also called nodes or points, and edges called lines. A graph may be undirected, meaning that there is no distinction between the two vertices associated with each edge or its edges; or directed, meaning there is distinction from one vertex to another.

Given a connected, undirected graph, a spanning tree of that graph is a subgraph, which is a tree that connects all the vertices together. A single graph can have many different spanning trees. For each edge, weights are assigned and the sum of the edge weights gives the weight of that spanning tree. A Minimum Spanning Tree (MST) or minimum weight spanning tree is then a spanning tree with weight less than or equal to the weight of every other spanning tree. Graph theory based on minimum spanning tree approach has been discussed in various papers with varied focuses. Application in the paper [13] presented an algorithm for finding the shortest path for power routing (DC) between two nodes in an electrical network used in the airlines. Paper [14] presented mathematically minimum spanning tree for network topological observability analysis.

In 1994, paper [15] dealt with application of the minimum spanning tree for finding the connectivity in the VLSI circuits. In 1997, the minimization of energy losses in distribution systems by applying a general search method to a Brazil power network has been presented in paper [16]. Here outages were not considered as an important factor to address. Paper [17] discussed about the application of Dijkstra's algorithm for various applications like airline electrical networks which was the main advantage of the algorithm. Paper [18] indicated the use of Floyd–Warshall's based minimum spanning tree to find the time scheduling in the data flow graph of a DSP. Paper [19] used the learning classifier system for loss minimization in a power system. Paper [20] calculated the reliability index of radial network using forward search method of minimum spanning tree. Reference [21] discussed the depth first search method used to find the minimum spanning tree for the optimal placement of the PMU devices in the power system. Distribution reconfiguration algorithm, named Core Schema Genetic Shortest–path Algorithm (CSGSA) proposed in paper [22] was based on the weight calculation method for each load condition based on line losses.

The above survey highlighted the extension of the application of graph theory for MV power distribution AC system, which has been attempted in this paper. Here, the mathematical formulation of Yixin Yu [22] has been applied to a PDN wherein loss minimization and service restoration have been fully addressed. An algorithm based on graph theory is used to restructure the PDN by considering the loss reduction and distribution branch outage, which form the major contribution of this paper.

In this context, the paper has been organized as follows: in section 2, the problem formulation; in section 3, the Kruskal's algorithm; in section 4 the feeder reconfiguration; in section 5, service restoration have been discussed; while section 6 is for conclusion.

Formulation of the problem

In this section, the network reconfiguration problem for loss minimization and service restoration is discussed in detail. To simplify the presentation, we will represent the system on a per phase basis and the load along a feeder section as constant P, Q loads placed at the end of the lines. It is assumed that every switch is associated with a line in the system. The objective of network reconfiguration problem for loss reduction involves the load transfer between the feeders or substations by changing the position of the switches. The radial configuration of distribution networks corresponds to a "spanning tree" of a graph representing the network topology. The network reconfiguration problem in graph theory can be stated as follows. A spanning tree is obtained such that the network losses are minimized while the following constraints are satisfied namely, (i) voltage constraints, (ii) radiality constraints, (iii) feeder capacity and (iv) line current capacity. This is a combinatorial optimization problem since the solution involves the consideration of all possible spanning trees.

Mathematical formulation

The loss reduction in network reconfiguration problem is formulated as

$$Min \sum_{i=0}^{n-1} \left(r_i \frac{P_i^2 + Q_i^2}{V_i^2} \right) \quad (1)$$

Such that

$$V_{i\min} < V_i < V_{i\max} \quad (2)$$

Where n – number of buses

r_i - Resistance of the branch

P_i - Real power flowing through the branch

Q_i - Reactive power flowing through the branch

V_i - Voltage at receiving end of the branch

The network reconfiguration has to obey the following rules:

1) No feeder section can be left out of service

2) Radial network structure must be retained.

Power flow equations

Power flow in a radial distribution network can be described by a set of recursive equations called Dist Flow branch equations [12] that use the real power, reactive power and voltage (Figure 2) at the sending end of a branch to express the same quantities at the receiving end of the branch as

$$P_{i+1} = P_i - r_i \frac{(P_i^2 + Q_i^2)}{V_i^2} - P_{L(i+1)} \quad (3)$$

$$Q_{i+1} = Q_i - x_i \frac{(P_i^2 + Q_i^2)}{V_i^2} - Q_{L(i+1)} \quad (4)$$

$$V_{i+1}^2 = V_i^2 - 2(r_i P_i + x_i Q_i) + \frac{(r_i^2 + x_i^2)(P_i^2 + Q_i^2)}{V_i^2} \quad (5)$$

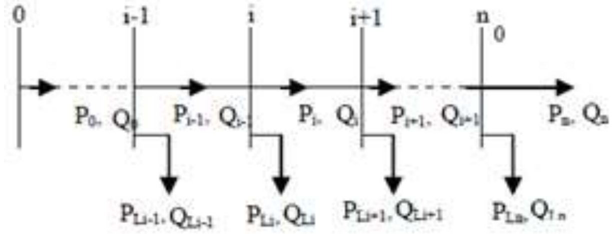

Figure 2. One line diagram of a radial network

The power loss in a branch is expressed as

$$LP_i = \frac{r_i (P_i + Q_i)}{V_i^2} \quad (6)$$

Where LP_i = power loss in the i[th] branch

Strategy – Kruskal's Algorithm

Kruskal's algorithm [29] is an algorithm in graph theory that finds a minimum spanning tree for a connected weighted graph. The strategy for selecting, the best switching option is further explained via the example system of figure 3 with 6 vertices and 10 edges. The graph shown here is a weighted, undirected network. Table 1 shows all the terms to be known for proceeding through Kruskal's algorithm**.**

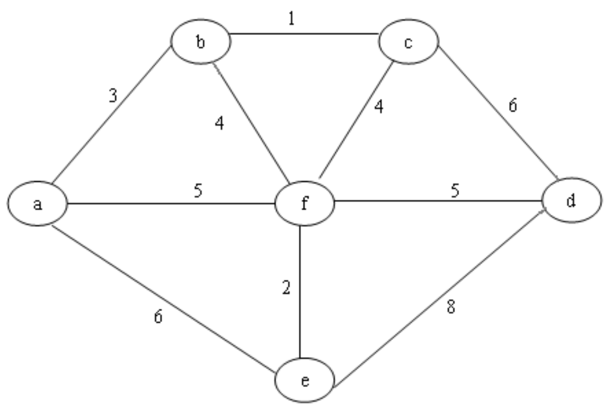

Figure 3. Sample network for example problem

Table 1. Symbols used in minimum spanning tree

Term	Meaning
	Vertex or node
	The line joining two nodes or vertices called an edge. Since the line does not show the direction, it is an undirected graph.
	An edge having a weight 5 being connected between the node 'a' and node 'b'

Now according to Kruskal's algorithm, the edges are arranged in the ascending order of their weights as given in table 2.

Table 2. Given data for example diagram

Edge	Weights
Node 'b' to node 'c'	1
Node 'f' to node 'e'	2
Node 'b' to node 'a'	3
Node 'b' to node 'f'	4
Node 'c' to node 'f'	4
Node 'a' to node 'f'	5
Node 'f' to node 'd'	5
Node 'a' to node 'e'	6
Node 'c' to node 'd'	6
Node 'd' to node 'e'	8

As per the algorithm the minimum weights of the edges are only required and hence the process is started with the edge having minimum weight. It is found that the minimum weight of the edge is between node 'b' and node 'c', which is 1, and the traversal is started with node 'b'. The traversal matrix T becomes, T = [b c]. Now the counter is set to 1. After each updation of traversal matrix the counter is incremented and it is checked that the counter value is equal to the number of N (where N = no of vertex – 1). If it is true the procedure is stopped otherwise the process is continued. Then the minimum weight for traversal is checked on node 'c'. Here the minimum weight is not found and the process is backtracked to node b. Now the minimum weight except for the node which is already visited is checked. It is found that the lowest weighted edge exists between the node 'b' and node 'a', which has a weight 3. The traversal matrix becomes, now

T = [b c
b a]

Then the counter is set to 2 and the above process is repeated. At node 'a' the minimum weight for traversal is checked, since it is not found the process is backtracked to node 'b'. Now the minimum weight except for the node which is already visited is checked. The lowest weighted edge is between the node 'b' and 'f', which has a weight 4. The traversal matrix now becomes,

T = [b c
b a
b f]

Now, the counter is set to 3. The process is repeated till the counter value becomes 5. The stopping condition is satisfied and hence the process is stopped. Thus, the traversal matrix becomes

T = [b c
b a
b f
f e
f d]

The resultant weight of the MST is 15 as shown in figure 4.

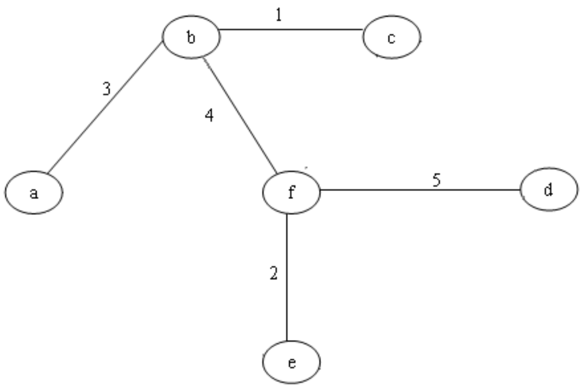

Figure 4. Example problem's result

Based on the above procedure a generalized pseudocode for Kruskal's algorithm is formed and is as follows.

Pseudocode for Kruskal's algorithm

- Sort E (edges) in increasing order of edge weights and the sorted edges are in A (arranged matrix).
- Initialize the set of tree edges and its size, T (resultant matrix).
- Counter ←0
- While counter < |V| – 1 // V total number of vertex

- If T U {Bik} is acyclic // Bik current branch selected
- T ← T U {Bik}
- Counter ← Counter+1

Return T

Flow chart for reconfiguration / restoration

In a radial distribution system to achieve a maximum amount of power restored or minimum amount of losses, the aim is to identify the appropriate switching options. In most of the techniques, the losses are calculated by using load–flow studies for each configuration, and the minimum loss configuration is found. In the proposed method, the distribution system is considered with all its laterals simultaneously, instead of determining the switching–options on loop by loop basis. Usually, the earlier techniques involved very complicated mathematical procedures and large computational time due to the combinatorial nature of the problem. The proposed method develops a switching algorithm, which minimizes the computational time by performing the effective search to the requisite switching combinations, because the MST converts the combinatorial optimization problem into a simple problem. However, the solutions obtained by this method achieve global optimum of loss minimization problem. To apply the MST the power system is modeled as graph. In the power system the buses and the feeders are considered as the vertex and the distribution lines are considered as edges. With this consideration the algorithm for the developed methodology and the flowchart for reconfiguration and restoration for any radial distribution network are shown in figure 5.

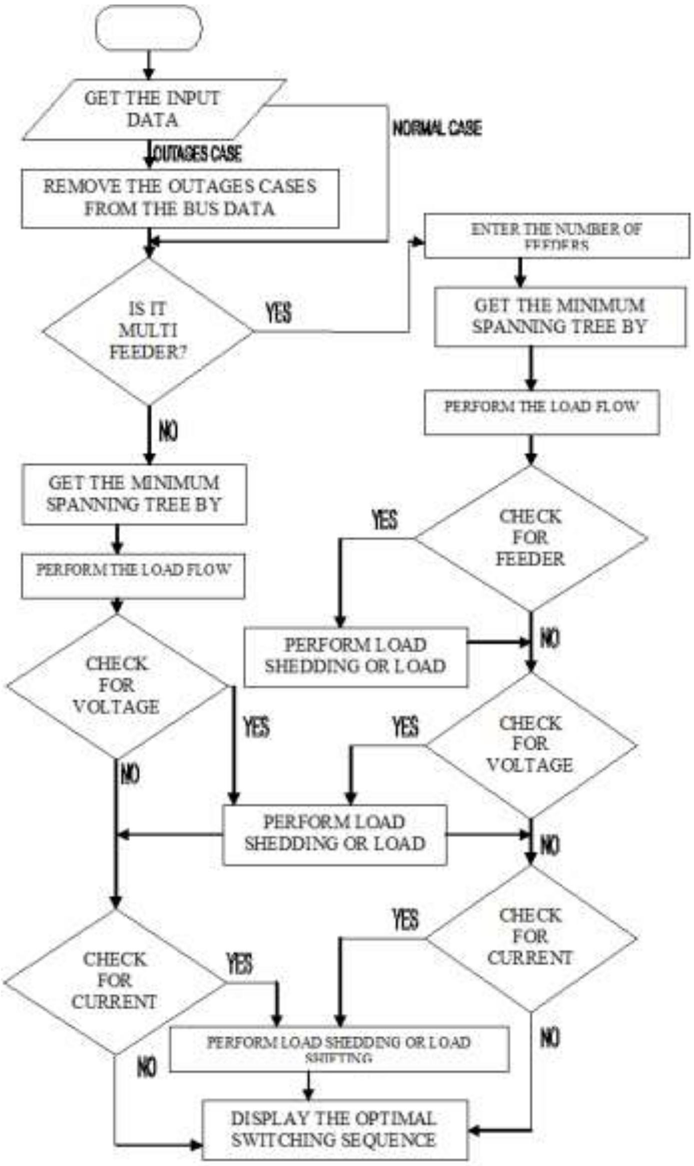

Figure 5. Flow chart of Kruskal's algorithm

Illustrative examples

Example 1

Consider the IEEE 16 – bus system [9] as shown in figure 1 with three feeders 28.7MW and 17.2Mvar capacity. Here, the Kruskal's algorithm is applied by assuming the distribution branch impedance as the weight of the edges. As per the algorithm the impedance (weights) are arranged in an ascending order and the initial traversal matrix for the IEEE 16–bus network is shown below.

T = [

SB	EB	R + j X
5	11	0.04 + j 0.04
6	7	0.04 + j 0.04
10	14	0.04 + j 0.04
15	16	0.04 + j 0.04
1	4	0.08 + j 0.1
4	5	0.08 + j 0.11
8	9	0.08 + j 0.11
9	12	0.08 + j 0.11
13	15	0.08 + j 0.11

13	14	$0.09+j\,0.12$
2	8	$0.11+j\,0.11$
3	13	$0.11+j\,0.11$
7	16	$0.12+j\,0.12$
4	6	$0.09+j\,0.18$
8	10	$0.11+j\,0.11$
9	11	$0.11+j\,0.11$]

For this traversal matrix after applying Kruskal's algorithm, the resultant network is shown in figure 6.

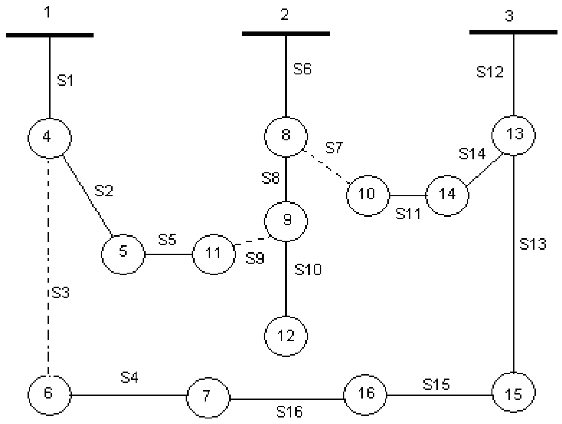

Figure 6. Example problem's result after applying kruskal's algorithm

The result obtained cannot be directly applied because for this result the feeder 3 capacity is 192% (overloaded), feeder 2 capacity is 91% and the feeder 1 capacity is 66% (under loaded). The individual feeder line currents (S1, S6 and S12) for this result are 60%, 140% and 100% of their capacity value. For the initial network [9] also the current capacity of the feeder lines are 80%, 160% and 60% of their capacity value.

As a result, load shifting is done by transferring the loads from feeder 3 to feeder 1 to reduce the capacity of feeder 3. If the terminal load of feeder 3 that is load 6 is transferred to feeder 1 by closing the switch S3 and opening S4, then also there is violation of feeder capacity i.e., feeder 3 is loaded at 151.1 % which is also over loading. So another load shifting is done by transferring the load 7 to feeder 1 from feeder 3 and the resultant network by satisfying all the constraints is shown in figure 7 and traversal matrix is rearranged as shown. The individual feeder line currents (S1, S6 and S12) for this result are 100%, 140% and 60% of their capacity value and the feeder 3 capacity is 121%, feeder 2 capacity is 91% and the feeder 1 capacity is 108%.

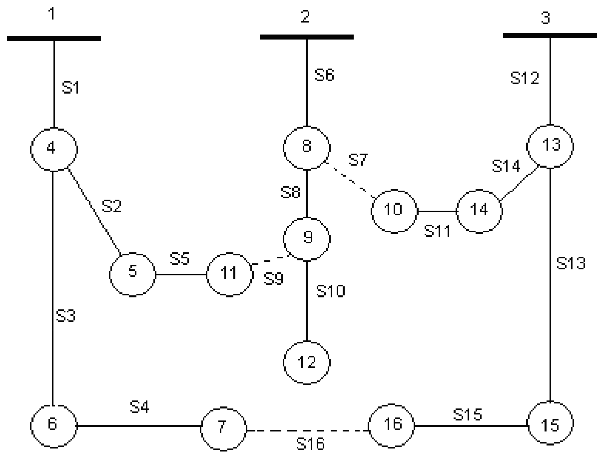

Figure 7. Example problem's result with Kruskal's algorithm after applying load shifting

T = [

SB	EB	R+ j X
5	11	$0.04+j\,0.04$
6	7	$0.04+j\,0.04$
10	14	$0.04+j\,0.04$
15	16	$0.04+j\,0.04$
1	4	$0.08+j\,0.1$
4	5	$0.08+j\,0.11$
8	9	$0.08+j\,0.11$
9	12	$0.08+j\,0.11$
13	15	$0.08+j\,0.11$
13	14	$0.09+j\,0.12$
2	8	$0.11+j\,0.11$
3	13	$0.11+j\,0.11$
4	6	$0.09+j\,0.18$]

The minimum node voltages, and total real power loss (TPL) obtained are shown in table 3. The results shown in table 3 are compared with the other reference papers. It is observed that the total power loss is decreased. The test results show that the total real power loss is 26.6% less than that of initial configuration due to the improvement of voltage from 0.95679 p.u. to 0.97089 p.u.

Example 2

Consider the second test system, which is a hypothetical 33–bus, 12.66 KV radial distribution network for which the line and load data is given in [10]. The summary of test results is given in table 4. After applying the proposed method to the 33–bus network the switches that are open are S7, S16, S34, S35 and S37. The total real power loss is less than that of initial configuration due to the improvement of voltage from 0.93784 p.u. to 0.93801 p.u.

Table 3. Test results of 16–bus system

System configuration	Open tie switches	System real power losses (KW)	Min voltage (p.u.)
Initial	S5, S11, S16	649.58	0.95310
Sivaraju and Ramana [24]	S7, S9, S16	599.56	0.95679
Jizhong and Chang [26]	S7, S9, S16	466.10	0.96421
Proposed	S7, S9, S16	440.00	0.97089

Table 4. Test results of 33–bus system

System configuration	Open tie switches	System real power losses (KW)
Initial	S33, S34, S35, S36, S37	202.40
Sivaraju and Ramana [24]	S7, S11, S14, S32, S37	141.04
Viswanadha and Bijwe [25]	S7, S11, S14, S32, S37	140.27
Jizhong and Chang [26]	S7, S10, S14, S33, S37	141.54
Proposed	S7, S16, S34, S35, S37	139.76

Example 3

The 69-bus, 12.66 kV systems given in [27] consists of five tie lines. The normally open switches are S69, S70, S71, S72 and S73. After applying the proposed method to the 69–bus network the switches that are open are S13, S55, S61, S69 and S70. The summary of test results is given in table 5.

Table 5. Test results of 69–bus system

System configuration	Open tie switches	System real power losses (KW)
Initial	S69, S70, S71, S72, S73	226.80
Ning Xiong [28]	S14, S46, S50, S69, S70	118.00
Proposed	S13, S55, S61, S69, S70	101.00

Service Restoration

In case of an outage in any part of the system, isolation of the faulty part and service / supply to the healthy part of the system is envisaged in service restoration. This will cause opening and closing of some of the switches in the system. The efficient way of achieving this, would be to operate those switches that cause minimum loss and satisfy the voltage, current and other constraints. Thus, the proposed algorithm of feeder reconfiguration can be extended for this restoration problem.

In any distribution system, there are always some loads, which are of the highest priority (e.g., hospital, big industrial factory, etc.). In the event of partial service restoration, the supply is initially restored to the highest priority customers and this fact is reflected in the final solution of the service restoration problem. On the other hand, the load shedding strategy is constructed by the priority levels of customers and the amount of important load within each service zone. Four priority levels are used to define how important is each customer class:

Level 1: VIP loads (hospital, fire station, important telecommunications, etc.)
Level 2: Industrial loads (oil refinery plants, high technology plants, etc.)
Level 3: Commercial loads (supermarkets, sport and entertainment facilities, etc.)
Level 4: Domestic loads (normal customers)

Example 1

The example of 3–feeder system (Figure 1) is used to demonstrate the application of proposed method for service restoration. An outage is assumed in sectionalizing branch S6. Using the proposed method of restoration, tie switches S5 and S11 are to be closed and sectionalizing switch S4 and S7 are to be opened as shown in figure 8. This resulted in service to all the loads in the network without violating any voltage limits at power loss of 1210 KW.

In this case there is a load shed of 8.5 MW of feeder–1and the shed loads belong to the type of level 3 and level 4 at bus 8, bus 9 and bus 12. However, the losses are slightly more in the proposed method, compared to [23] which is due to higher load served in absence of any load shedding. The minimum voltage of 0.95427 p.u. was obtained by Sivaraju and Ramana [24] at node 12. Lin and Chin [23] have also reported that closure of tie switch S11 violated the voltage limit. The minimum voltage of 0.91446 was observed at node 12. The results of proposed method and methods of Lin and Chin [23] and Sivaraju and Ramana [24] are tabulated in table 6. It can be seen from this table that the proposed method produces a better restoration plan compared to methods of Lin and Chin [23] and Sivaraju and Ramana [24], which is based on the amount of load shed.

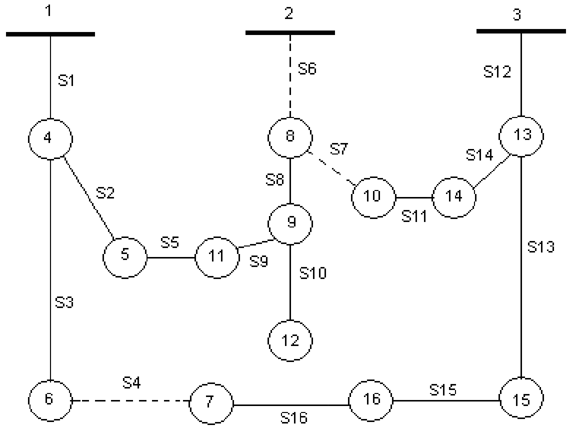

Figure 8. Result of IEEE 16–bus system for a outage at line S6

Table 6. Comparison of restoration results for IEEE–16 bus system

System configuration	Open switches	Minimum Voltage node	Voltage p.u.	Power loss KW	Load shed	Load shedding
Proposed	S4, S6, S7	S12	0.92807	1210	(LOAD SHEDDING AT BUS 8, 9 & 12 of feeder 1) BY 8.5 MW	8.5 of feeder 1
Sivaraju and Ramana [24]	S6, S8, S16	S12	0.95427	835.6	Load shed by 9.3 MW	6.6 of feeder 1 and 2.7 of feeder 3
Lin and Chin [23]	S6, S11, S16	S8	0.94848	656	Load shed by 12.5 MW	12.5 of feeder 1

Reference [24] used a graphical method based on some heuristic rules and reference [23] used a method based on the switching index, whereas the proposed method uses the minimum spanning tree concept. Table 7 gives the result obtained using the minimum spanning tree concept for all the single line outage and the results show the switches that are open during the particular outage case. Table 8 shows the switches that are open when there are simultaneously two outages at a time. This algorithm can be extended to any number of outages at a time and it also provides the total amount of load to be shed.

Table 7. Sample System Results for Single Line Outages using Kruskal's Algorithm

Outage on line	Switches that are open			Amount of load shedding
S1	S1	S3	S14	No
S2	S2	S11	S16	No
S3	S3	S9	S14	No
S4	S4	S11	S5	No
S6	S6	S4	S7	Yes (8.5 MW)
S7	S7	S5	S16	No
S8	S8	S3	S14	Yes (3 MW)
S9	S9	S16	S11	No
S10	Power cannot be restored			Nil
S12	S12	S9	S13	No
S13	S13	S7	S2	No
S14	S14	S16	S5	No
S15	S15	S5	S11	No

Table 8. Sample System Results for Outages at Two Lines Simultaneously Using Kruskal's Algorithm

Outage on line	S1	S2	S3	S4	S6	S7	S8	S9	S10	S12	S13	S14	S15
S1	S1, S3, S14	S1, S2, S14	S1, S3, S14	S1, S4, S14	S1, S5, S6	S1, S2, S7	S1, S8, S14	S1, S9, S14	S1, S3, S10, S14	S1, S4, S12	S1, S13, S14	S1, S3, S14	S1, S14, S15
S2	S1, S2, S14	S2, S11, S16	S2, S3, S14	S2, S4, S14	S2, S6, S13	S2, S7, S15	S2, S8, S14, S15	S2, S9, S14, S15	S2, S10, S11, S16	S2, S12, S14	S2, S7, S13	S2, S14, S16	S2, S7, S15
S3	S1, S3, S14	S2, S3, S14	S3, S9, S14	S3, S4, S9, S14	S3, S6, S7	S3, S7, S9	S3, S8, S14	S3, S9, S14	S3, S9, S10, S14	S3, S9, S12	S3, S7, S9, S13	S3, S9, S14	S3, S7, S9, S15
S4	S1, S4, S14	S2, S4, S14	S3, S4, S9, S14	S4, S5, S11	S4, S6, S7	S4, S7, S9	S4, S8, S14	S4, S9, S14	S4, S5, S10, S11	S4, S9, S12	S4, S9, S13, S14	S4, S9, S14	S4, S9, S14, S15
S6	S1, S5, S6	S2, S6, S13	S3, S6, S7	S4, S6, S7	S2, S4, S7	S3, S6, S7	S3. S6. S8	S6, S9, S13	S2, S4, S7, S10	S6, S11, S12	S6, S8, S13	S3, S6, S14	S6, S8, S15
S7	S1, S2, S7	S2, S7, S15	S3, S7, S9	S4, S7, S9	S3, S6, S7	S3, S8, S14	S3, S7, S8	S7, S9, S16	S3, S8, S10, S14	S2, S7, S12	S2, S7, S13	S2, S7, S14, S16	S2, S7, S15
S8	S1, S8, S14	S2, S8, S14, S15	S3, S8, S14	S4, S8, S14	S3. S6. S8	S3, S7, S8	S5, S7, S16	S4, S8, S9, S14	S5, S7, S10, S16	S3, S8, S12	S8, S13, S14	S3, S8, S14	S8, S14, S15
S9	S1, S9, S14	S2, S9, S14, S15	S3, S9, S14	S4, S9, S14	S6, S9, S13	S7, S9, S16	S4, S8, S9, S14	S9, S11, S16	S9, S10, S11, S16	S9, S12, S14	S7, S9, S13	S9, S14, S16	S7, S9, S15
S10	S1, S3, S10, S14	S2, S10, S11, S16	S3, S9, S10, S14	S4, S5, S10, S11	S2, S4, S7, S10	S3, S8, S10, S14	S5, S7, S10, S16	S9, S10, S11, S16	*	S9, S10, S12, S13	S5, S10, S14, S16	S2, S7, S10, S13	S5, S10, S11, S15
S12	S1, S4, S12	S2, S12, S14	S3, S9, S12	S4, S9, S12	S6, S11, S12	S2, S7, S12	S3, S8, S12	S9, S12, S14	S9, S10, S12, S13	S9, S12, S13	S2, S12, S13	S2, S12, S14	S2, S12, S15
S13	S1, S13, S14	S2, S7, S13	S3, S7, S9, S13	S4, S9, S13, S14	S6, S8, S13	S2, S7, S13	S8, S13, S14	S7, S9, S13	S5, S10, S14, S16	S2, S12, S13	S5, S14, S16	S2, S13, S14	S2, S7, S13, S15
S14	S1, S3, S14	S2, S14, S16	S3, S9, S14	S4, S9, S14	S3, S6, S14	S2, S7, S14, S16	S3, S8, S14	S9, S14, S16	S2, S7, S10, S13	S2, S12, S14	S2, S13, S14	S2, S7, S13	S2, S14, S15
S15	S1, S14, S15	S2, S7, S15	S3, S7, S9, S15	S4, S9, S14, S15	S6, S8, S15	S2, S7, S15	S8, S14, S15	S7, S9, S15	S5, S10, S11, S15	S2, S12, S15	S2, S7, S13, S15	S2, S14, S15	S5, S11, S15

* Power cannot be restored

Example 2

Consider the second test system as a 33–bus, 12.66 KV radial distribution network for which the line and load data is given in [10]. The summary of test results by considering a single line outage and their corresponding switches that are open are given in table 9.

Example 3

Similarly the algorithm is applied for the 69 – bus [27] distribution network. Here, an example of single outage case is considered say an outage between [8 9] and the corresponding open switches between the buses are

	14	15	27	45	39
8 9	15	69	54	46	48

Table 9. Result of 33 bus distribution network

Outage on line	Switches that are open				
NORMAL	S35	S27	S16	S34	S33
S1	If fault occurs in this bus power system cannot be restored				
S2	S2	S27	S16	S34	S35
S3	S3	S16	S33	S34	S35
S4	S4	S16	S33	S34	S35
S5	S5	S16	S33	S34	S35
S6	S6	S27	S33	S34	S35
S7	S7	S27	S33	S34	S35
S8	S8	S27	S33	S34	S35
S9	S9	S27	S33	S34	S35
S10	S10	S27	S33	S34	S35
S11	S11	S27	S33	S34	S35
S12	S12	S27	S33	S34	S35
S13	S13	S27	S33	S34	S35
S14	S14	S27	S33	S34	S35
S15	S15	S27	S33	S34	S35
S16	S16	S27	S33	S34	S35
S17	S17	S27	S34	S33	S35
S18	S18	S27	S16	S34	S35
S19	S19	S27	S16	S34	S35
S20	S20	S27	S16	S34	S35
S21	S21	S27	S16	S34	S33
S22	S22	S16	S34	S33	S35
S23	S23	S16	S34	S33	S35
S24	S24	S16	S34	S33	S35
S25	S25	S16	S34	S33	S35
S26	S26	S16	S34	S33	S35
S27	S27	S16	S34	S33	S35
S28	S28	S16	S34	S33	S35
S29	S29	S27	S34	S33	S35
S30	S30	S27	S34	S33	S35
S31	S31	S27	S34	S33	S35
S32	S32	S27	S34	S33	S35

Example 4

The developed algorithm was tested in a radial network of the Thiruvanmiyur area of Chennai a sub–system of Tamil Nadu, INDIA. The network consists of 59 buses, 54 lines and 9 tie lines.

The single line diagram of this network is shown in figure 9 and table 10 provides the list of switches that are open for the corresponding single line outage case, after applying the proposed algorithm.

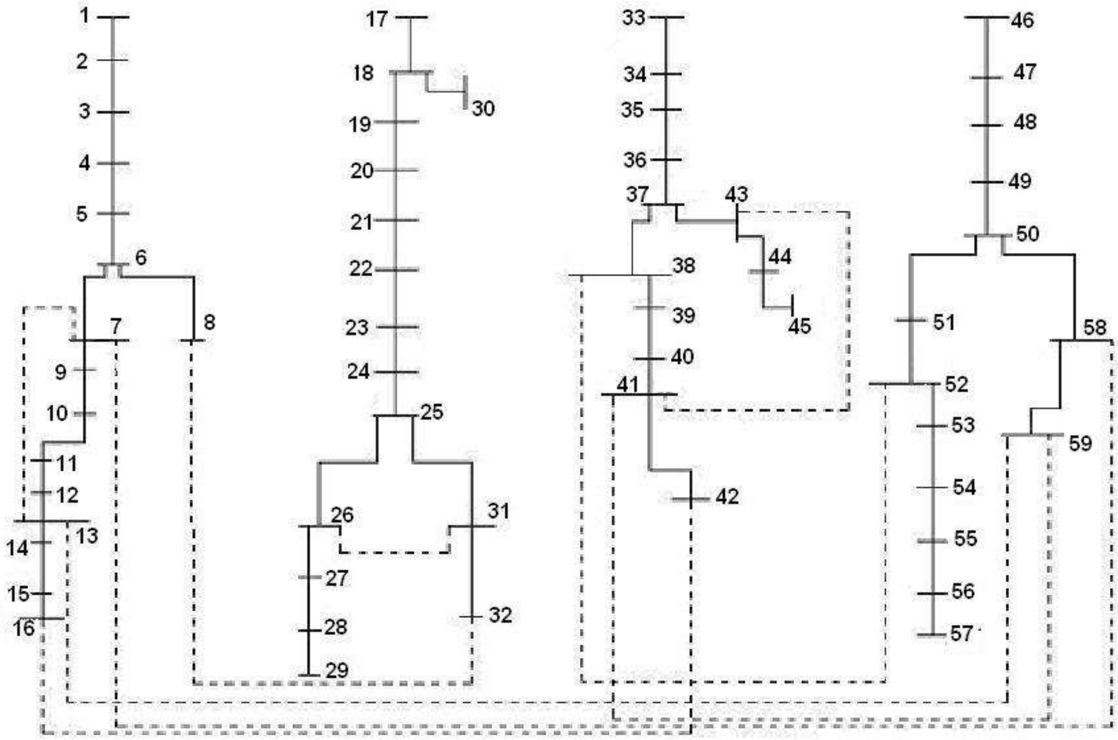

Figure 9. Real time TNEB network

Table 10. Test system results for single line fault

SB	EB	LINE	OPEN SWITCHES								
1	2	S1	S1	S6	S9	S12	S56	S61	S62	S63	S64
2	3	S2	S2	S6	S9	S12	S56	S61	S62	S63	S64
3	4	S3	S3	S6	S9	S12	S56	S61	S62	S63	S64
4	5	S4	S4	S6	S9	S12	S56	S61	S62	S63	S64
5	6	S5	S5	S6	S9	S12	S56	S61	S62	S63	S64
6	7	S6	S6	S9	S12	S15	S56	S61	S62	S63	S64
7	9	S7	S7	S57	S58	S59	S60	S61	S62	S63	S64
9	10	S8	S8	S57	S58	S59	S60	S61	S62	S63	S64
10	11	S9	S9	S57	S58	S59	S60	S61	S62	S63	S64
11	12	S10	S10	S57	S58	S59	S60	S61	S62	S63	S64
12	13	S11	S11	S57	S58	S59	S60	S61	S62	S63	S64
13	14	S12	S12	S56	S57	S58	S60	S61	S62	S63	S64
14	15	S13	S13	S56	S57	S58	S60	S61	S62	S63	S64
15	16	S14	S14	S56	S57	S58	S60	S61	S62	S63	S64
6	8	S15	S15	S56	S57	S58	S59	S61	S62	S63	S64
17	18	S16	S16	S6	S11	S12	S56	S61	S62	S63	S64
18	19	S17	S17	S6	S11	S12	S56	S61	S62	S63	S64
19	20	S18	S18	S6	S11	S12	S56	S61	S62	S63	S64
20	21	S19	S19	S6	S11	S12	S56	S61	S62	S63	S64
21	22	S20	S20	S6	S11	S12	S56	S61	S62	S63	S64
22	23	S21	S21	S6	S11	S12	S56	S61	S62	S63	S64
23	24	S22	S22	S6	S11	S12	S56	S61	S62	S63	S64
24	25	S23	S23	S6	S11	S12	S56	S61	S62	S63	S64
25	26	S24	S24	S56	S57	S58	S59	S60	S62	S63	S64
26	27	S25	POWER CAN NOT BE RESTORED								
27	28	S26	POWER CAN NOT BE RESTORED								
23	29	S27	POWER CAN NOT BE RESTORED								
25	31	S28	S28	S56	S57	S58	S59	S60	S62	S63	S64

SB	EB	LINE	OPEN SWITCHES								
31	32	S29	S29	S56	S57	S58	S59	S61	S62	S63	S64
18	30	S30	POWER CAN NOT BE RESTORED								
33	34	S31	S31	S15	S36	S56	S57	S58	S61	S63	S64
34	35	S32	S32	S15	S36	S56	S57	S58	S61	S63	S64
35	36	S33	S33	S15	S36	S56	S57	S58	S61	S63	S64
36	37	S34	S34	S15	S36	S56	S57	S58	S61	S63	S64
37	38	S35	S35	S56	S57	S58	S59	S60	S61	S62	S63
38	39	S36	S36	S56	S57	S58	S59	S60	S61	S62	S63
39	40	S37	S37	S56	S57	S58	S59	S60	S61	S62	S63
40	41	S38	S38	S56	S57	S58	S59	S60	S61	S62	S63
41	42	S39	S39	S56	S57	S58	S60	S61	S62	S63	S64
42	43	S40	S40	S56	S57	S58	S59	S60	S61	S62	S63
43	44	S41	POWER CAN NOT BE RESTORED								
44	45	S42	POWER CAN NOT BE RESTORED								
46	47	S43	S43	S15	S48	S55	S56	S59	S61	S63	S64
47	48	S44	S44	S15	S48	S55	S56	S59	S61	S63	S64
48	49	S45	S45	S15	S48	S55	S56	S59	S61	S63	S64
49	50	S46	S46	S15	S48	S55	S56	S59	S61	S63	S64
50	51	S47	S47	S56	S57	S58	S59	S60	S61	S63	S64
51	52	S48	S48	S56	S57	S58	S59	S60	S61	S63	S64
52	53	S49	POWER CAN NOT BE RESTORED								
53	54	S50	POWER CAN NOT BE RESTORED								
54	55	S51	POWER CAN NOT BE RESTORED								
55	56	S52	POWER CAN NOT BE RESTORED								
56	57	S53	POWER CAN NOT BE RESTORED								
50	58	S54	S54	S56	S58	S59	S60	S61	S62	S63	S64
58	59	S55	S55	S56	S58	S59	S60	S61	S62	S63	S64
7	13	S56	TIE LINE								
7	58	S57	TIE LINE								
13	59	S58	TIE LINE								
16	42	S59	TIE LINE								
8	32	S60	TIE LINE								
26	31	S61	TIE LINE								
38	52	S62	TIE LINE								
41	59	S63	TIE LINE								
41	43	S64	TIE LINE								

Conclusions

A feeder reconfiguration method for loss reduction of radial distribution system is presented. From the important observations of the present study it could be concluded that: The power losses of distribution systems can be effectively reduced by proper feeder reconfiguration. in addition to power–loss reduction, the voltage profile can also be improved by the proposed method, based on the flowchart the feeder loads and load flow are performed each time, so that the effect of unbalanced PDN is also considered. The proposed method was extended for service restoration. Test results obtained indicate that, this method results in better restoration plan when compared to prove reported in other reference papers.

Conflict of interest

Authors declare there are no conflicts of interest.

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