Reconfiguration of Radial Distribution Network using Tellegen Theorem

G. Pranava[1], Dr. Ravindranath Gurram[2], Dr. K. Ramesh Reddy[3]

[1]*Assistant Professor, Department of EEE, Vasavi College of Engineering, Hyderabad, India*

[2]*Professor, Department of EEE, Matrusri Engineering College, Hyderabad, India*

[3]*Professor, Department of EEE, G. Narayanamma Institute of Technology and Science, Hyderabad, India*

***Abstract*—This paper presents an approach for optimal reconfiguration of Radial Distribution Network with laterals for minimal loss using the Tellegen theorem. An effective algorithm using the basic Tellegen theorem is used to find the power lossesand a standard reconfiguration technique is applied to find economical solution. The Tellegen theorem concept is used to a distribution network with main feeder and laterals and a non-trigonometric and no higher order expressions objective function is used for the load flow solution. The feeder reconfiguration problem chooses the on/off status of the switches in a distribution network in order to minimize the power losses. A heuristic search consists of repeated application of branch exchange, where some loads are transferred from one feeder to another feeder while maintaining the radial structure of the network, until power losses are minimum.The present technique is applied on a 33 bus system and MATLAB2013 is used.**

I. INTRODUCTION

The restoration of a distribution system is an important operation problem in demand side management. Feeder reconfiguration is very important to enhance the quality and reliability of the distribution system. Network reconfiguration in distribution systems is performed by opening sectionalizing (normally closed) and closing tie (normally open) switches of the network. These switching are performed in such a way that the radially of the network is maintained and all the loads are energized. A normally open tie switch is closed to transfer a load from one feeder to another while an appropriate sectionalizing switch is opened to restore the radial structure. Branch exchange method which used to apply in this study starts with a feasible solution for distribution network operating in a radial configuration. During applying reconfiguration technique, the tie switch has to be closed and on the other hand, the sectionalizing switch has to be opened in the loop created, which restores radial configuration. The switch pairs are chosen through heuristics and approximate formulae for the change in losses. Branch exchange process is repeatedly applied till no more loss reductions are available. A radial distribution network can be represented by several loops. This is because, when it is connected, one tie-line can only make one loop; the number of loops is equal to the number of tie-lines. There is a voltage difference across the normally open tie-switch in the tie-line.

Many studies were carried on reconfiguration of distribution network. S.Civanlar [1] et al identified the computational complexity in distribution network and criterion has been developed to reduce the number of candidate options. A simple formula has been developed which reduced the conduction of numerous load flow studies and the computational requirements. Mesus. E.Baran[2] et al developed approximate load flow methods and defined load balance indexing for loss reduction and also for balancing loads. Hugh Rudwick [3] et al used the Power Summation method for load flow calculations to help the search for configurations. Hernan Prieto Schmidt [4] et al addressed the state of switching devices in primary distribution network by taking radiality and capacity constraints into account.Farza Hosseinzadeh [5] et al proposed a new algorithm for distribution network reconfiguration which has simple calculations and is very fast. E.Dolatdar[6] et al obtained the optimal solution by determining the best trees of the network based on graph theory and refined genetic algorithm. This algorithm gave reduced number of load flows and reduced switching configurations to obtain an optimum solution. R.Srinivasa Rao [7] et al demonstrated the algorithm into two parts. First thing was to find out the optimal switching combination with less computational effort and second one was to find out best switching combination which gives optimum power loss calculation. Tamer M Khalil[8] et al used Selective Particle Swarm Optimization technique for search the optimal combination of switches.

In this paper, the power losses in the distribution network are minimized by feeder reconfiguration using a basic theorem called Tellegen therm. A method to determine the state of switches which gives minimum losses is developed and described. A program using MatlabR2013bis developed to obtain the optimal switching configuration.

II. PROBLEM FORMULATION

A distribution system consists of buses, distribution lines, and (sectionalizing and tie) switches that can be opened or closed. There are two types of buses. Substation buses are connected to a transmission network from which they receive bulk power, and load buses that receive power from the substation buses. During normal operation the switches are configured so that 1)The network is radial, i.e., has a tree topology.2) Each bus is connected to a single substation. A subtree is formed that is rooted through at each substation bus as a feeder; hence each feeder is served by a single substation. Optimal feeder reconfiguration is the problem of reconfiguring the switches to minimize losses. It is assumed that there is an on/off switch on each line (i.e., modeling the subsystem between each pair of switches as a single line), and focus on an iterative greedy algorithm.

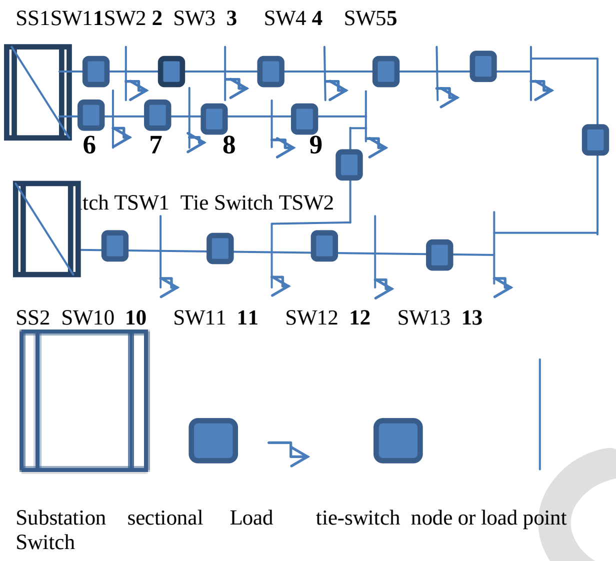

Fig1. Radial Distribution Network with Laterals

The algorithm on the simple network is explained

Two substations SS1 and SS2 where the SS1 is connected with two feeders and one feeder has nodes 1,2,3,4,5having sectional switches SW1,SW2,SW3,SW4,SW5 and second feeder has nodes 6,7,8,9 sectional switches SW6,SW7,SW8,SW9, and the substation SS2 has one feeder having nodes 10,11,12,13 with sectional switches S10,S11,S12,S13.There aretie switches between 5 and 13 say TSW1, 9 and 11 say TSW2. The sectional switches are normally closed and tie switches are open.

III. PROPOSED METHOD

The voltage differences across all the tie switches are obtained. The tie switch with maximum voltage difference is selected and closed. When the tie switch is closed, if forms a loop. To maintain the radiality of the network, a sectionalizing switch in that loop is opened. Load flow solution using Tellegen theorem is executed. One sectionalizing switch at a timeis opened and losses are calculated from the load flow solution. That switch in the loop which gives minimum losses and voltage at each bus lies within the limits, is selected and finally opened.

IV. RECONFIGURATION OBJECTIVE FUNCTION

Minimize $P_{loss}= \Sigma I_i^2 R_i$ where I_i and Ri are the currents and resistances of each branch and n is the total number of branches.Subjected to the constraint $V_{imin}<V_i<Vi_{max}$, where V_i is the voltage of ith bus, Vi_{min} and $Vi_{max}$are the minimum and maximum limits of the i_{th} bus.

V. LOAD FLOW PROBLEM FORMULATION WITH LATERALS

The Tellegen theorem says that " Sum of instantaneous complex powers in a network is equal to zero",

$$\sum_{k=1}^{N_b} V_k I_k^* = 0 \qquad (1)$$

For the given distribution network

$$(0-V_1)I_1 + (V_1 - V_2)I_1 + P_{L1} + jQ_{L1} + (V_2 - V_3)I_2 + \ldots$$

$$.(V_{NB-1} - V_{NB})I^*{NB-1} + P_{LNB} + jQ_{LNB} = 0$$

The current through the branch

$$I_i = (V_1 - V_2)(r_1 + jx_1)$$

$$I_i = (V_1 - V_2)(r_1 - jx_1)/(r_1^2 + x_1^2) \qquad (2)$$

The power fed into the network is given by

$$V_1 I_1^* = NewPP + jNewQQ \qquad (3)$$

For a radial feeder having NB buses and branches (N_{B-1}) , the real and reactive power injected into the system is given by

$$NewPP = \sum_{i=1}^{N_b} \frac{(V(i)-V(i+1))^2}{r(i)^2 + x(i)^2} r(i) + \sum_{i=1}^{N_b} P_L(i) \qquad (4)$$

$$NewQQ = \sum_{i=1}^{N_b} \frac{(V(i)-V(i+1))^2}{r(i)^2 + x(i)^2} x(i) + \sum_{i=1}^{N_b} Q_L(i) \qquad (5)$$

The above equations are called objective equation.

The real and reactive powers flowing in the branch between i and i+1 buses are

$$P(i+1) = P(i) - R(i) - P_L(i) \qquad (6)$$

$$Q(i+1) = Q(i) - X(i) - Q_L(i) \qquad (7)$$

where

$$R(i) = \sum_{i=1}^{N_b} \frac{(V(i)-V(i+1))^2}{r(i)^2 + x(i)^2} r(i) \qquad (8)$$

$$X(i) = \sum_{i=1}^{N_b} \frac{(V(i)-V(i+1))^2}{r(i)^2 + x(i)^2} x(i) \qquad (9)$$

The bus voltage magnitude is

$$\frac{(V(i)-V(i+1))^2}{r(i)^2 + x(i)^2} = \frac{P(i)^2 + Q(i)^2}{V(i)^2} \qquad (10)$$

$$V(i+1)=\frac{(V(i)xV(i)-k3)}{V(i)} \qquad (11)$$

where $k3=\sqrt{(P(i)^2+Q(i)^2)(r(i)^2+x(i)^2)}$ (12)

OldPP and OldQQ are real and reactive powers injected into the distribution system at the beginning of the iteration.

$$delP = NewPP - OldPP \qquad (13)$$

$$delQ = NewQQ - OldQQ \qquad (14)$$

A. Variables Used In the Algorithm

Number of buses = N_B

Voltage magnitude at bus = V_i

Branch resistance and reactance = r_i+jx_i

Load at each bus = P_L+jQ_L

Real power injected at the beginning of the iteration into the network = OldPP

Real power injected in the next iteration = NewPP

Reactive power injected at the beginning of the iteration into the network = OldQQ

Reactive power injected in the next iteration = NewQQ

VI. BUS AND BRANCH INDEXING

To improve the computational efficiency, the bus and branches are indexed in such way that the data retrieving and storing is made simple. The main feeder bus and branches are indexed first and the lateral bus and braches which is very immediate to the main source node of main feeder is indexed and the indexing procedure is continued. Each main feeder or lateral (L) has source node sn(L), start node lb(L) and end node eb(L).For example, for L=1 which is main feeder has source node sn(1)=1, start node lb(1)=2 and end node eb(1)=18 and for L=2, source node sn(2)=2, start node lb(1)=19 and end node eb(1)=22. The table2 gives the detailed explanation.

TABLE1. BUS AND BRANCH INDEXING

Lateral no L	Source node sn(L)	Start node lb(L)	End node eb(L)
1	1	2	18
2	2	19	22
3	3	23	25
4	6	26	33

VII. LOAD FLOW ANALYSIS

The load flow study is carried out in two stages.

A. FIRST STAGE

The distribution network is reduced to a network with main feeder by lumping all the lateral loads at their nodes to the node where the lateral branched from the main feeder. The load flow study is carried using the algorithm defined for the main feeder case and the node voltages of the main feeder are determined.

B. SECOND STAGE

Each lateral is treated as a main feeder and the source node voltage is the node voltage at which the lateral is branched. The load flow algorithm for the main feeder case is carried out for each lateral.

Algorithm for the distribution networks with main feeder and laterals using “Tellegen theorem method”

1. Read the feeder data- resistance and reactance of the branch connected to the node, the connected load powers, the source node voltage magnitude of the main feeder and tolerance.
2. Read the number of laterals connected, the node at which lateral is connected and the start node and end node of each lateral.
3. The lateral node loads are lumped to the node at which the lateral is branched, converting the network into a main feeder case only. The Load Flow Solution of Distribution Network with main feeder case is
   a. Assume a flat voltage profile.
   b. Set OldPP, OldQQto zero.
   c. Compute new powers injected NewPP, NewQQ into the distribution network using eqns (4) and (5).
   d. Compute the difference between (OldPP and NewPP) and (OldQQ and NewQQ).
   e. If the tolerance is not met, increment the iteration count.
   f. Set OldPP=NewPP and OldQQ=NewQQ.The real and reactive powers injected into network and the new node voltage magnitudes are calculated by using eqns (6),(7),(12), then goto step (e).
   g. If tolerance is met, the node voltages of main feeder are obtained. From the node voltages of main feeder, the lateral node voltages are determined.
4. Identify the nodes at which laterals are connected.
5. Set source node voltage computed in the previous step as the source voltage for the corresponding lateral considered.
6. Each lateral is treated as a main feeder case and proceeds from step3.
7. It tolerance is met, print the results.

VIII. ALGORITHM FOR RECONFIGURATION

1. Read the system input data and configuration data
2. Run load flow solution for base case. Voltage magnitudes at all buses and power losses are obtained.
3. Compute the voltage difference across each tie switch which is open in state.
4. Close the tie switch with maximum voltage difference.
5. To maintain the radiality of the system, open each sectionalizing switch in the so formed loop.
6. If the system is radial then only run load flow for each sectionalizing switch opened. Form the data for load flow (main feeder, laterals and sub laterals) for the change in status of switches.
7. Obtain the sectionalizing switch which when opened gives minimum losses in the loop, satisfying voltage limits. Keep this switch open throughout the procedure.
8. The voltage difference among the opened tie switches are calculated. If all tie swiches are closed goto next step, otherwise goto step 4.
9. The final configuration gives the optimal combination of tie switches closedand sectionalizing switches opened. Print the results.

IX. SIMULATION RESULTS

The reconfiguration of distribution network is implemented by Matlab software for a 12.66KV 33 bus system. The data is obtained from [7].

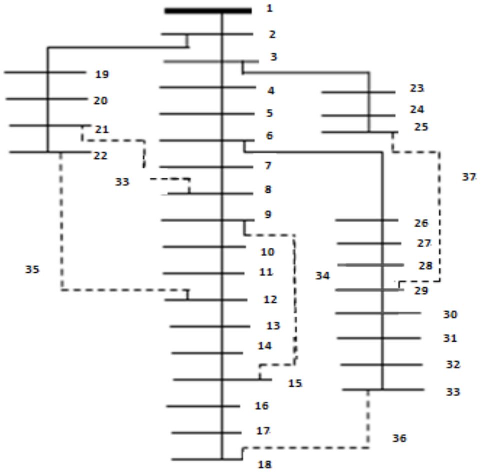

Figure 2.33 Bus Radial Distribution System

Load flow solution is obtained for the 33 bus system using Tellegen theorem. The system has 5 tie switches, 32 sectionalizing switches with 33 nodes. The active power losses obtained from this base case is 202.4KW. The minimum value of voltage obtained is 0.9020pu. The tie switch with maximum voltage difference is 35 and it is closed. Each sectionalizing switch is opened in the so formed loop and load flow using Tellegen theorem is executed. When sectionalizing switch 7-8 is opened, it gives the minimum losses compared to other sectionalizing switches. The procedure is repeated by closing other tie switches also. Radiality is checked at every stage. The results for final reconfiguration are shown in the tables 2 and 3

TABLE 2. BUS VOLTAGES IN PU BEFORE AND AFTER RECONFIGURATION

Bus No.	Before Reconfiguration (Voltage in pu)	After Reconfiguration (Voltage in pu)
1	1	1
2	0.9970	0.9971
3	0.9832	0.9873
4	0.9758	0.9855
5	0.9684	0.9840
6	0.9505	0.9808
7	0.9454	0.9798
8	0.9317	0.9404
9	0.9253	0.9423
10	0.9193	0.9477
11	0.9185	0.9486
12	0.9169	0.9506
13	0.9106	0.9480
14	0.9080	0.9471
15	0.9064	0.9375
16	0.9050	0.9357
17	0.9026	0.9324
18	0.9020	0.9313
19	0.9964	0.9950
20	0.9927	0.9778
21	0.9919	0.9728
22	0.9912	0.9641
23	0.9796	0.9800
24	0.9728	0.9654
25	0.9694	0.9542
26	0.9485	0.9805
27	0.9458	0.9802
28	0.9345	0.9796
29	0.9281	0.9400
30	0.9242	0.9364
31	0.9198	0.9328
32	0.9188	0.9320
33	0.9185	0.9304
Power in loss in KW	202.04	131.49

TABLE 3. RECONFIGURATION RESULTS

Tie Switch Closed	Sectionalizing Switch opened	Power Loss in KW
All open	All closed	202.04
35	7-8	136.66
37	28-29	132.94
36	32-33	131.5
34	14-15	131.49

X. CONCLUSIONS

The reconfiguration of distribution network is implemented by Matlab software. Each time, a lateral switch is closed and sectionalizing switch in the formed loop has been opened. Radiality has been checked and configuration which gives least power losses subjected to voltage constraints are found. From the results, it is observed that the losses have minimized by 70.55 KW i.e, by 34.91% with the final configuration. The minimum voltage obtained after reconfiguration is 0.9304 pu and 0.9020 pu before reconfiguration.

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