Identification of optimal path through Network Reconfiguration in Distribution System

P L Nongkynrih[1], Rishandonborlang Mawrie[2], Lyon Ch Marak[3], Pushpanjalee Konwar[4], Mriganka Gogoi[5]

[1,2,3,4] Department of Electrical and Electronics Engineering, School of Technology, Assam Don Bosco University
Airport Road, Azara, Guwahati-781017, Assam, INDIA
[1]meo.awezomenatz@gmail.com, [2]sakaenoch8@gmail.com, [3]lyonmarak14@gmail.com,*
[4]pushpanjalee.konwar@dbuniversity.ac.in

[5]Department of Electronics and Communication Engineering, School of Technology, Assam Don Bosco University,
Airport Road, Azara, Guwahati -781017, Assam, INDIA.
[5]mriganka.gogoi@dbuniveristy.ac.in

Abstract: ***Network Reconfiguration is basically the changing the topological structure of the tie and sectionalizing switches. Distribution Networks are operated either in meshed or in radial configuration. Optimal reconfiguration of a primary meshed distribution network results in better performances and minimizing the overall conductor length during installation. The search for the optimal radial reconfigured network from a large number of feasible configuration is done by the selection of the best set of switches on the feeders that are to be opened or closed so that each existing feeder can be operated close to its optimal load-ability limit and the resulting optimal network is supposed to operate at lowest power loss and overall highest voltage stability index. This theoretical concept is however difficult to implement in practice due to heavy computational burden and unacceptably long search durations, therefore Heuristic search approaches are more common. In the project, we use Edmond's Maximal Spanning Tree Algorithm to achieve an optimal solution.***

Keywords: Edmond's Maximal Spanning Tree algorithm; Kruskal's algorithm; Radial Distribution Network; Voltage Stability.

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1. Introduction

The Optimal Power Flow (OPF) problems were first defined in the early 1960's as a supplement of the standard viable dispatch problem. The OPF problems require determination of the optimal settings of control variables subject to the operating constraints such that the operating costs are minimized. As a result of the continuous research efforts over the last three and a half decades, the OPF algorithms have significantly matured alongside developments in the other areas of technology. Modern OPF algorithms cover both real and reactive power dispatch and can solve very large and complex formulations in a relatively short time, the OPF algorithms are constantly reviewed, and newer methods are evolved in a continuous effort to address these new concerns and better the existing methods. The activities of optimal reactive power planning of a power system assume significance in view of their overbearing financial and operational implications. Proper reactive power planning has a wide-ranging effect on the operation and control of power system. Voltage security and voltage stability of a power system are profoundly affected by reactive power planning. System voltage profile, transmission loss, etc. are among many that can be improved by effective network reconfiguration.

In this paper, Edmonds Maximal Spanning Tree Algorithm has been proposed to generate optimal radial network from a Meshed network, which may be considered a step forward as it consumes less time and delivers a more effective solution to the problem.

2. Background Theory

2.1 Voltage Stability Assessment by L-Indicator

In the present study, the single–feeder equivalence method of distribution network consisting of multiple Feeders has been used for voltage stability assessment. The single feeder system is illustrated in Figure 1.

Figure 1: Single feeder

Where, P = Injected Real Power,
Q = Injected Reactive Power, r = Resistance of Feeder; V_s= Sending End Voltage, V_R = Receiving end voltage, X = Reactance of Feeder, δ_1 and δ_2 are phase angles.

From Figure1, the current flowing through the branch, $I = \frac{V_S\angle\delta_1 - V_R\angle\delta_2}{R+jX}$ …..(1)

$P - jQ = V_R^* I$, substituting value of I from eqn.(1):

$\therefore$ P - jQ = $\frac{V_S V_R\angle(\delta_1-\delta_2)-V_R^2}{R+jX}$

(P - jQ)(R + jX) = $V_S V_R\angle(\delta_1 - \delta_2) - V_R^2$

V_R^2 + (RP+XQ) + j(XP-RQ) = $V_S V_R\angle\delta_1 - \delta_2$ …(2)

The real term of the above equation is

$V_S V_R \cos(\delta_{1-}\delta_2) = V_R^2 + (RP + XQ)$ ………(3)

The imaginary term is

$V_S V_R \sin(\delta_1 - \delta_2) = XP - RQ$ ……………..(4)

Squaring and adding eqn.(3) and eqn.(4), we get

$V_R^4 + V_R^2(2RP + 2XQ - V_S^2) + (P^2 + Q^2)R^2X^2 = 0$

The above equation is a quadratic equation of V_R^2

The system is stable if $V_R^2 \geq 0$. It is attainable when $b^2 - 4ac \geq 0$

i.e., $[2(RP+XQ)-V_S^2)]^2-4(P^2 + Q^2)(R^2 + X^2) \geq 0$

Simplifying the above equation, we get

$4(PX-RQ)^2 + 4V_S^2(RP+XQ) \leq V_S^4$ …………(5)

Dividing both sides of eqn.(5) by V_S^4, we get

$4[\frac{PX-RQ}{V_S^2}]^2 + 4[\frac{RP+XQ}{V_S^2}] \leq 1$

$\therefore L_{INDEX} \leq 1$

Where, $L_{INDEX} = 4[\frac{PX-RQ}{V_S^2}]^2 + 4[\frac{RP+XQ}{V_S^2}]$ ……(6)

The stability index (L_{INDEX}) ranges between 0 to 1, with the value close to '0' indicates stable systems and a value closer to '1' indicates the possibility of voltage collapse.

2.2 Reconfiguration Strategy

A 4-node distribution power network is shown in Figure2 may be considered to illustrate the proposed reconfiguration strategy.

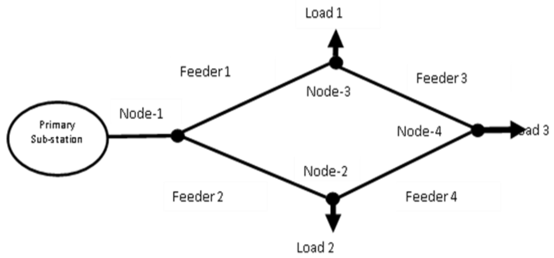

Figure 2: A 4-node mesh Distribution System

Considering the reactances (p.u.) of Feeder-1, Feeder-2, Feeder-3, Feeder-4 to be X_1, X_2, X_3, X_4 respectively and voltages (p.u.) at node 1, node 2, node 3 and node 4 to be $V_1\angle\theta_1$, $V_2\angle\theta_2$, $V_3\angle\theta_3$, $V_4\angle\theta_4$ respectively, the load carrying capability of feeders 1 to 4 can be formulated as:

$$LC_1 = \left| \left(\frac{V_1 V_3}{X_1}\right) \sin(\theta_1 - \theta_3) \right| \quad \text{……………………..(7)}$$

$$LC_2 = \left| \left(\frac{V_1 V_2}{X_2}\right) \sin(\theta_1 - \theta_2) \right| \quad \text{……………………...(8)}$$

$$LC_3 = \left| \left(\frac{V_3 V_4}{X_3}\right) \sin(\theta_3 - \theta_4) \right| \quad \text{……………………...(9)}$$

$$LC_4 = \left| \left(\frac{V_2 V_4}{X_3}\right) \sin(\theta_2 - \theta_4) \right| \quad \text{…………………….(10)}$$

Also, let us consider that the load carrying capabilities of feeder-1 to feeder-4 are in decreasing order. Since, the load carrying capability of the feeder-4 is the minimum, while forming a radial network, as shown in Figure 3, the most desirable option would be opening the sectionalizing switch of feeder-4. The power will be fed to node 4 via feeder-3, in that case. Under this condition, the feeder-3 shall not become overloaded, provided, the load carrying capability of the feeder-3 is greater than approximately the sum of power flow through feeder-3 and feeder-4 before the opening of the switch. The new radial configuration ensures that all the feeders have higher load carrying capability than earlier.

In the present study, Edmond's Maximal Spanning Tree algorithm has been successfully utilized to achieve this goal for larger networks with the help of the Cost Matrix of the edges of the graph corresponding to the network. The generalized Cost Matrix(Weight matrix) for an 'n' node distribution network is of size n × n and a_{ij} presents a cost- matrix element which refers to the load carrying capability(p.u.) of the feeder connected between nodes i and j node. The Edmond's Maximal Spanning Tree search a radial network having feeders with a higher load carrying capacity, and rejects those with lower load carrying capacity.

Thus, in the proposed technique sectionalizing switches on the feeders would be opened in such manner that the feeders with load carrying capabilities in descending order are selectively chosen and the lower load carrying capability feeders are kept out of service by opening sectionalizing switches.

The present problem can, therefore, be formulated as a multi-objective optimization problem to achieve the goals of low overall power loss and maximum overall voltage stability under given operating condition, subject to the constraints that none of the nodes is left isolated or supply of power to each and every load is ensured, and power flow through none of the feeders exceeds the maximum power transfer capability limit. The primary tool that has been used to realize this practice is first to radialize an originally meshed distribution network configuration and then to employ an efficient search algorithm like "Edmond's Maximal Spanning Tree" algorithm to search for an optimal radial configuration, looking for those trees (Set of feeders) which delivers the desired optimization goal subject to constraint satisfaction.

There are 30 feeders in the test systems and hence the total number of possible network configuration would be 2^{30}. The best voltage stability condition will result in from a unique switching configuration out of these huge combinations. However, it would be tedious task to study each one of this huge number of possible combinations individually, as each of configured network Distribution Load Flow Analysis solution would take an unacceptably long time. Thus for on Feeder operation, repetitive Distribution Load Flow Analysis solution is not at all a practical solution to the problem.

2.3 Kruskal Algorithm

The Kruskal algorithm is explained stepwise:

1) Examining the Issues to be to form a simple weighted graph is not governed.
2) A table is produced that lists the sides and weights, from a simple weighted graph is not governed has been described in step 1, and then list on the side of the table are sorted in terms of weighing the smallest to the largest.
3) All the points covering the graph portrayed without including all sides to form an empty graph.
4) The sides that weigh the smallest on the table that was depicted in step 2 is made so that it attaches the two points on the blank graph above.
5) Separate the Side and the weight that was used in Step 4 from the table.
6) Repeat step 4 on the condition that the graph does not appear as a mesh.
7) If the graph is shaped circuit then go back to step5
8) Repeat steps 4 until the number of edges in the graph is one less than the number of vertices.
9) Since the number of trees is one less than the number of vertexes then the Kruskal's algorithm processing is stopped.

2.4 Edmond's Algorithm

Edmond'salgorithm is applicable for a directed graph. The algorithm begins by traversing the directed graph (Digraph) and examines vertices and edges. The examined vertices are placed in a so-called Vertex Bucket (BV). Provisionally selected edges are placed in an Edge Bucket (BE). Throughout the execution of the algorithm BE always contains an acyclic collection of directed edges with at most one edge being incident on any vertex not in BV.

This algorithm works in two phases, as described below:

1. *BV = BE = Φ*
2. *i = 0*
3. *if* $BV \neq V_i$ (V_i → *set of total vertices of the graph* G_i)
   Go to 4.
   Else
   Go to 8.
4. *For some vertex* $v \notin BV$ *and* $v \in V_i$,
   Do
   a. $BV = BV \cup \{v\}$
   b. *Find an edge* $e = \{x,v\}$ *such that* $w(e) = max\{w(y,v) \mid (y,v) \in E_i\}$($E_i$ → *set of all edges of the graph* G_i)
   c. *If* $w(e) \leq 0$, *then go to 3 (don't select negative weight edges)*
   Done
5. *If* $BE \cup \{e\}$ *contains a circuit*
   a. $i = i + 1$
   b. *Construct* G_i *by shrinking* C_i *to new vertex* u_i.
   c. *Modify BE, BV and corresponding edge weights*
6. $BE = BE \cup \{e\}$

7. *Go to 3*
8. *While i ≠ 0,*
   Do
   a. *Reconstruct G_{i-1} and rename some edges in BE*
   b. *If u_i was a root of an outbound tree in BE, then*
      $BE = BE \cup \{e \mid e \in C_i \text{ and } e \neq e_i^0\}$
      Else
      $BE = BE \cup \{e \mid e \in C_i \text{ and } e \neq \tilde{e_i}\}$
   c. *i = i - 1*
   Done
9. *Maximum Branching Weight* = $\sum_{e \in BE} w(e)$

3. Description of the test system

A test system of a 30-node mesh network system is shown in Figure 3. In the network, each individual feeder consists of single series sectionalize switch and are assigned as S1 to S40. The data is incurred from IEEE-30 bus system, and the total real and reactive power demands on the system are 283.40MW and 126.20MVAR.The cost values of the network edges are utilized to find the maximal directed spanning tree which is the optimal radial network. In the next phase, the developed graph is optimized using the Edmond's Maximal Spanning Tree algorithm described in section. The Optimal graph is depicted in Figure 4.

To show the effectiveness of the proposed algorithm, alternative system radial configurations obtained manually and Kruskal's Spanning Tree algorithm have been compared with the result obtained by Edmond's algorithm.

A few samples of Voltage stability indicator and active power loss data corresponding to different switch combinations of radial networks have been presented in Table 1.

Using the proposed method, the optimal radial configuration has been found in an efficient manner. The comparative results obtained using different means such as manual, Edmond's algorithm and Kruskal's algorithm for 30 nodes. The 1st configuration corresponds to arbitrarily (and manually) chosen network configuration. The 2nd configuration is obtained using Edmond's algorithm, while the 3rd example is of the configuration obtained using Kruskal's Maximal Spanning Tree algorithm.

The graph of the network is developed after the simulation is performed using Edmond's algorithm shown in Figure 4. The sectionalised switches are disconnected as according to the nodes which are not connected in the below obtained graph as shown in Figure 5. The voltage stability index is calculated for the newly obtained sectionalised switch configuration, and the results are clearly indicative of the fact that the present algorithm is by far superior obtained by manual and the kruskal algorithm, as it succeeded in finding even better (Optimal) switching combination.

4. Results

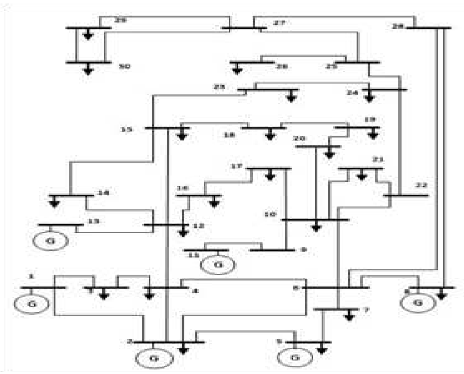

Figure 3: 30-bus system under study

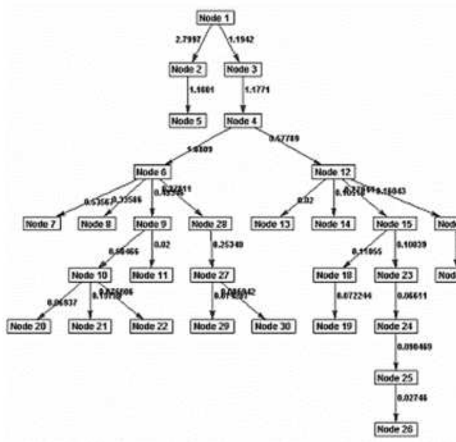

Figure 4: Optimal radial path of the 30 bus system

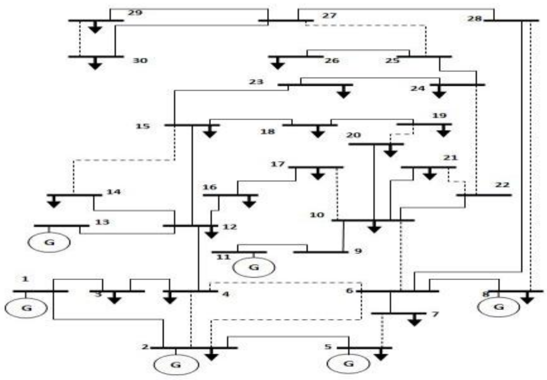

Figure 5: Optimal Configurations obtained from Edmond's algorithm

Table 1: Sectionalizing Switch placement data for 30-bus System

START BUS	END BUS	SWITCH
1	2	S1
1	3	S2
2	4	S3
3	4	S4
2	5	S5
4	6	S6
5	7	S7
6	7	S8
6	8	S9
6	9	S10
6	10	S11
9	11	S12
9	10	S13
4	12	S14
12	13	S15
12	14	S16
12	15	S17
12	16	S18
14	15	S19
16	17	S20
15	18	S21
18	19	S22
19	20	S23
10	20	S24
10	17	S25
10	21	S26
10	22	S27
21	23	S28
15	23	S29
22	24	S30
23	24	S31
24	25	S32
25	26	S33
25	27	S34
28	27	S35
27	29	S36
27	30	S37
29	30	S38
8	28	S39
6	28	S40

Table 2: Comparison of different radial configuration manual configuration (1-3), Kruskal's configuration (4) and Edmond's configuration (5)

Radial configuration no.	Switches Which Are open	Active power loss (p.u.)	Voltage Stability
1	S3,S6,S8, S12,S20, S24,S26, S29,S31, S35,S39, S40.	0.30584	0.75904
2	S3,S4,S9 S10,S14, S17,S21, S23,S32, S33,S38.	0.41121	0.7938
3	S3,S4,S8, S10,S14, S20,S22, S26,S28, S32,S33, S39.	1.22419	0.9461
4 (Kruskal's)	S3,s8,S12, S20,S21, S23,S29, S32,S33, S39,S40.	1.7599	0.2821
5 (Edmond's)	S3,S6,S8, S12,S20, S24,S26, S29,S31, S35,S39, S40	1.45484	0.1685

5. Conclusion

Topology change in Power Distribution Network by means of Sectionalizing Switches to achieve better operating condition was attempted in the paper. An efficient search algorithm is essential, as the number of alternative configuration is usually huge and the normal search takes an unacceptably long time. In our project, Edmond's Maximal Directed Spanning Tree algorithm to render a fast and efficient search for optimal network configuration. The test of Edmond's algorithm in our 30-bus system was found better to reduce system losses and to improve voltage stability condition.

6. Future Research

The research done in this report prevailed over some of the awaiting processes. The proposed algorithm does play a significant and vital role in finding the optimal radial reconfigured network from a large number of feasible configurations, obtaining the highest voltage stability index. In future, the proposed algorithm will be tested on the IEEE 67-bus distribution network aiming to prove the proposed Edmond's algorithm to be feasible for all the available IEEE distribution network.

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Authors' Profiles

Jerrymeo P L Nongkynrih, is pursuing BTECH, 8th semester, in Electrical and Electronics Engineering, School of Technology, Assam Don Bosco University, Airport Road, Azara, Guwahati -781017, Assam, INDIA.

Rishandonborlang Mawrie, is pursuing BTECH, 8th semester, in Electrical and Electronics Engineering, School of Technology, Assam Don Bosco University, Airport Road, Azara, Guwahati -781017, Assam, INDIA.

Lyon Ch Marak, is pursuing BTECH, 8th semester, Electrical and Electronics Engineering, School of Technology, Assam Don Bosco University, Airport Road, Azara, Guwahati -781017, Assam, INDIA.

Pushpanjalee Konwar, is working as Assistant Professor, Department of Electrical and Electronics Engineering, School of Technology, Assam Don Bosco University, Airport Road, Azara, Guwahati -781017, Assam, INDIA.

Mriganka Gogoi, is working as Assistant Professor, Department of Electronics and Communication Engineering, School of Technology, Assam Don Bosco University, Airport Road, Azara, Guwahati -781017, Assam, INDIA.