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Prim's Algorithm for Loss Minimization and Service Restoration in Distribution Networks

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Abstract

Network reconfiguration for loss minimization and service reconfiguration is the determination of switching-options that minimizes the power losses for a particular set of loads and the availability of lines on a distribution system. In this paper, a graph theory based method called prim's algorithm is proposed by formulating a methodology to reconfigure distribution networks for loss minimization and service restoration. An efficient technique is used to determine the switching combinations, select the status of the switches, and find the best combination of switches for minimum loss. In the first stage the prim's algorithm is used to determine the switching combination, select the status of the switches and find the best combination of the switches for minimum loss and service restoration. In the second stage, if the constraints are not satisfied then load transferring or shedding is done to maintain the stability. The proposed method has been tested on single feeder networks like a 33-bus system and a 66-bus network and on multifeeder network like three feeder 16- bus network and a portion of real time network of Tamil Nadu Electricity Board (TNEB) with four feeders 59-bus network. The results have been compared with those of established methods reported earlier and a comparative study is presented. With the proposed method, for any input load conditions of the system, the optimum switching configuration can automatically be identified within a reasonable computer time and hence the method can be effectively employed for continuous reconfiguration for loss reduction and service restoration. The method can be effectively used to plan and design power systems before actually implementing the distribution networks for locating the tie switches and providing the minimum number of sectionalizing switches in the branches to reduce installation and switching costs.

Keywords: Loss minimization, Network reconfiguration, Distribution automation, and Switching combinations.

Introduction

Distribution systems are normally configured radial for effective coordination of their protective systems. Most distribution networks use sectionalizing-switches that are normally closed, and tie-switches that are normally opened. From time to time, modifying the radial structure of the feeders by changing the on/off status of the sectionalizing and tie switches to transfer loads from one feeder to another may significantly improve the operating conditions of the overall system. Feeders in a distribution system normally have a mixture of industrial, commercial, residential and lighting loads. The peak load on the substation transformers and feeders occur at different times of the day, and therefore, the distribution system becomes heavily loaded at certain times of the day and lightly loaded at other times. Reduction in power losses is obtained by transferring loads from the heavily loaded feeders to lightly loaded feeders by reconfiguring the network so that the radial structure of the distribution feeders can be modified from time to time. This is done in order to reschedule the loads more efficiently for minimizing the losses in the system. Reconfiguration also allows smoothening out the peak demands improves the voltage profile in the feeders and increases the network reliability. Besides, the following requirements should be enforced during the reconfiguration process [1] :

i. Minimum Losses
ii. Voltage Limits
iii. Current Limits
iv. Feeder Capacity

During certain conditions there may be outage in the lines which may be lead to the disturbance in the network. To restore the network the topology of the network has to be altered and this process is known as service restoration. All the requirements of network configuration should be followed for service restoration also. In this context, the paper has been organized as follows: in section 2, a brief survey on the work done on loss minimization and the use of minimum spanning tree are discussed; in section 3, switching algorithm for loss reduction; in section 4 the test system with results and discussion; while section 5 is for conclusion respectively.

A Brief Survey

A number of researches have been done on the reconfiguration of the network by closing/opening the tie and sectionalizing switches respectively to minimize losses in a distribution system. A branch exchange type heuristic algorithm has been suggested by Civanlar et. al. [2], where, a simple formula has been developed for determination of change in power loss due to a branch exchange. A different method has been proposed by Baran and Wu [3] to identify the branches to be exchanged using heuristic approach to minimize the search for selecting the switching options. Merlin and Back [4] have used the branch and bound type optimization technique to find the minimum loss configuration. Following the method of reference [4], Shknohammdi and Hong [5] have developed a heuristic algorithm. In their method, the solution is obtained by first closing all the switches, which are then opened one after another so as to establish the optimum flow pattern in the network. Goswami and Basu also have proposed a heuristic algorithm for feeder reconfiguration by solving the KVL and KCL equations for the network with line impedances replaced by their corresponding resistances only. Broadwater et. al. [7] have applied the Civanlar's method [2] and Huddleston's quadratic loss function and multiple switching pair operation method to solve the minimum loss reconfiguration problem. Peponis et. al. [9] have used the switch-exchange and sequential switch opening methods for reconfiguration of the network for loss reduction. The methods proposed by Rubin Taleski et. al. [10] and Kashem et. al. [11] are also based on branch exchange technique for reconfiguration to minimize distribution losses. In all the above methods, the environments under which the calculations are made do not correspond to the actual operating conditions of the system under consideration. They depend on some heuristics and approximations, as the simultaneous switching of the feeder reconfiguration is not considered due to combinatorial explosive nature of the switching options to be encountered. Methods [12,13] have been suggested to implement on-line control strategies for power system planning and operations based on continuous network reconfiguration for loss minimization.

However, the optimal switching strategies proposed by most articles need to consider every candidate switch 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. A graphical approach has been developed to solve the switching problem with minimum numerical burden. Under normal operational state, the network is considered for loss reduction; under restorative state, the network is considered for load reconnection. Computer simulations were conducted to show the effectiveness of the proposed methodology.

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. Conceptually, it is a straightforward matter to determine whether the new system obtained through a feeder reconfiguration would incur lower losses. In this article, the formula proposed in [14] is used to estimate the line loss. The change in the losses can easily be computed from the results of load flow studies simulating the system configurations before and after the feeder reconfiguration.

The problem in question is now illustrated using the 3 feeder distribution system shown in figure 1. The dotted branches S5, S11and S16 represent ties connecting feeders; normally open tie switches are assumed to be present on these branches. For notational convenience, the corresponding tie numbers will identify these tie switches. 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.

The load at node 11 can be transferred to feeder–1 by closing the tie switch S5 and opening the sectionalizing switch S9, similarly the loads at nodes 9, 11, and 12 can be transferred to feeder–1 by closing the tie switch S5 and opening the sectionalizing switch S8. Throughout this article the focus will be on feeder reconfiguration by closing a single tie switch and opening a single sectionalizing switch to preserve radiality of the two feeders that are under consideration.

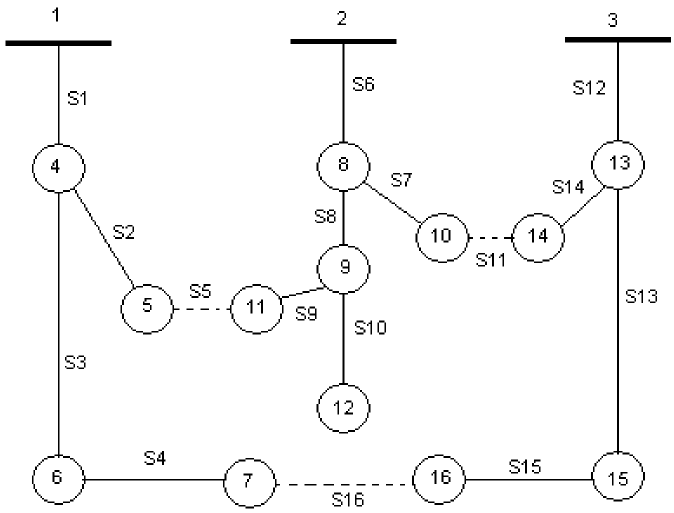


Figure 1 : Single Line Diagram Of Ieee 16–Bus System

The main drawback faced during the maintenance, dispatching and abnormal conditions is the difficulty in identifying all the distribution braches used for the power to flow, in PDN. In order to overcome this drawback, a graph theory based approach is tried. Graphs, the basic subject studied by 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, a number representing how unfavorable it is, and the sum of the edge weights give 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 [15] presents an algorithm for finding the shortest path for power routing (DC) between two nodes in an electrical network used in the airlines. Paper [16] presents mathematically minimum spanning tree for network topological observability analysis. In 1994, paper [17] dealt with application of the minimum spanning tree is applied 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 [18]. Here outages were not been considered as an important factor to address. Paper [19] discusses about the application of Dijkstra's algorithm for various applications like airline electrical networks which is the main advantage of the algorithm. Paper [20] indicates the use of Floyd–Warshall's based minimum spanning tree to find the time scheduling in the data flow graph of a DSP. Paper [21] uses the learning classifier system for loss minimization in a power system. Paper [22] calculates the reliability index of radial network using forward search method of minimum spanning tree. Reference [23] discusses 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 [24] is based on the weights 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 [24] 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.

Switching Algorithm for Loss Reduction

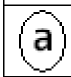
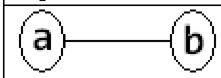
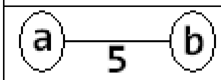
In a radial distribution system to achieve a maximum reduction in power loss, the aim is to identify the appropriate switching options. In most of the techniques, the losses are calculated by using load-flow studies for each configuration, and the minimum loss configuration is found. In the proposed method, the distribution system is considered with all its laterals simultaneously, instead of determining the switching-options on loop by loop basis. Usually, this type of technique involves very complicated mathematical techniques and large computational time due to the combinatorial nature of the problem. However, the solutions obtained by these methods achieve global optimum of loss minimization problem [10]. The proposed method develops a switching algorithm, which minimizes the computational time by performing the effective search to the requisite switching combinations.

Determination of Switching Status

In general, any tie or/and sectionalizing switches can be closed or/and opened to perform various network reconfigurations without creating any closed loop or leaving out any branch unconnected. Any reconfiguration which forms a closed loop, or leaving one or more branches unconnected is classified as infeasible switching combination for network configuration [25]. To avoid any infeasible switching combinations, the connectivity from the source to all the nodes of the system is checked. If a valid path exists, then the configuration is a feasible one, otherwise it is infeasible. It is important to note that every tie switch or sectionalizing switch selected for closing or opening for reconfiguration is considered together with its two immediate neighboring switches. If a tie switch is closed, then a closed loop will be formed. To avoid a closed loop and restore the radial structure, one of the neighboring sectionalizing switches must be opened. To obtain this configuration here prim's algorithm is explained.

If an exhaustive–search approach to construct a minimum spanning tree tried, two serious obstacles arise namely; first, the number of spanning trees grows exponentially with the graph size; second, generating all spanning trees for a given graph is not easy; In this section, outline of *Prim's algorithm*, is discussed which goes back to at least 1957 [Pri57]. Prim's algorithm 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 2 with 6 vertices and 10 edges. The vertex a is taken as the generation point. The graph shown here is a weighted, undirected network. Since it is a weighted graph there are weights given on the edges joining two nodes. Table 1 show all the terms to be known for proceeding through Prim's algorithm.

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 1 and node 2

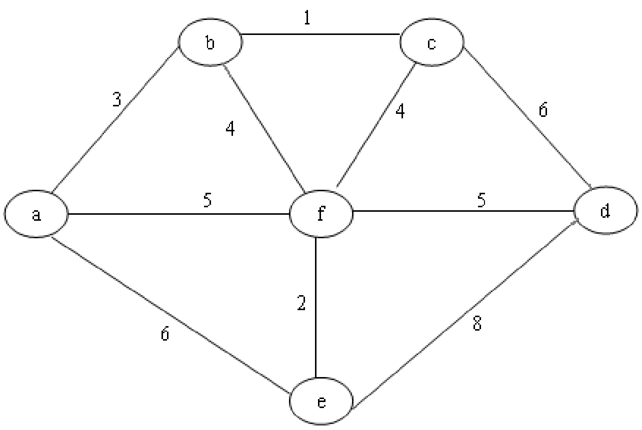


Figure 2 : Sample Network For Example Problem

Prim's algorithm constructs a minimum spanning tree through a sequence of expanding subtrees. The initial subtree in such a sequence consists of a single vertex selected arbitrarily from the set *V* of the graph's vertices. In the following iterations the current tree expands in the greedy manner by simply attaching to it the nearest vertex not in that tree. (By the nearest vertex, a vertex not in the tree connected to a vertex in the tree by an edge of the smallest weight.) The algorithm stops after all the graph's vertices have been included in the tree being constructed. Since the algorithm expands a tree by exactly one vertex on each of its iterations, the total number of such iterations is *n* — 1, where *n* is the number of vertices in the graph. The tree generated by the algorithm is obtained as the set of edges used for the tree expansions.

Here is a pseudocode of this algorithm.

ALGORITHM *Prim(G)*

//Prim's algorithm for constructing a minimum spanning tree
//Input: A weighted connected graph G = *(V, E) where V is vertex and E is edge*
//Output: E_T, the set of edges composing a minimum spanning tree of *G*
$V_T \leftarrow \{v_0\}$ //the set of tree vertices can be initialized with any vertex
$E_T \leftarrow \phi$
$for\ i \leftarrow 1\, to |V| - 1$ do
find a minimum–weight edge $e^* = (v^*, u^*)$ among all the edges *(v,u)*
such that *v* is in V_T and *u* is in $V - V_T$
$V_T \leftarrow V_T \cup \{u^*\}$
$E_T \leftarrow E_T \cup \{v^*\}$
return E_T

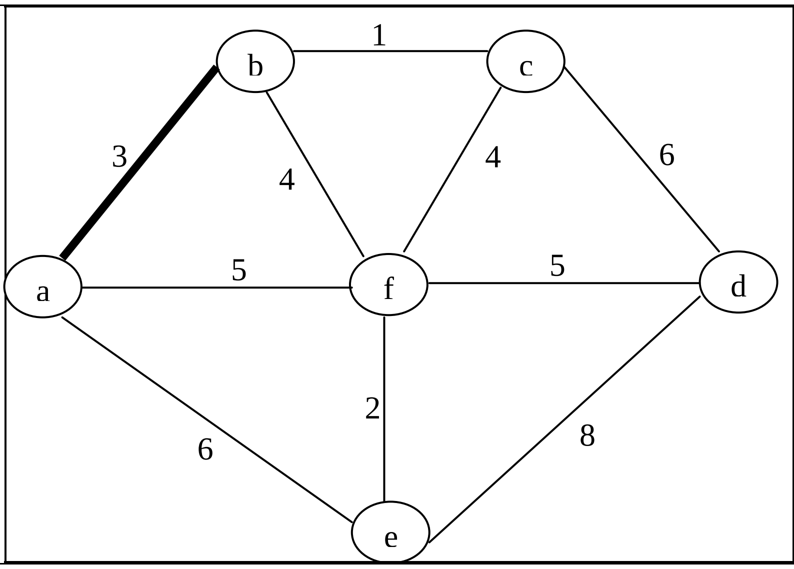
The nature of Prims algorithm makes it necessary to provide each vertex not in the current tree with the information about the shortest edge connecting the vertex to a tree vertex. The information's are provided by attaching two labels to a vertex: the name of the nearest tree vertex and the length (the weight) of the corresponding edge. Vertices that are not adjacent to any of the tree vertices can be given the ∞ label indicating their "infinite" distance to the tree vertices and a null label for the name of the nearest tree vertex. With such labels, finding the next vertex to be added to the current tree $T = (V_T, E_T)$ becomes a simple task of finding a vertex with the smallest distance label in the set $V - V_T$.

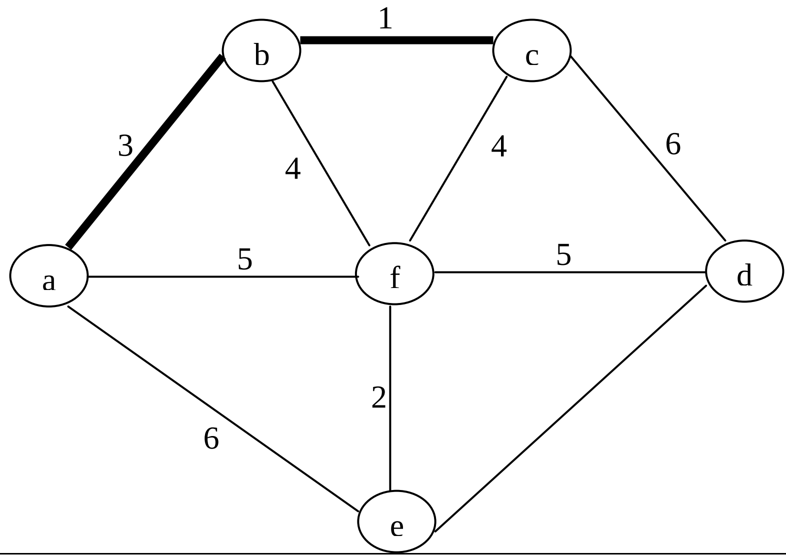
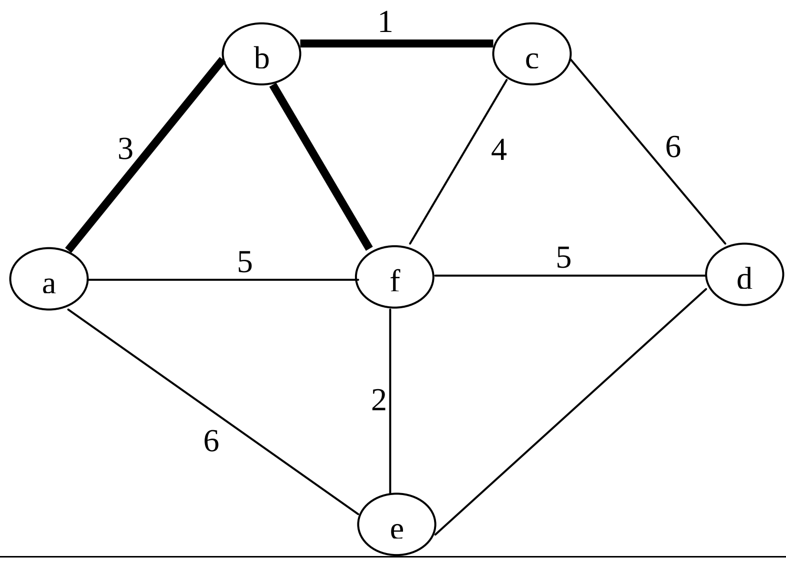
After a vertex *u** is identified which is to be added to the tree, two operations has to be perform:

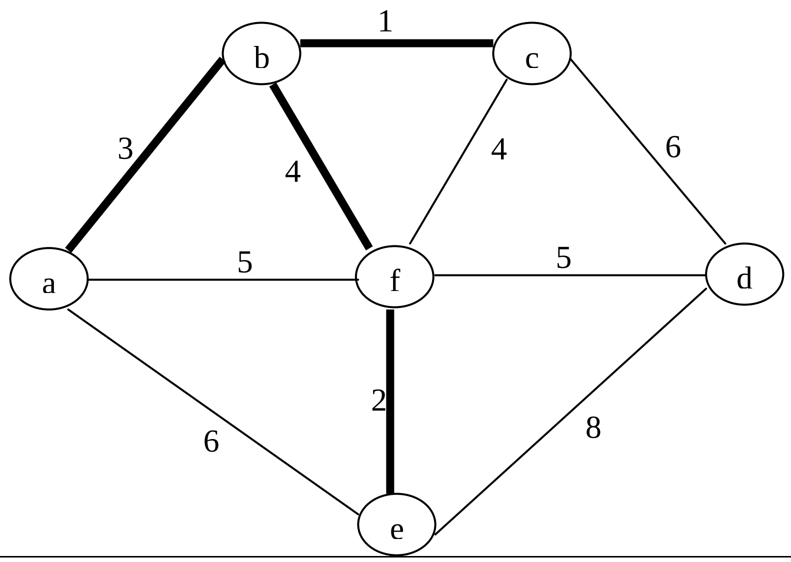
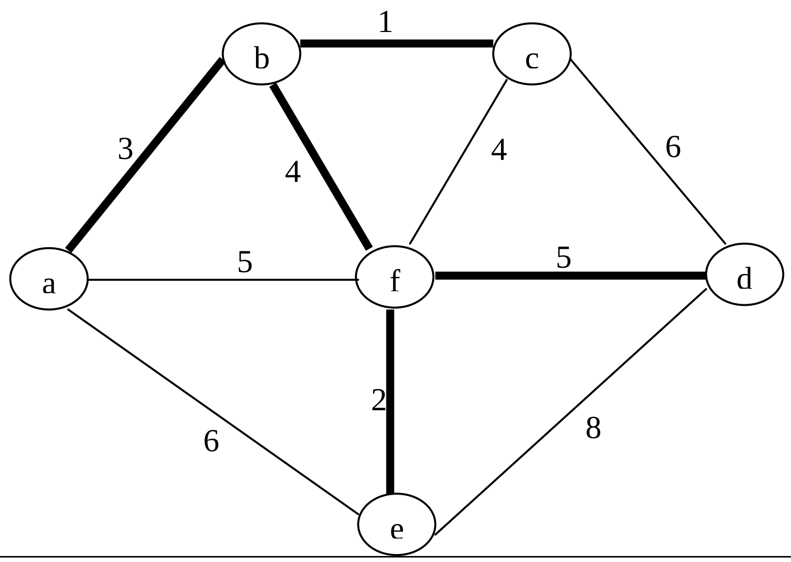
- Move u* from the set $V - V_T$ to the set of tree vertices V_T.
- For each remaining vertex *u* in $V - V_T$ that is connected to u* by a shorter edge than the *u's* current distance label, update its labels by *u** and the weight of the edge between u* and u, respectively. (If the implementation with the fringe–unseen split is pursued, all the unseen vertices adjacent to *u** must also be moved to the fringe).

Prim’s algorithm always yield a minimum spanning tree, which is proved by induction, that each of the subtrees T_i, $i = 0,\ldots, n — 1$, generated by Prim's algorithm is a part (i.e., a subgraph) of some minimum spanning tree. (This immediately implies, of course, that the last tree in the sequence, $T_{n–1}$, is a minimum spanning tree itself because it contains all n vertices of the graph.) The basis of the induction is trivial, since T_0 consists of a single vertex and hence must be a part of any minimum spanning tree. For the inductive step, let us assume that $T_{i–1}$ is part of some minimum spanning tree T. It has to be proved that T_i, generated from $T_{i–1}$ by Prim's algorithm, is also a part of a minimum spanning tree. This is proved through contradiction by assuming that no minimum spanning tree of the graph can contain T_i. Let $e_i = (v,u)$ be the minimum weight edge from a vertex in T_{i-1} to a vertex not in T_{i-1} used by Prim's algorithm to expand T_{i-1} to T_i. By our assumption, e_i cannot belong to the minimum spanning tree T. Therefore, if we add e_i to T, a cycle must be formed. In addition to edge e_i = (v,u), this cycle must contain another edge $(v’,u')$ connecting a vertex $v' \in T_{i–1}$ to a vertex u' that is not in $T_{i–1}$. (It is possible that v' coincides with v or u' coincides with u but not both.) If we now delete the edge $(v’,u')$ from this cycle, we obtain another spanning tree of the entire graph whose weight is less than or equal to the weight of T since the weight of e_i is less than or equal to the weight of (v’,u’). Hence, this spanning tree is a minimum spanning tree, which contradicts the assumption that no minimum spanning tree contains T_i. Here table 2 explains the step by step procedure of obtaining the minimum spanning tree from the stating vertex ‘a’ for the above sample network.

Table 2 : Application of Prim’s algorithm to a specific graph

Tree Vertices	Remaining Vertices	Illustration
a(–,–)	b(a,3); c(–,∞); d(–,∞); e(a,6); f(a,5)	

b(a,3)	c(b,1); d(–,∞); e(a,6); f(b,4)	
c(b,1)	d(c,6); e(a,6); f(b,4)	

f(b.4)	d(f,5); e(f,2)	
e(f,2)	d(f,5)	

Finding the Total Losses of a Network by Using Simplified Distflow

Power flow equations for a radial distribution network using real power, reactive power, voltages at the sending and receiving ends of a branch proposed by Baran and Wu [3] are,

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

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

$$V_{i+1}^2 = V_i^2 - 2(r_i P_i + x_i Q_i) + \frac{(r_i^2 + x_i^2)(P_i^2 + Q_i^2)}{V_i^2} \tag{3}$$

The above equations are called Distflow equations, where, P_i, Q_i, V_i are the real power, reactive power, and voltage at the sending end and P_{i+1}, Q_{i+1}, and V_{i+1} are the receiving end quantities respectively. The quadratic terms in the equations represent the losses on the branches and hence they are much smaller than the power terms P_i and Q_i. Hence, by dropping the second order terms the set of new branch equations can be written as,

$$P_{i+1} = P_i - P_{L(i+1)} \tag{4}$$

$$Q_{i+1} = Q_i - Q_{L(i+1)} \tag{5}$$

$$V_{i+1}^2 = V_i^2 - 2(r_i P_i + x_i Q_i) \tag{6}$$

The solution for the simplified Distflow equations for a radial network can be obtained as [2],

$$P_{i+1} = \sum_{i+2}^{n} P_{Lk} \tag{7}$$

$$Q_{i+1} = \sum_{i+2}^{n} Q_{Lk} \tag{8}$$

$$V_{i+1}^2 = V_i^2 - 2(r_i P_i + x_i Q_i) \tag{9}$$

The power loss on a branch is calculated as,

$$Loss_i = \frac{r_i (P_i + Q_i)}{V_i^2} \tag{10}$$

The total system loss is the sum of all the branch losses given by,

$$Total\_loss = \sum_{i=0}^{n-1} Loss_i = \sum_{i=0}^{n-1} \frac{r_i (P_i + Q_i)}{V_i^2} \tag{11}$$

Unlike the other load-flow techniques that take a lot of iterations and computational time, in the simplified DistfJow, power-flows are calculated in one cycle of iteration. Therefore, it is suitable for on-line implementation as it reduces computational time.

Finding the Optimal Configuration for Loss Minimization and Service Restoration

The network reconfiguration for loss minimization is performed by opening and/or closing the sectionalizing and tie-switches in such a way that the radiality of the network is retained and at the same time power losses are minimized. In the proposed method, a systematic approach is employed to perform automatically all types of operations needed for (i) obtaining the feasible combinations, (ii) determining the switching status of the individual switches, (iii) identifying the minimum loss configuration which might be a local or global minimum from among the feasible switching combinations, and (iv) finally making a search to find the global optimum for loss minimization and service restoration by moving to the left or right of each of the open lines or tie lines.

Once the input parameters of the base configuration or any other configuration of a radial system under consideration, are fed to the methodology, the methodology automatically reassigns the branches and loads, for any other switching configuration. The detailed flow chart for the loss minimization and service restoration for any radial distribution network is shown in figure 3.

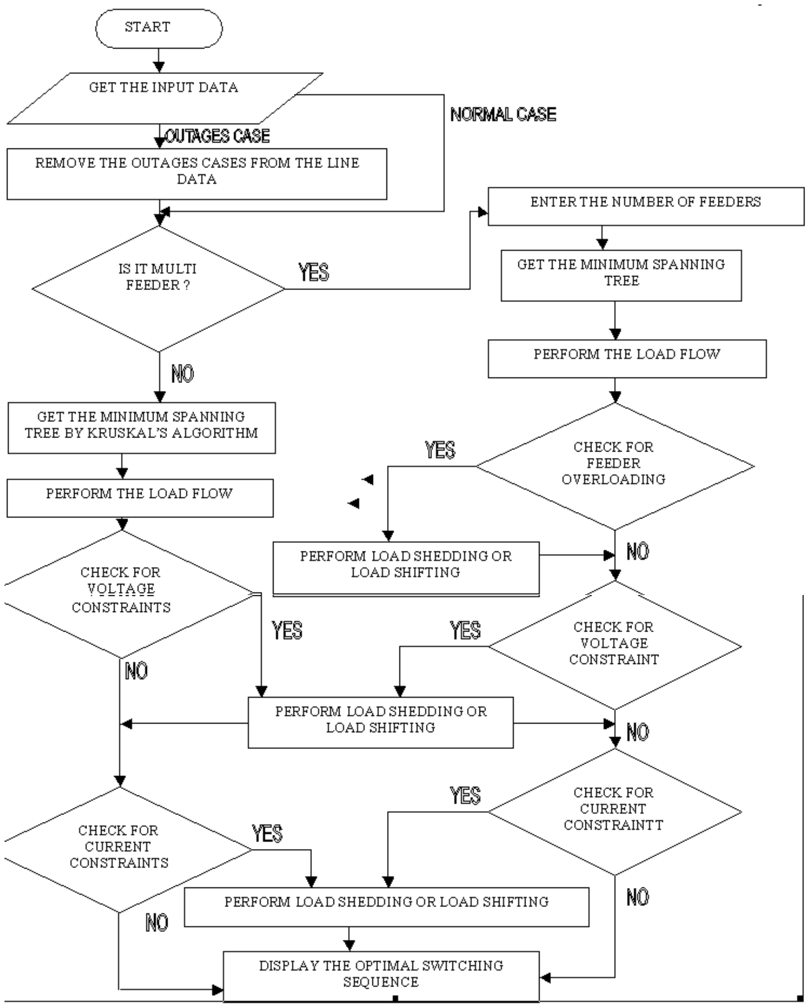


Figure 3 : Flow Chart Of Prim's Algorithm

Test System with Results

Example 1

Consider the IEEE 16 – bus system [9] as shown in figure 1. Here the Prim's algorithm is applied by assuming the distribution branch impedance as the weights of the graph. As per the algorithm the results are obtained for the IEEE 16–bus network for which the step by step procedure is shown in the table 3, by considering the starting node as 1,2,3; which are the three feeders of the network.

Table 3 : Application of Prim's algorithm to IEEE 16–bus network

Tree Vertices	Remaining Vertices
1(–,–); 2(–,–); 3(–,–)	4(1, $0.08 + j\,0.1$); 5(–,∞); 6(–,∞); 7(–,∞); 8(2, $0.11 + j\,0.11$); 9(–,∞); 10(–,∞); 11(–,∞); 12(–,∞); 13(3, $0.11 + j\,0.11$); 14(–,∞); 15(–,∞);16(–,∞)
4(1, $0.08 + j\,0.1$); 8(2, $0.11 + j\,0.11$); 13(3, $0.11 + j\,0.11$)	5(4, $0.08 + j\,0.11$); 6(4, $0.09 + j\,0.18$); 7(–,∞); 9(8, $0.08 + j\,0.11$); 10(8, $0.11 + j\,0.11$); 11(–,∞); 12(–,∞); 14(13, $0.09 + j\,0.12$); 15(13, $0.08 + j\,0.11$); 16(–,∞)
5(4, $0.08 + j\,0.11$); 9(8, $0.08 + j\,0.11$); 15(13, $0.08 + j\,0.11$)	6(4, $0.09 + j\,0.18$); 7(–,∞);10(8, $0.11 + j\,0.11$); 11(5, $0.04 + j\,0.04$); 12(9, $0.08 + j\,0.11$); 14(13, $0.09 + j\,0.12$); 16(15, $0.04 + j\,0.04$)
11(5, $0.04 + j\,0.04$); 12(9, $0.08 + j\,0.11$); 16(15, $0.04 + j\,0.04$)	6(4, $0.09 + j\,0.18$); 7(–,∞);10(8, $0.11 + j\,0.11$); 14(13, $0.09 + j\,0.12$)
6(4, $0.09 + j\,0.18$); 10(8, $0.11 + j\,0.11$); 14(13, $0.09 + j\,0.12$);	7(6, $0.04 + j\,0.04$)

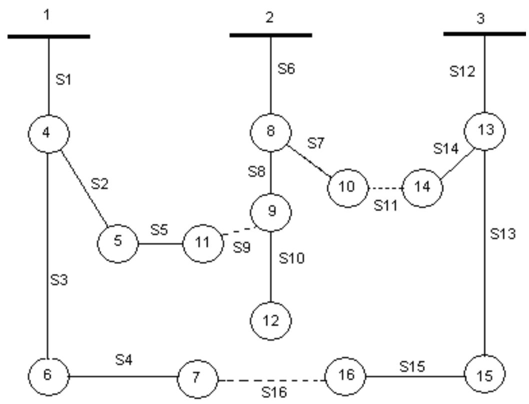


Figure 4 : Example Problem's Result After Applying Prim's Algorithm

For this result after applying Prim's algorithm, the resultant network is shown in figure 4. For the resultant network the feeder 3 capacity is 100%, feeder 2 capacity is 98% and the feeder 1 capacity is 108%. The individual feeder line currents (S1, S6 and S12) for this result are 100%, 150% (maximum current limit allowed by TNEB (Tamil Nadu Electricity Board) standards) and 50% of their capacity value. The minimum node voltages, and total real power loss (TPL) obtained are shown in table 4. 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 result shows the improvement of voltage to 0.96846 p.u.

Table 4 : 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 [27]	S7, S9, S16	599.56	0.95679
Jizhong Zhu, C.S. Chang [28]	S7, S9, S16	466.1	0.96421
Prim's algorithm	S7, S9, S16	490	0.96846

Service Restoration

In case of 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)

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 5. 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. However, the losses are slightly more in the proposed method, compared to Lin and Chin 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 [26] at node 12. Lin and Chin [29] have also reported the results for this case, they found, through their method, that closure of tie switch S11 violates 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 [29] and Sivaraju and ramana [26] are tabulated in Table 5. It can be seen from this table that the proposed method produces a better restoration plan compared to methods of Lin and Chin [29] and Sivaraju and Ramana [26], which is based on the amount of load shed.

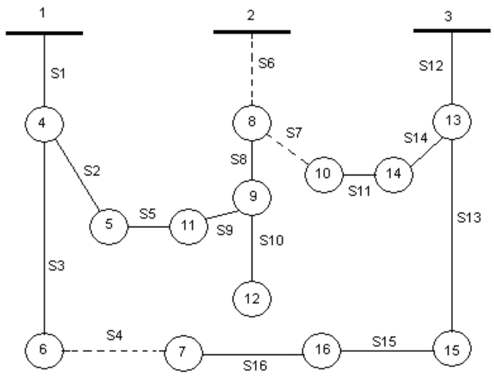


Figure 5 : Result of IEEE 16–bus system for a outage at line S6

Table 5 : 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
Prim's algorithm	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 [26]	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 [29]	S6, S11, S16	S8	0.94848	656	Load shed by 12.5 MW	12.5 of feeder 1

Table 6 gives the result for all the single line outage and the results show the switches that are open during the particular outage case. Table 7 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 also it provides the total amount of load to be shed.

Table 6 : Sample System Results for Single Line Outages Using Prim'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 CAN NOT BE RESTORED			Nil
S12	S12	S9	S13	No
S13	S13	S7	S2	No
S14	S14	S16	S5	No
S15	S15	S5	S11	No

Table 7 : Sample System Results for Outages at Two Lines Simultaneously Using Prim'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 can not be restored

Discussions

The proposed algorithm is most suited to be used with SCADA (Supervisory Control and Data Acquisition

Systems) and DAC (Distribution Automation and Control) as the algorithm requires only the inputs to be supplied and any other subsequent manipulations such as partitioning, forming loops or sub-systems etc. are not necessary. In most of the methods available so far, some form of heuristics is employed and near optimal or optimal solution is obtained. In these methods the implementation of the loss minimization has not been fully automated. As the loss minimum configuration has been obtained by some heuristics and approximations, these methods do not guarantee global optimum. Since the heuristic methods depend on the loads at a particular time, and as loads vary with time, they are not reliable in load varying conditions. Whatever may be the combination of consumer types, the proposed method will offer reliable solutions for the loss minimization problems by properly reconfiguring the distribution systems. The proposed method can be applied for proper planning and efficient operation for on-line systems, since any change in loads does not need any change to be made in the algorithm and the optimum switching configuration can be easily found without much effort. The problem of non-coincidence of peak loads and diversity of load categories are not a matter of concern in the proposed system. Since simultaneous evaluation of power losses in all the branches are done for a set of switching combinations, the method is more reliable and gives better results. Also, the method gives a lot of flexibility to limit or extend the search simply by specifying the branch numbers to which the search is to be done on both ends of each tie-switch in the system. The proposed method can be reliably employed for loss minimization as it has been found to be most effective and gives the best optimal solutions compared to the methods available for loss minimization and service restoration by reconfiguring the radial distribution network.

Conclusion

A switching algorithm is formulated for network reconfiguration based loss reduction, and service restoration by using prim's algorithm is proposed in this paper. To reduce the combinatorial explosive switching problems into a realizable one, an efficient technique has been introduced for reconfiguration of distribution networks. The method has been compared with other methods and a comparative study is presented. From the test results and comparative study it can be concluded that the proposed method can effectively identify the appropriate switches for loss minimization and service restoration with minimum computational effort. The technique can be effectively installed in real time on-line systems under widely varying load conditions, and this is suitable for power system planning and operations. The proposed method is suitable for continuous reconfiguration for loss reduction. And it can also be used for planning and design of power systems to reduce installation and switching costs.

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