

MINIMUM SPANNING TREES DETERMINATION FOR ELECTRICAL DISTRIBUTION NETWORKS RECONFIGURATION

L. Zerna L. Kotni

Department of Electrotechnics, Electrical Engineering Faculty, University of Sciences and Technology of Oran, Oran, Algeria, zerna1@yahoo.fr, kotni_dz@yahoo.fr

Abstract- Distribution network restoration occurs after a default affecting all or part of the network by altering its topological configuration while maintaining operating constraints. Optimal reconfiguration can be obtained at the expense of prohibitive cost due to combinatorial explosion on open/closed state switches. In this case, operators focus on a configuration that, even if not optimal, respects admissible voltage limit, maximizing number of restored load and radial network structure constraints. A slightly modified Kruskal's algorithm, an instance of minimum spanning tree (MST) algorithms, is used to reach radial network structure and maximum restored load objective by representing distribution networks, designed according to a meshed architecture, as connected undirected graph. Proposed approach is based on different dimensionless weights assignment for edges associated with sectionalizing faulted zone switches and tie-switches. Furthermore, when distribution network includes more than one feeder, resulting solution do not respect radial network structure constraint. Heuristics rules associated to binary decision trees are then used to overcome this difficulty. Kirchhoff's spanning tree algorithm allows to obtain all spanning trees and an implementation is used to enumerate and generate the number of MST and MST respectively. Simulation results obtained from fictitious multi-feeders' distribution network, modified three feeders IEEE 16 bus and IEEE 15 bus single feeder distribution system test cases demonstrates the effectiveness of the proposed approach.

Keywords: Network Reconfiguration, Minimum Spanning Trees, Kruskal's Algorithm, Binary Decision Tree, Admissible Voltage Limit, Radial Network Structure Constraint Heuristic's Rules.

1. INTRODUCTION

Distribution networks become increasingly sophisticated and penetration of distributed power generation and control means ensure more reliable exploitation in terms of energy quality and service continuity while respecting operational constraints. Despite introduction of decentralized production which have bring changes in operating paradigms [1-2], particularly intelligent systems, distribution networks,

becoming active electrical circuits set in which power flows and voltages are governed not only by loads but also by power sources, are subject to changes in topology and defaults whose impact on customers must be minimized [3]. Network reconfiguration after a default occurrence therefore becomes main concern for operators to satisfy operating constraints and continuity of service through power losses minimization, admissible voltage limit and a radial configuration.

Several approaches were used to distribution network reconfiguration based on switches states modification. A review of distribution network restoration methods is presented in [4]. These methods for solving the restoration problem are categorized as either centralized or decentralized. Centralized methods utilize expert systems, heuristic algorithms, graph theory, and multi-agent systems to solve the problem according to specific rules and procedures derived from domain-specific knowledge and heuristics. Decentralized methods employ mathematical programming and meta-heuristic algorithms to solve the problem based on a mathematical optimization model.

In [5] state-of-the-art reconfiguration techniques for service restoration in distribution systems are discussed. These techniques take into account various practical considerations other than mathematical programming and traditional artificial intelligence techniques. They incorporate factors such as load variations, load priority, cold load pickup, network connectivity representation, and distributed generation penetration to enhance the practicality of the solution. Binary decision trees [6] allows to find optimal radial configuration with some operating heuristics avoiding combinatorial explosion due to switches states changes. After a default, concerning area (zone) is isolated from the rest of the network and all the switches (sectionalizing switch and tie-switch) are put in an unknown state that must be determined (open or closed) by depth-first search algorithm through binary decision trees. Obtained results lead generally only to local optimum configurations. Depth-first search and breadth-first algorithm [7] were used in an unweight graph representing distribution network to obtain optimal reconfiguration maintaining radial topology.

Branch and bound and reallocating branch exchange lines were used with only approximate local optimums solutions [8]. Metaheuristic methods try to find optimal configurations including genetic algorithm [9], Tabu search [10], Ant Colony [11], Particle Swarm Optimization [12], which while yielding convincing results, are only applicable to small-scale networks. Switching operation minimization was adopted [13] using evolutionary methods combined with heuristics on a Brazilian local distribution network comprising more than a hundred buses, without resorting to network simplification. Mixed Integer Programming gives significant results allowing to find optimal configurations reducing losses and maximizing the reallocation of loads but in a prohibitive time [14-16].

Two heuristics methods based on switches ranking and load shedding are proposed in [17] to find an effective and fast solution switch selection indices analytical approach and graph-based method. Proposed method does not detect loops when distribution network contains more than one power source. Several studies about distribution network reconfiguration based on altering network configuration in steady-state and restoration state were performed using minimum spanning tree algorithms with the aim of primarily reducing power losses [18-21]. In [22] Edmond's maximal spanning tree search algorithm has been proposed to generate an optimal radial network from a meshed distribution network. It assimilates the distribution network as a directed (oriented) graph in order to create a radial network that has feeders with higher load-carrying capacity and rejects those with lower load-carrying capacity. In [23], a modified version of Prim's algorithm is used to construct a spanning tree. This algorithm includes the assignment of weighting coefficients to all branches in the de-energized area, aiming to reduce the number of switching operations. Harmony search algorithm [24] investigates the impact of limiting the number of switching on the loss reduction of the network. However, the number of actions on the switches to obtain an optimal configuration is previously determined.

In this paper, proposed approach objective is to minimize switching operation to obtain configurations structures not necessarily optimal after a default in a multi-feeder and a single feeder distribution network. Obtained configuration must spans all but the default zone. A modified version of Kruskal's algorithm, based on graph theory is used for this purpose. It consists on a simple heuristic that assigns dimensionless weight to tie-switches and sectionalizing switches, depending on their connection to the default area. Therefore, distribution network is represented as non-complete planar undirected weighted graph where vertices and edges represent electrical buses (or zones) and lines (or switches) respectively. However, Kruskal's algorithm provides only a single configuration which limits exploration of other configurations. To obtain all spanning trees (ST) configurations, Kirchoff's algorithm is used. This algorithm is based on Laplacian matrix of the related graph involving adjacency and degrees matrices.

From obtained ST, the number of MST configurations can be determined by implementing a pseudo-code given in next section. Resulted MST configurations for a multi-feeder distribution network doesn't correspond generally to radial network constraint which is not the case for a single feeder distribution network. To obtain radial configuration, heuristics rules associated to binary decision tree is used where only tie-switches states will be altered, sectionalizing switches remaining closed. Using a simple heuristic based on tie-switches states allows objective to obtain a particular configuration constituting a solution respecting only two operating constraints: radial network configuration (overloaded or not and feeding all loads) and admissible voltage limit. Proposed approach is evaluated on fictitious multi-feeders distribution network from, modified IEEE 16 bus three feeders and IEEE 15 bus single feeder test distribution networks.

2. DISTRIBUTION NETWORK RECONFIGURATION

Distribution network reconfiguration under steady-state normal operation or after default occurrence is formulated as multi-constraints (bus voltage and branches current limits) and multi-objective problem (minimize active power losses, out-of-service areas and switching operations, maximize loads). In a multi-feeders meshed distribution network operating radially containing sectionalizing and tie-switches, each feeder supplies a set of zones connected by sectionalizing switches, while tie-switches ensure continuity of service between zones supplied by different feeders after a default or topology change. Reconfiguration strategies maintaining radial network structure, admissible voltage drop, balance feeder loadings and maximum load power flow is based on actual topology alteration by changing switch's status.

A part of reconfiguration techniques is based on graph theory by assimilating distribution network structure representation to a weighted undirected planar graph in which nodes represent supplied zones and edges represent electrical lines equipped with switches. Greedy algorithms class, a spanning tree instance, is used in normal operation and for a single feeder distribution network to obtain radial structure. The problem consists in a complete or non-complete connected undirected weighted planar graph to find an edge's subset constituting a tree including all vertices such that sum edge's weight is minimal (or maximal). Weighted edges are generally assigned according to desired reconfiguration (loss minimization, maximum load power flow). In the proposed approach, distribution network reconfiguration after a default in a particular zone is based on open/close action's minimization on switches. For this purpose, edges in related graph will have a dimensional weight so that open/close actions apply to the tie-switches only. Nevertheless, for multi-feeders meshed distribution network, obtained configuration may not respect radial network constraint since the same zone can be supplied by two or more different feeders. In this case a radial configuration respecting admissible voltage drop and balancing loads, even not optimal, must be identified using adapted problem's heuristics.

Kruskal algorithm, used in this paper, provide a unique configuration which perhaps not corresponds to an appropriate solution. To explore different configurations, Kirchhoff's spanning tree algorithm is used to determine the number of minimum spanning trees. To generate all spanning trees for undirected weighted graph Algorithm S [25] is implemented [26]. Distribution network performance is evaluated on the basis of the voltage profile. Then maintaining voltage profile within admissible limits is the main concern of operator's distribution networks. In distribution network, due to the negligible ratio between the reactive power generated by the line and the apparent maximum power transited by the same line, voltages across successive sending-end and receiving-end buses are determined with no quadrature axis of voltage drop account. In this case, voltage drop is found for the entire network and not for each line section:

$$\Delta V = \sqrt{3} \left(\sum_{k=1}^n i_{ka} R_k + \sum_{k=1}^n i_{kr} X_k \right) = \tag{1}$$

$$= \frac{1}{V_{nom}} \left(\sum_{k=1}^n p_k R_k + \sum_{k=1}^n q_k X_k \right)$$

where, ΔV is voltage drop from supply bus to the n -load bus application, V_{nom} nominal voltage, i_{ka} , i_{kr} , p_k and q_k are active and reactive load current and power at bus k , R_i and X_i lines sections resistance and reactance from supply bus to k -load application, while $r_{(i-j)}$, $x_{(i-j)}$ represent resistance and reactance of line section between buses i and j .

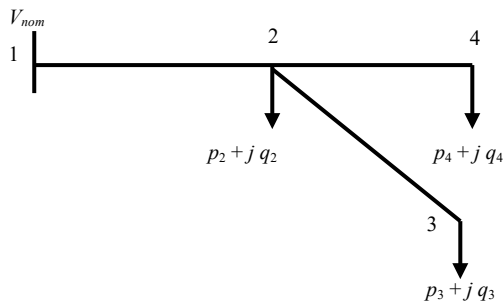


Figure 1. Radial distribution network

From Figure 1, for the section (1-3) and section (1-4) voltage drops are:

$$\Delta V_{(1-3)} = \frac{1}{V_{nom}} (p_2 R_2 + p_3 R_3 + q_2 X_2 + q_3 X_3) =$$

$$= \frac{1}{V_{nom}} \left[p_2 r_{(1-2)} + p_3 (r_{(1-2)} + r_{(2-3)}) + q_2 x_{(1-2)} + q_3 (x_{(1-2)} + x_{(2-3)}) \right]$$

$$\Delta V_{(1-4)} = \frac{1}{V_{nom}} (p_2 R_2 + p_4 R_4 + q_2 X_2 + q_4 X_4) =$$

$$= \frac{1}{V_{nom}} \left[p_2 r_{(1-2)} + p_3 (r_{(1-2)} + r_{(2-4)}) + q_2 x_{(1-2)} + q_4 (x_{(1-2)} + x_{(2-4)}) \right]$$

Generally, voltage drop is less than or equal admissible voltage drop ΔV_{adm} estimated approximately at 6÷8% of the rated voltage: $\Delta V \leq \Delta V_{adm} = (6 \div 8)\% V_{nom}$. If for example $\Delta V_{(1-3)} < \Delta V_{(1-4)}$, then $\Delta V_{adm} = \Delta V_{(1-3)}$.

2.1. Counting Minimum Spanning Trees

Suppose an undirected complete weighted planar graph $G = (V, E, W)$, where V , E and W represent respectively vertices, edges and edge's weight of G . A spanning tree is a subgraph G_T of G containing all the vertices of G and has no cycles (no loops). From G objective is to find a tree T , such that sum of weighted edges is minimal. Determining such tree T is called a minimal spanning tree problem. Kruskal's algorithm, an instance of MST, is based on sorting edge's weight in ascending order so that each edge with a minimum weight is added to the tree without forming a cycle [27]. Thus, Kruskal's algorithm grows the tree by adding one edge at a time. It selects the smallest edge that does not create a cycle and ensures the inequality $|MST| < V-1$ is satisfied such as $|MST|=E < V-1$, where $|MST|$ is the number of edges in obtained tree. From Figure 2a, by applying Kruskal's algorithm, a tree T of Figure 2b containing all vertices A, B, C and D is obtained with a minimal cost of 6.

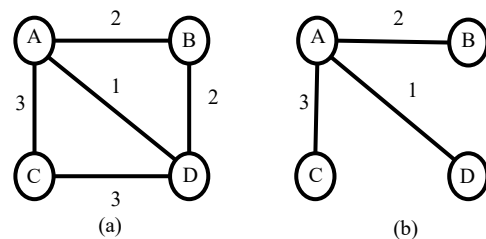


Figure 2. a) Undirected graph, b) Kruskal's minimum spanning tree

The number of spanning trees for an incomplete undirected weighted graph is obtained using Kirchhoff's spanning trees procedure, stated as follow [28]:

1. Create a square adjacency matrix $A[n][n]$ for the given graph, n corresponding to matrix dimension.
2. Create a square degree matrix $D[n][n]$ from the given graph. $D[n][n]$ is a diagonal matrix obtained from adjacency matrix where each diagonal element corresponds to vertex degree, the number of edges attached to each vertex, while non-diagonal elements are set to zero.
3. Calculate Laplacian matrix $L[n][n]$ by subtracting adjacency matrix from degree matrix: $L=D-A$
4. Calculate co-factor of any element in the Laplacian matrix, such as:

$$c_{ij} = (-1)^{i+j} \det(L_{ij}) = (-1)^{i+j} M_{ij}$$

where, c_{ij} is co-factor of element corresponding to row i and column j in $L[n][n]$, M_{ij} is minor of matrix $L[n][n]$, and co-factor c_{ij} is the number of spanning trees.

Let $minMST$ represents minimum cost of spanning tree and $countMST$ is the number of minimum spanning trees. For example, for the undirected weighted graph in Figure 2a obtained results are (nodes A, B, C and D correspond to rows 1, 2, 3 and 4 respectively in matrices A, D and L):

$$A = \begin{pmatrix} 0 & 2 & 3 & 1 \\ 2 & 0 & 0 & 2 \\ 3 & 0 & 0 & 3 \\ 1 & 2 & 3 & 0 \end{pmatrix}, D = \begin{pmatrix} 6 & 0 & 0 & 0 \\ 0 & 4 & 0 & 0 \\ 0 & 0 & 6 & 0 \\ 0 & 0 & 0 & 6 \end{pmatrix}, L = \begin{pmatrix} 6 & -2 & -3 & -1 \\ -2 & 4 & 0 & -2 \\ -3 & 0 & 6 & -3 \\ -1 & -2 & -3 & 6 \end{pmatrix}$$

$$N = c_{11} = \begin{pmatrix} 4 & 0 & -2 \\ 0 & 6 & -3 \\ -2 & -3 & 6 \end{pmatrix} = 84, \min MST = 6, \text{countMST} = 4$$

Among N 's spanning trees (ST), the four MST are numbered according to their order of classification in a N 's list are:

- ST 3: (A, C) (A, B) (A, D)
- ST 4: (A, C) (A, D) (B, D)
- ST 7: (B, D) (C, D) (A, D)
- ST 8: (C, D) (A, D) (A, B)

2.2. Proposed Method

To illustrate proposed method, consider a fictitious multi-feeders meshed distribution network operating radially containing sectionalizing switches and tie-switches, according to Figure 3a [6]. Feeders A, B and C supply, respectively zones (1, 2), (3, 4), and (5, 6). Switches are labelled according to zones they connect. In normal operation (Figure 3a), circuit breakers CB, A, CB B, CB, C and sectionalizing switches 12, 34, 56 are closed while tie-switches 13, 24, 35 and 46 are open. Loading capacity are 50 kVA and 45 kVA for feeders A and C, respectively. Zone load demands are in Figure 3a. After a default in zone 3, circuit breaker CB, B and tie-switches 13, 35 and sectionalizing switch 35 open to isolate this zone from network until it is restored. As consequence, zone 4 is unsupplied. Zone 4 can be supplied in radial structure from either feeder A or C by closing tie-switches 24 or 46, respectively, sectionalizing switches 12 and 56 remaining closed.

To ensure supplying zone 4, distribution network is formulated as a planar connected undirected weighted graph $G = (V, E, W)$ where V represents a load zone, E switches and W a weight associated to edges. On this graph edges related to sectionalizing switch will have same weight, edges related to tie-switch will have a slightly higher but same weight, and edges related to faulty zone will have prohibitive weights. Weights assigned to edges are considered as dimensionless. Figure 3b illustrates this graph state network representation where for simplicity sectionalizing and tie-switched are omitted, and weights are assigned as 1 and 2 to edges related to sectionalizing switch and tie-switches respectively, and 100 to edges connected to faulty zone 3. Adopted approach is to modify only tie-switches state, sectionalizing switches remaining closed.

In order to execute Kruskal's algorithm edges corresponding to sectionalizing switches/tie-switches already open between zones in normal operation will be re-established and to obtain minimum spanning tree where default zone is removed the criterion is $|MST| = E < V - 2$. In this case $N = 1$, $\min MST$ is 6 and countMST is 1.

Although a minimum spanning tree represented in Figure 3c is obtained, this configuration doesn't respect

operating radial structure constraint; feeders A and C are connected through zones 1, 2, 4, 6 and 5. To obtain radial configuration, binary decision tree is used where only tie-switches states will be altered, sectionalizing switches remaining closed. The binary decision variable x_n denotes the status (open or closed) of the n th tie-switch:

$$x_n = \begin{cases} 1 & \text{if the } n\text{-th tie-switch is closed} \\ 0 & \text{if the } n\text{-th tie-switch is open} \end{cases}$$

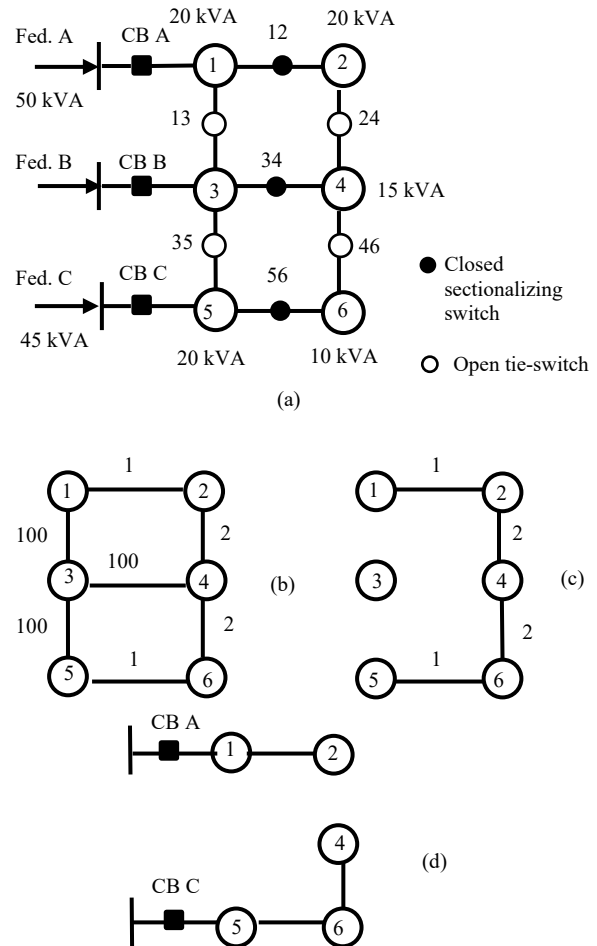


Figure 3. a) Fictitious meshed distribution network in normal operation [6], b) Distribution network graph representation after a default in Zone 3, c) Minimum spanning tree obtained from Kruskal's algorithm, d) Optimal radial structure configuration

In our case, since there are 2 binary decision variables x_{12} and x_{46} corresponding to two tie-switches 12 and 46, 2^2 tie-switches combinations states are obtained. In order to generalize, a set of closed tie-switches containing related binary decision variable is determined and decision table is then obtained in which each row corresponds to a combination of open/closed decision variables. Since switches are labelled according to zones they connect, the set of closed tie-switches is composed of zones belonging to different feeders. More generally, if there are m tie-switches, there will be 2^m combinations which can cause a combinatorial explosion. But since the number of tie-switches is generally much lower than sectionalizing switches, combinatorial explosion can be avoided (around few dozen or hundreds of cases).

However, for a multi-feeder's network with a significant number of zones, the number of combinations, although reduced, does not allow to determine radial configurations for each combination (that doesn't constitute a loop). To circumvent this difficulty and obtain radial structures, some heuristic rules are adopted. Nevertheless, these rules are quasi-optimal, adapted to some configurations and needing to be refined for others. These rules determine whether more than two zones belonging to two different feeders connected by a tie-switch according to the state of their respective circuit breakers (closed or open) constitute a circuit. From the set of closed tie-switches composed of zones belonging to different feeders, heuristic rules can be stated as follows:

• Rule 1: Direct Circuit Detection

If two zones belong to two different feeders, if these two zones are connected by a tie-switch belonging to closed tie-switches set, if circuit breakers in both zones are closed. Then a loop is detected.

• Rule 2: Indirect Circuit Detection

If two zones belong to two different feeders, if these two zones are connected by a tie-switch belonging to closed tie-switches set, if the circuit breaker of one of the two zone is closed and the other is open, if the zone whose circuit breaker is open is connected by a tie-switch belonging to closed tie-switches set to another zone of another feeder whose circuit breaker is closed. Then a loop is detected.

• Rule 3: Indirect Circuit Detection

If there is more than one zone belonging to the same feeder whose circuit breaker is open, if each of these zones is a member of closed tie-switches set, if each of these zones is connected to a zone of a different feeder whose circuit breaker is closed. Then a loop is detected.

• Rule 4: No Circuit Detection

If two zones belong to two different feeders, if these two zones are connected by a tie-switch belonging to closed tie-switches set, if the circuit breaker of one of the two zones is closed and the other is open, if the zone whose circuit breaker is open is not connected to any other zone of another feeder. Then no loop detected (probably radial configuration).

For Figure 3c, Table 1 resume tie-switches states according to binary decision variables x_{12} and x_{46} and rule 2. Two radial configurations are obtained and compared in pairs to find an optimal solution according to the maximum power delivered by each of the feeders A and C, each pair representing a potential solution:

1. (A -1-2-4) and (C -5-6)
2. (A -1-2) and (C -5-6-4)

The two radial configurations of first pair feeder A supplies zones 1, 2 and 4, and feeder C supplies zones 5 and 6, respectively, while for second pair the two radial configurations a supplies zones 1 and 2 and 4, and feeder C supplies zones 5, 6 and 4, respectively. Two options for selecting optimal configuration for each pair are possible: admissible voltage drop according to Equation (1), and/or Load Balancing Index (LBI) [6].

Table 1. Tie-switches binary decision variables

Combination	x_{12}	x_{46}	Decision
1	0	0	Excluded
2	0	1	Allowed
3	1	0	Allowed
4	1	1	Excluded

Lack of data about distribution network electrical lines characteristics (resistance and reactance particularly) doesn't allow to use equation (2), and since supplied power at each zone is known, LBI will be used. In accord to [6], LBI is a comparison indicator such as:

$$LBI = \frac{1}{n} \sum_{i=1}^n \sqrt{(y_{avg} - y_i)} \tag{2}$$

where, n is the number of active primary feeders, y_i is the normalized loading on feeder i and y_{avg} is the average of the normalized loadings y_i (actual loading divided by loading limit). LBIs of each configuration are compared to select optimal one, lowest index configuration (practically much lower than 1) being preferred. LBI_1 and LBI_2 for configurations 1 and 2 respectively are 0.0788 and 0.0707. Noticed that $LBI_2 < LBI_1$, therefore second configuration represents optimal solution (Figure 5d).

3. CASE STUDIES

Proposed method including Kruskal's algorithm and the heuristic rules is implemented in CLIPS [29], a programming language belonging to the declarative and logical language paradigm, designed primarily as a tool for the development of rule and object-based expert systems, in order to take advantage of its flexible structure representation of distribution network components and set manipulation functions. Kruskal's algorithm is implemented and integrated as an external function written in C language with CLIPS. Three cases are presented, a fictitious four feeders twenty zones [6], modified three feeders IEEE 16 bus system and IEEE 15 bus system single feeder [30].

3.1. Case 1

Figure 4a represents fictitious test meshed distribution network operating radially containing four feeders A, B, C and D associated with circuit breakers CB A, CB B, CB D and CB D, respectively. The network also includes normally closed sectionalizing switches and open tie-switches. Each feeder supplies zones connected by closed sectionalizing switches. Total MVA demand of each zone is listed in Table 2. The loading capacity of each feeder is 10 MVA. Consider a permanent fault in zone 7, breaker CB B cleared the fault (remaining open) and switches 5, 6, 18 and 22 were opened to isolate the faulted zone; as a consequence, zones 6, 8, 9 and 10 became no longer supplied. Operator's objective following fault in zone 7 is to ensure continuity supplying for healthy zones 6, 8, 9, and 10. Figure 4b represents undirected graph obtained when zone 7 is in default. Kruskal's algorithm finds configurations ensuring power supply zones that remain healthy from graph in Figure 4b. According to adopted method $minMST$ is 22 and $countMST$ is 60.

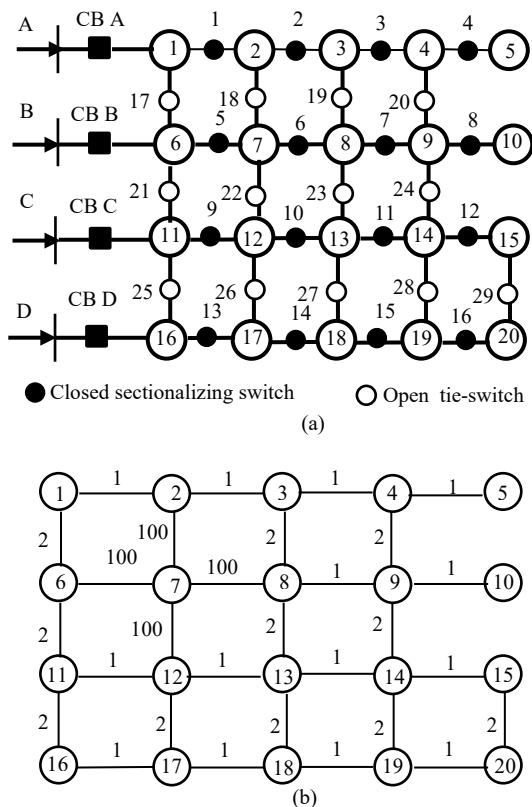


Figure 4. a) Fictitious 20 zones distribution network [6], b) Corresponding weighting undirected graph

Table 2. Zone loads [6]

Zone No.	Load	Zone No.	Load	Zone No.	Load	Zone No.	Load
1	1.6	6	1.5	11	3	16	1.5
2	0.7	7	1.5	12	3.5	17	2
3	1.8	8	1	13	0.7	18	1.8
4	0.5	9	0.5	14	1	19	1.5
5	1.9	10	0.8	15	0.6	20	0.5

Table 3 resumes results obtained from [24] where ST 5804 corresponding to a configuration obtained by Kruskal's algorithm:

Algorithm 1. Kruskal's algorithm

(3,8)(9,10)(8,9)(4,5)(3,4)(14,15)(11,16)(2,3)(11,12)
 (1,6)(1,2)(18,19)(17,18)(19,20)(13,14)(6,11)(12,13)
 (16,17)

Each number in parenthesis represents a zone and both correspond to switch between two zones. For instance, (3, 8) corresponds to tie-switch between zones 3 and 8 denoted by number 19 in Figure 4a. Obtained configuration doesn't respect radial structure constraint, closed tie-switches 17, 19, 21 and 25 forming loops between feeders A, C and D. Possibility to find configurations respecting radial structure constraint and service continuity, is to exploit obtained MST by binary decision tree application on closed tie-switches 17, 19, 21 and 25. The four decision variables x_{17} , x_{19} , x_{21} and x_{25} give 2^4 combinations. Applying heuristic rules, two combinations among the sixteen combinations are allowed and tabulated in Table 4, other combinations being

excluded (for simplicity, only combination 7 and 13 appear). Figures 5a and 5b resume these two configurations. LBIs being equals ($LBI_1 = LBI_2 = 0.0491$) for these two radial configurations, both can be considered as optimal.

Table 3. Network reconfiguration ST 5804

Switch	State	Switch	State	Switch	State
1	Closed	11	Closed	21	Closed
2	Closed	12	Closed	22	Open
3	Closed	13	Closed	23	Open
4	Closed	14	Closed	24	Open
5	Open	15	Closed	25	Closed
6	Open	16	Closed	26	Open
7	Closed	17	Closed	27	Open
8	Closed	18	Open	28	Open
9	Closed	19	Closed	29	Open
10	Closed	20	Open		

Table 4. Tie-switches binary decision variables for fictitious network

Combination	x_{17}	x_{19}	x_{21}	x_{25}	Decision
7	0	1	1	0	Allowed
13	1	1	0	0	Allowed

In comparison with [31], where breadth-first search technique is used with binary decision tree and binary decision variables, obtained results are quite similar with a greatly reduced number of combinations in our approach.

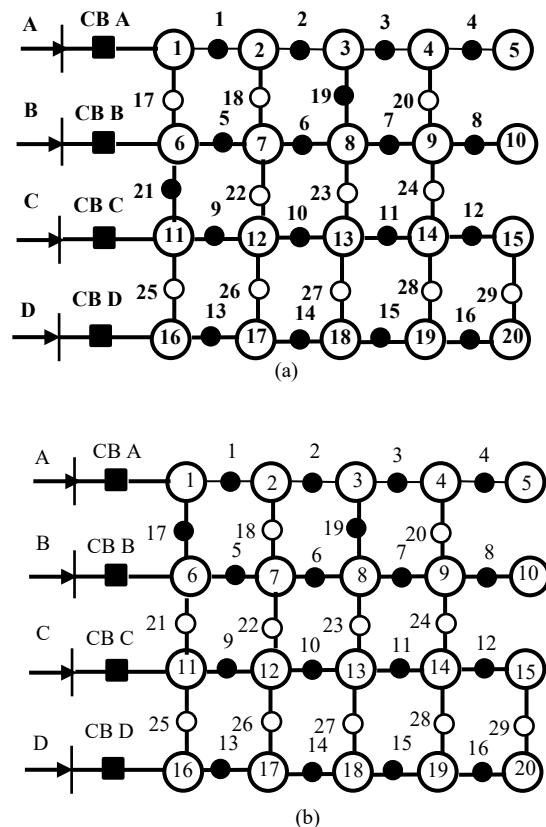


Figure 5. a) first radial configuration, b) second radial configuration for Fictitious 20 zones distribution network

Table 5 provides an overview of MST costs and number of MST for defaults on each zone of distribution

network of Figure 4a. To validate the proposed approach, in addition to the ST 7, nine additional MST were randomly selected: ST 15, ST 19, ST 20, ST 26, ST 31, ST 40, ST 50, ST 51 and ST 52. Table 6 resume allowed structure with minimum LBI for each MST combination. By calculating the standard deviation, it is possible to estimate whether the results obtained are within acceptable ranges. For n samples, standard deviation is expressed as:

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \mu)^2} \quad (3)$$

Table 5. MST number and MST cost on default on each zone for fictitious distribution network

Default Zone	costMST	minMST	Default Zone	costMST	minMST
1	265	23	11	212	23
2	130	24	12	287	24
3	170	24	13	412	24
4	NaN	NaN	14	207	24
5	520	23	15	416	23
6	105	22	16	416	23
7	60	22	17	312	24
8	120	23	18	416	24
9	NaN	NaN	19	312	24
10	520	23	20	416	23

Table 6. Allowable radial configurations for default in zone 7

	N	x_{17}	x_{19}	x_{21}	x_{25}	LBI
ST 7	7	0	1	1	0	0.0491
	N	x_{17}	x_{19}	x_{24}	x_{27}	LBI
ST 15	11	1	0	1	0	0.0491
	N	x_{17}	x_{19}	x_{23}	x_{28}	LBI
ST 19	11	1	0	1	0	0.0491
	N	x_{19}	x_{21}	x_{23}	x_{27}	LBI
ST 20	13	1	1	0	0	0.0491
	N	x_{17}	x_{20}	x_{24}	x_{27}	LBI
ST 26	13	1	1	0	0	0.0491
	N	x_{20}	x_{21}	x_{24}	x_{27}	LBI
ST 31	13	1	1	0	0	0.0491
	N	x_{17}	x_{20}	x_{23}	x_{29}	LBI
ST 36	13	1	1	0	0	0.0491
	N	X	x_{20}	x_{21}	x_{25}	LBI
ST 40	7	0	1	1	0	0.0491
	N	x_{17}	x_{21}	x_{23}	x_{26}	LBI
ST 51	11	1	0	1	0	0.1077
	N	x_{17}	x_{21}	x_{23}	x_{28}	LBI
ST 52	11	1	0	1	0	0.1077

Where, σ , μ , and x_i are standard deviation, average value of samples and value of each sample. From Table 6, $n=10$ and represents the total number of optimal configurations, x_i is the LBI value of the optimal configuration corresponding to each ST and μ is the average LBI value of the optimal configurations. From obtained results, $\mu=0.06082$, $\sigma=0.0247$, standard deviation is very small. Therefore, it can be concluded that for a default in zone 7 each of the 60 MST can be a potential solution.

3.2. Case 2

The IEEE 16 bus distribution system in Figure 6a operates at 12.66 kV and contains three feeders 1, 2 and 3 (data of this distribution system are in [30]). This network is modified according to Figure 6b where feeders 1, 2 and 3 becomes A, B and C, respectively, and zone 1 is

aggregate of buses 4 and 5, zone 4 is aggregate of buses 8 and 10, zone 5 is aggregate of buses 9 and 11, zone 7 is aggregate of buses 13 and 14. Buses 6, 7, 12, 15 and 16 renamed as zone 2, 3, 6, 8 and 9, respectively. Added branches representing tie-switches have electrical characteristic of original branch 6-7 in [30], $R=0.0250$ (pu) and $X=0.0250$ (pu), base quantities are $U_b=12.66$ kV $S_b=100$ MVA. Corresponding weighted undirected planar graph to Figure 6b is in Figure 7. Total active and reactive demand of each zone is listed in Table 7. Tables 8 and 9 provide an overview of $minMST$ and $countMST$, MST and binary decision variables, respectively, for defaults on each zone of distribution network of Figure 7.

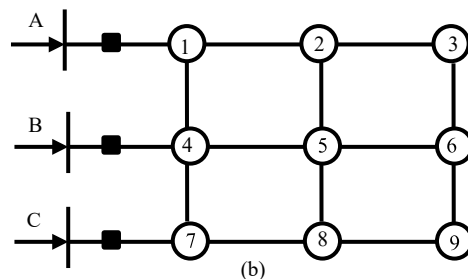
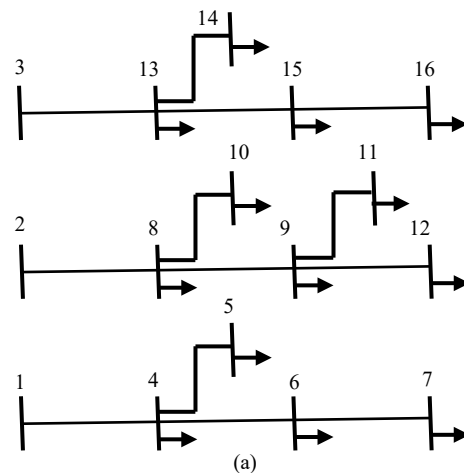


Figure 6. a) Original [30], b) modified IEEE 16 bus distribution system

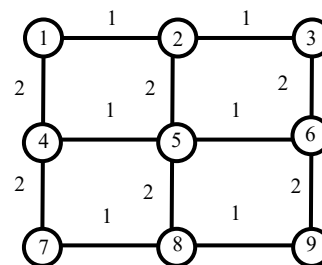


Figure 7. Undirected weighted graph of modified IEEE 16 bus distribution system

For each default zone's ST in Table 9 corresponds an MST and according to binary decision variable to this MST one or more radial configurations can be obtained by applying heuristics rules.

Table 7. Load demand of modified IEEE 16 bus [30]

Zone	P_L (kW)	Q_L (kVAR)	Zone	P_L (kW)	Q_L (kVAR)
1	5004.56	2006.26	6	4500	-1700
2	2000	-400	7	2001.23	-198.34
3	1500	1200	8	1000	900
4	5001.23	3601.23	9	2100	-800
5	5600.41	1300.41			

Table 8. MST numbers and MST cost on default on each zone in modified IEEE 16 bus

Default Zone	minMST	costMST	Default Zone	minMST	costMST
1	6	9	6	4	9
2	3	10	7	6	9
3	6	9	8	3	10
4	4	9	9	6	9
5	4	10			

For example, in default zone 5, for each MST two radial configurations are obtained from Table 10 where each combination N corresponds to a radial configuration according to binary decision variables values (other combinations are excluded). Some radial configurations are identical as represented in Figure 8. Voltage drops for each section of the four STs are:

- $\Delta V_{(C-9)} = 68.017$ V; $\Delta V_{(C-6)} = 123.721$ V
- $\Delta V_{(C-4)} = 117.595$ V; $\Delta V_{(A-3)} = 117.379$ V
- $\Delta V_{(A-4)} = 130.808$ V; $\Delta V_{(A-6)} = 332.555$ V

Based on obtained results, all voltage drops are below admissible voltage drop $\Delta V_{adm} = 0.7596$ kV \div 1.0128 kV. However, pair of configurations ST 1-ST 2 can constitute a potential solution. Table 11 resume voltage drops for radial configurations obtained by applying heuristics rules in other zones.

Table 10. Radial configurations according binary decision variables for a default in zone 5

	N	$x_{(1-4)}$	$x_{(4-7)}$	$x_{(6-9)}$
ST 1	3	0	1	1
	5	1	0	1
ST 2	3	0	1	1
	6	1	1	0
ST 3	5	1	0	1
	6	1	1	0
ST 4	3	0	1	1
	6	1	1	0

3.3. Case 3

Figure 9 represents IEEE 15 bus subsystem distribution network used for this case. It operates at a nominal voltage $V_{nom} = 11$ kV, with fifteen (15) buses, fourteen (14) branches and a single feeder in bus 1 (solid lines in Figure 9). Distribution network data characteristics can be found in reference [30]. Modifications have been made by adding branches to reconfigure network in a case of fault occurrence (hashed lines in Figure 9). Added branches (5-14), (7-11), (8-15), (10-14) and (13-15) have characteristics chosen from branch (3-4), such that $R = 0.4827$ (p.u) and $X = 0.4722$ (p.u). Solid lines represent sectionalizing switches, while hashed lines represent tie-switches. Under normal operating conditions, added branches are normally open.

Table 9. MST and binary decision variables on default on each zone in modified IEEE 16 bus

Default zone	ST	MST	Binary decision variables
1	1	(7,8)(5,8)(5,6)(4,5)(2,5)(2,3)(8,9)	(5-8) (2-5)
	2	(7,8)(5,8)(5,6)(4,5)(3,6)(2,3)(8,9)	(5-8) (3-6)
	3	(7,8)(4,5)(2,5)(2,3)(6,9)(8,9)(5,6)	(6-9) (2-5)
	4	(7,8)(4,5)(2,5)(2,3)(4,7)(8,9)(5,6)	(4-7) (2-5)
	5	(7,8)(4,5)(3,6)(6,9)(5,6)(8,9)(2,3)	(3-6) (6-9)
	6	(7,8)(4,5)(3,6)(2,3)(4,7)(8,9)(5,6)	(3-6) (4-7)
2	1	(6,9)(8,9)(7,8)(1,4)(3,6)(4,5)(5,6)	(1-4)(3-6) (6-9)
	2	(1,4)(3,6)(5,6)(7,8)(5,8)(8,9)(4,5)	(1-4)(3-6) (5-8)
	3	(1,4)(3,6)(5,6)(7,8)(8,9)(4,5)(4,7)	(1-4)(3-6) (4-7)
3	1	(8,9)(7,8)(4,7)(4,5)(1,4)(1,2)(5,6)	(4-7) (1-4)
	2	(8,9)(7,8)(4,7)(4,5)(2,5)(5,6)(1,2)	(4-7) (2-5)
	3	(8,9)(7,8)(1,4)(1,2)(5,6)(5,8)(4,5)	(1-4)(5-8)
	4	(8,9)(7,8)(1,4)(1,2)(5,6)(4,5)(6,9)	(1-4)(6-9)
	5	(8,9)(7,8)(4,5)(2,5)(5,6)(5,8)(1,2)	(2-5)(5-8)
	6	(8,9)(7,8)(4,5)(2,5)(5,6)(1,2)(6,9)	(2-5)(6-9)
4	1	(7,8)(5,8)(5,6)(2,5)(2,3)(1,2)(8,9)	(5-8) (2-5)
	2	(7,8)(5,8)(5,6)(1,2)(3,6)(2,3)(8,9)	(5-8) (3-6)
	3	(7,8)(1,2)(2,5)(6,9)(8,9)(2,3)(5,6)	(6-9) (2-5)
	4	(7,8)(1,2)(6,9)(8,9)(5,6)(3,6)(2,3)	(6-9) (3-6)
5	1	(6,9)(8,9)(7,8)(4,7)(1,4)(1,2)(2,3)	(6-9)(4-7)(1-4)
	2	(6,9)(8,9)(7,8)(4,7)(3,6)(2,3)(1,2)	(6-9)(4-7)(3-6)
	3	(6,9)(8,9)(7,8)(3,6)(2,3)(1,2)(1,4)	(6-9) (3-6) (1-4)
	4	(3,6)(2,3)(1,2)(1,4)(4,7)(7,8)(8,9)	(3-6) (1-4) (4-7)
6	1	(8,9)(7,8)(4,7)(4,5)(1,4)(1,2)(2,3)	(4-7)(1-4)
	2	(8,9)(7,8)(4,7)(4,5)(2,3)(2,5)(1,2)	(4-7)(2-5)
	3	(8,9)(7,8)(2,3)(5,8)(1,4)(1,2)(4,5)	(1-4) (1-2)
	4	(8,9)(7,8)(2,3)(5,8)(4,5)(2,5)(1,2)	(2-5) (1-2)
7	1	(8,9)(5,8)(5,6)(4,5)(1,4)(1,2)(2,3)	(5-8) (1-4)
	2	(8,9)(5,8)(5,6)(4,5)(2,5)(2,3)(1,2)	(5-8) (2-5)
	3	(8,9)(5,8)(5,6)(4,5)(1,2)(3,6)(2,3)	(5-8) (3-6)
	4	(8,9)(4,5)(1,4)(2,3)(6,9)(5,6)(1,2)	(1-4)(6-9)
	5	(8,9)(4,5)(6,9)(5,6)(3,6)(1,2)(2,3)	(6-9)(3-6)
	6	(8,9)(4,5)(6,9)(5,6)(1,2)(2,5)(2,3)	(6-9)(2-5)
8	1	(3,6)(5,6)(4,7)(4,5)(6,9)(1,2)(2,3)	(3-6) (4-7) (6-9)
	2	(4,7)(6,9)(2,3)(4,5)(2,5)(5,6)(1,2)	(4-7) (6-9) (2-5)
	3	(4,7)(6,9)(2,3)(4,5)(5,6)(1,2)(1,4)	(4-7) (6-9) (1-4)
9	1	(5,6)(7,8)(4,7)(4,5)(1,4)(1,2)(2,3)	(4-7)(1-4)
	2	(5,6)(7,8)(4,7)(4,5)(2,5)(2,3)(1,2)	(4-7) (2-5)
	3	(5,6)(7,8)(4,7)(4,5)(1,2)(3,6)(2,3)	(4-7)(3-6)
	4	(5,6)(7,8)(5,8)(1,4)(2,3)(1,2)(4,5)	(5-8) (1-4)
	5	(5,6)(7,8)(5,8)(3,6)(4,5)(1,2)(2,3)	(5-8) (3-6)
	6	(5,6)(7,8)(5,8)(4,5)(1,2)(2,5)(2,3)	(5-8) (2-5)

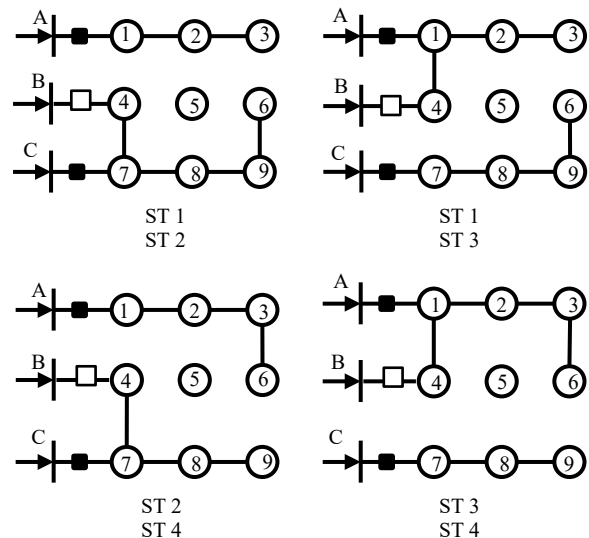


Figure 8. Radial configurations from Table 8

Table 11. Voltage drops in radial configurations of modified IEEE 16 bus

Default Zone	ST	Section	C-9	B-3	B-6	
1	ST1	Section	C-9	B-3	B-6	
		$\Delta V(V)$	68.017	269.874	232.961	
	ST2	Section	C-9	B-2		
		$\Delta V(V)$	68.017	410.290		
2	ST1	Section	C-9	B-3	B-1	
		$\Delta V(V)$	68.017	304.751	149.423	
3	ST1	Section	C-9	B-2		
		$\Delta V(V)$	68.017	185.290	232.961	
	ST5	Section	C-9	B-1	B-6	
		$\Delta V(V)$	68.017	405.684	232.961	
4	ST1	Section	C-9	C-6	C-5	
	ST2	$\Delta V(V)$	68.017	235.24	320.682	
	ST3	Section	A-3	A-5	A-6	
	ST4	$\Delta V(V)$	117.379	130.808	332.555	
6	ST1	Section	C-9	C-6	C-5	C-4
	ST2	$\Delta V(V)$	68.017	123.721	246.042	117.595
	ST3	Section	A-3	A-4	A-5	
	ST4	$\Delta V(V)$	117.379	130.808	242.778	
7	ST1	Section	A-3	B-9	B-6	
		$\Delta V(V)$	117.379	243.802	232.961	
	ST4	Section	A-3	B-8		
		$\Delta V(V)$	117.379	317.799		
8	ST1	Section	C-9	B-3	B-1	
		$\Delta V(V)$	68.017	304.751	149.723	
9	ST1	Section	A-3	B-8	B-6	
		$\Delta V(V)$	117.379	137.690	232.961	
	ST4	Section	A-3	B-6	B-7	
		$\Delta V(V)$	117.379	232.961	261.168	

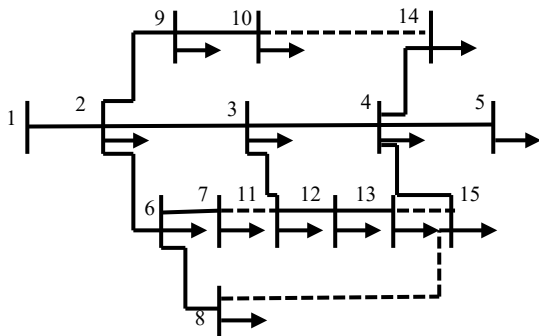


Figure 9. IEEE 15 bus distribution network [30]

Assume a default in bus 4 after which this bus is isolated from the rest of the network. Thus, buses 5, 14 and 15 are no longer supplied, even though they are not faulty. Figure 10a represents the undirected graph associated to distribution network according to adopted method. In this *minMST* is 16 and *countMST* is 2. Figure 10b-c represent obtained MST configurations ST 17 and ST 26, later one corresponding to Kruskal's algorithm application:

2. Algorithm Kruskal's

ST 17:(12,13)(13,15)(5,14)(10,14)(9,10)(2,9)(1,2) (11,12)(6,7)(3,11)(2,3)(2,6)(6,8)
ST 26: (12,13)(5,14)(10,14)(9,10)(2,9)(1,2)(11,12) (6,8)(8,15)(6,7)(3,11)(2,3)(2,6)

Network sections (1-5), (1-7), (1-8) and (1-15) voltage drops in (p.u) for ST 17 are in Table 12. For ST 26 network sections (1-5), (1-7) (1-13) and (1-15) voltage drops in

(p.u) are in Table 13. Voltage drops in considered sections are within the allowable voltage limit and configuration ST 26 is selected for distribution network reconfiguration.

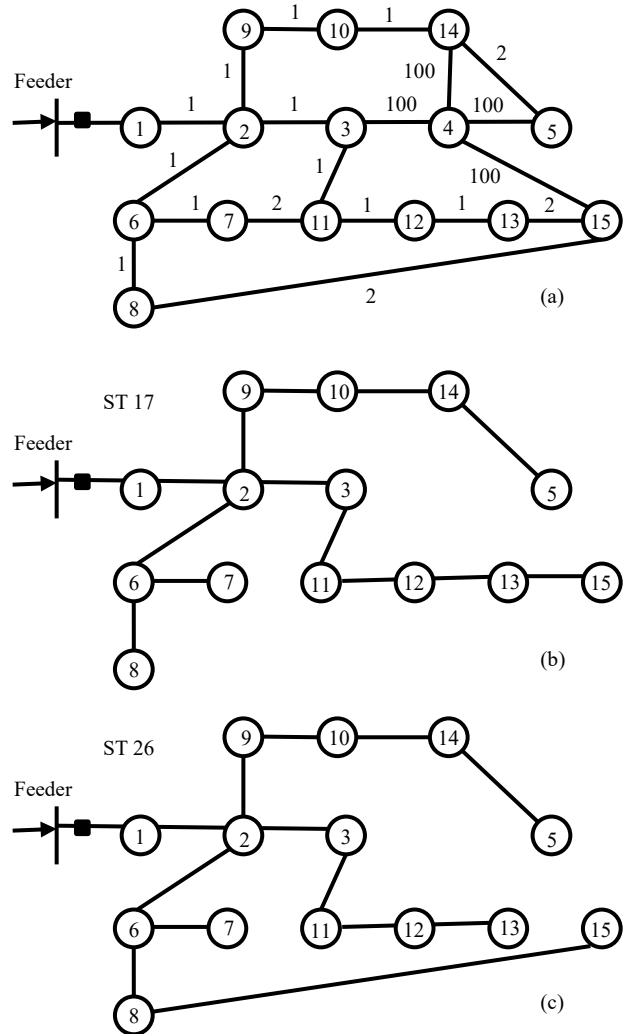


Figure 10. a) IEEE 15 bus network graph, b,c) Related Minimum Spanning Trees: ST 17, ST 26

Table 12. ST 17 Voltage drops

$\Delta V_{(1-5)}$	$\Delta V_{(1-7)}$	$\Delta V_{(1-8)}$	$\Delta V_{(1-15)}$
0.0254	0.0253	0.0229	0.0409

Table 13. ST 26 Voltage drops

$\Delta V_{(1-5)}$	$\Delta V_{(1-7)}$	$\Delta V_{(1-13)}$	$\Delta V_{(1-15)}$
0.0254	0.0253	0.0292	0.0346

4. CONCLUSIONS

Distribution network reconfiguration after a default is one of the challenges for operators. Reconfiguration can be obtained by state's switches modification while respecting operating constraints as admissible voltage limit, maximizing number of restored loads, minimizing power loss and maintaining network radial structure. An optimal solution is not sought during first phase of the reconfiguration due to combinatorial explosion due to

switches open/close actions. In this case, operators focus on a configuration respecting radial network structure (overloaded or not and feeding all loads) and admissible voltage limit constraints.

Kruskal's algorithm, a minimum spanning tree instance, associated to Kirchhoff's algorithm to count MST, allows solving this problem by considering distribution network as a related undirected planar weighted connected graph and assigning dimensionless weights to links (considered as sectionalizing and tie-switches). However, resulting configuration may not respect radial structure constraint, particularly for distribution network with multiple feeders. In this case, heuristics rules are used in conjunction with binary decision tree notion to determine tie-switches that can create loops after applying Kruskal's algorithm. Obtained results on fictitious multi-feeder distribution network, modified three feeders IEEE 16 bus and IEEE 15 bus single feeder distribution systems test cases largely meet the assigned objectives: a radial network structure with voltages respecting admissible limits.

REFERENCES

- [1] H. Wu, P. Dong, M. Liu, "Distribution Network Reconfiguration for Loss Reduction and Voltage Stability with Random Fuzzy Uncertainties of Renewable Energy Generation and Load", *IEEE Transactions on Industrial Informatics*, Vol. 16, Issue 9, pp. 5655-5666, September 2020.
- [2] P. Prabawa, D.H. Choi, "Multi-Agent Framework for Service Restoration in Distribution Systems with Distributed Generators and Static/Mobile Energy Storage Systems", *IEEE Access*, Vol. 8, pp. 51736-51752, March 2020.
- [3] S.A. Heydari, T. Heydarzadeh, Naser M. Tabatabaei, "A Combined Approach for Loss Reduction and Voltage Profile Improvement in Distribution Systems", *International Journal on Technical and Physical Problems of Engineering (IJTPE)*, Issue 26, Vol. 8, No. 1, pp 30-35, March 2016.
- [4] F. Shen, Q. Wu, S. Huang, J.C. Lopez, C. Li, "Review of Service Restoration Methods in Distribution Networks", *The 8th IEEE PES Innovative Smart Grid Technologies Conference IEEE*, pp. 1-6, Sarajevo, Bosnia and Herzegovina, October 2018.
- [5] A.E.B. Abu Elanien, M.M.A. Salama, et al., "Modern Network Reconfiguration Techniques for Service Restoration in Distribution Systems: A Step to a Smarter Grid", *Alexandria Engineering Journal*, Vol. 57, pp. 3959-3967, March 2018.
- [6] A.L. Morelato, A. Monticelli, "Heuristic Search Approach to Distribution System Restoration", *IEEE Transactions on Power Delivery*, Vol. 4, No. 4, pp. 2235-2239, October 1989.
- [7] S. Eng, O. Penangsang, R.S. Wibowo, "Distribution System Restoration Using Spanning Tree Based on Depth First Search Visual in GUI", *The 5th Int. Conference on Science and Technology (ICST)*, pp. 1-6, Yogyakarta, Indonesia, 2019.
- [8] N. Swarnkar, N. Gupta, K. Niazi, "A Novel Codification for Meta-Heuristic Techniques Used in Distribution Network Reconfiguration", *Electric Power Systems Research*, Vol. 81, Issue 7, pp. 1619-1626, April 2011.
- [9] Y.Y. Hong, S.Y. Ho, "Determination of Network Configuration Considering Multi-Objective in Distribution Systems Using Genetic Algorithms", *IEEE Transactions on Power Systems*, Vol. 20, No. 2, pp. 1062-1069, May 2005.
- [10] A. Abdelaziz, F. Mohamed, S. Mekhamer, M. Badr, "Distribution System Reconfiguration Using a Modified Tabu Search Algorithm", *Electric Power Systems Research*, Vol. 80, Issue 8, pp. 943-953, January 2010.
- [11] E. Carpaneto, G. Chicco, "Distribution System Minimum Loss Reconfiguration in the Hyper-Cube Ant Colony Optimization Framework", *Electric Power Systems Research*, Vol. 78, Issue 12, pp. 2037-2045, (Special Issue Papers Presented at the 6th World Energy System Conference, 6th World Energy System Conference), Torino, Italia, July 2008.
- [12] W.C. Wu, M.S. Tsai, F.Y. Hsu, "A New Binary Coding Particle Swarm Optimization for Feeder Reconfiguration", *Proc. Int. Conf. Intelligent Systems Applications to Power Systems ISAP*, pp. 1-6, Kaohsiung, Taiwan, November 2007.
- [13] M.H.M. Camillo, R.Z. Fanucchi, M.E.V. Romero, "Determination of Switching Sequence of Service Restoration in Distribution Systems: Application and Analysis on a Real and Large-Scale Radial System", *IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, pp. 991-995, Texas, USA, May 2016.
- [14] R.A. Jabr, R. Singh, B.C. Pal, "Minimum Loss Network Reconfiguration Using Mixed-Integer Convex Programming", *IEEE Transactions on Power System*, Vol. 27, Issue 2, pp. 1106-1115, May 2012.
- [15] J.A. Taylor, F.S. Hover, "Convex Models of Distribution System Reconfiguration", *IEEE Transactions on Power System*, Vol. 27, Issue 3, pp. 1407-1413, August 2012.
- [16] S. Poudel, A. Dubey, "A Graph-theoretic Framework for Electric Power Distribution System Service Restoration", *IEEE Power and Energy Society General Meeting (PESGM)*, pp. 1-5, Portland, USA, August 2018.
- [17] M. Gholami, J. Moshtagh, N. Ghadernejad, "Service Restoration in Distribution Networks Using Combination of Two Heuristic Methods Considering Load Shedding", *Journal of Modern Power Systems and Clean Energy*, Vol. 3, Issue 4, pp. 556-564, July 2015.
- [18] T.D. Sudhakar, K.N. Srinivas, "Power System Restoration Based on Kruskal's Algorithm", *The 1st International Conference on Electrical Energy Systems (ICEES)*, pp. 281-287, Chennai, Tamil Nadu, India, January 2011.
- [19] H. Mohamed, W.I. Faezi, N.A. Salim, S. Shahbudin, Z.M. Yasin, "Power System Restoration in Distribution Network Using Minimum Spanning Tree-Kruskal's Algorithm", *Indonesian Journal of Electrical Engineering and Computer Science*, Vol. 16, No. 1, pp. 1-8, October 2019.

[20] H. Ahmadi, J.R. Marti, "Minimum-Loss Network Reconfiguration, A Minimum Spanning Tree Problem", Sustainable Energy, Grids and Networks, Vol. 1, pp. 1-9, 2015.

[21] D. Sarkar, D. Abhinandan, C. Chandan Kumar, S. Goswami, "Kruskal's Maximal Spanning Tree Algorithm for Optimizing Distribution Network Topology to Improve Voltage Stability", Electric Power Components and Systems, Vol. 43, Issue 17, pp. 1921-1930, 2015.

[22] S. Dipu, K. Pushpanjalee, D. Abhinandan, G. Sanjay, "A Graph Theory Application for Fast and Efficient Search of Optimal Radicalized Distribution Network Topology", Journal of King Saud University - Engineering Sciences, pp. 1-10, February 2019.

[23] S. Dimitrijevic, N. Rajakovic, "An Innovative Approach for Solving the Restoration Problem in Distribution Networks", Electric Power Systems Research, Vol. 81, Issue 10, pp. 1961-1972, July 2011.

[24] M. Habibi, M. Kazemi, "Intelligent Reconfiguration of Distribution Networks Via Harmony Search Algorithm", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 18, Vol. 6, No. 1, pp. 131-134, March 2014.

[25] D.E. Knuth, "The Art of Computer Programming, (Combinatorial Algorithms, Part 1)", Addison-Wesley, 4th Edition, Vol. A, pp. 464-465, Massachusetts, USA, 2011.

[26] Matthias Hotz, (2023) "generateSpanningTrees(A)", www.mathworks.com/matlabcentral/fileexchange/53787-generatespanningtrees-a, MATLAB Central File Exchange.

[27] J.B. Kruskal, "On the Shortest Spanning Subtree of a Graph and the Traveling Salesman Problem", The American Mathematical Society, Vol. 7, Issue 1, pp. 48-50, February 1956.

[28] M. Chakraborty, S. Chowdhury, J. Chakraborty, R. Mehera, R. Kumar Pal, "Algorithms for Generating all Possible Spanning Trees of a Simple Undirected Connected Graph: An Extensive Review", Complex and Intelligent Systems, Vol. 5, Issue 3, pp. 265-281, 2018.

[29] https://sourceforge.net/projects/clipsrules/files/CLIP_S/6.30/

[30] Y. Latreche, H.R.E.H. Boucekara, K. Naidu, H. Mokhlis, W.M. Dahalan, "Comprehensive Review of Radial Distribution Test Systems", TechRxiv, Preprint., pp. 1-65, 2020.

[31] K.P. Swaroop, D.P. Garapati, P.K. Nalli, S.S. Duvvuri, "Service Restoration in Distribution System Using Breadth-First Search Technique", The 7th International Conference on Electrical Energy Systems (ICEES), pp. 403-407, 2021.

BIOGRAPHIES



Name: Lahouari

Surname: Zerna

Birthday: 20.08.1962

Birthplace: Oran, Algeria

S.E. Degree: Electrotechnics, University of Science and Technology of Oran, Oran, Algeria, 1988

Master: Electrotechnics, University of Science and Technology of Oran, Oran, Algeria, 1991

Doctorate: Electrotechnics, Artificial Intelligence applied to Power Systems Restoration, University of Science and Technology of Oran, Oran, Algeria, 2017

The Last Scientific Position: Senior Lecturer, Electrical Engineering, Department of Electrotechnics, Electrical Engineering Faculty, University of Science and Technology of Oran, Oran, Algeria, Since 1991

Scientific Publications: 1 Paper

Research Interests: Artificial Intelligence Technics application on Power System Restoration, Expert Systems and Machine Learning Particularly



Name: Lahouari

Surname: Kotni

Birthday: 04.05.1954

Birthplace: Oran, Algeria

S.E.: Electrotechnics, University of Science and Technology of Oran, Oran, Algeria, 1979

Doctorate: Power Systems, Power Engineering Institute (MPEI), Moscow, Russia, 1985

The Last Scientific Position: Prof., Electrical Engineering, Department of Electrotechnics, Electrical Engineering Faculty, University of Science and Technology of Oran, Oran, Algeria, Since 1987

Scientific Publications: 4 Papers, 15 Theses

Research Interests: Power Systems, Design of Electrical Overhead Lines, Thermal and Mechanical Strength Calculation of Overhead Transmission Lines