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Abstract
Network reconfiguration in distribution system is realized by changing the status of sectionalizing switches, and is usually done for the purpose of loss reduction. Loss reduction can result in substantial benefits for a utility. Other benefits from loss reduction include increased system capacity, and possible deferment or elimination of capital expenditures for system improvements and expansion. There is also improved voltage regulation as a result of reducing feeder voltage drop. Research work included by this paper focuses on using branch exchange method to minimize losses and solve the problems over different radial configuration. Solution's algorithm for loss minimization has been developed based on two stages of solution methodology. The first stage determines maximum loss-reduction loop by comparing the size of circles for every loop. In a distribution system, a loop is associated by a tie-line and hence there are several loops in the system. To obtain the maximum lossreduction loop, size of modified zero loss-change circles are compared, and the loop within the largest circle is identified for maximum loss-reduction. The second stage determines the switching operation to be executed in that loop to reach a minimum loss network configuration by comparing the size of the loop circle for each branch-exchange. The smallest circle is to be identified for the best solution; the size of the loop circle is reduced when the losses are minimized. The performance of the proposed branch exchange method is tested on 16-bus distribution systems.

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Network Reconfiguration Using PSAT for Loss Reduction in Distribution Systems

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Abstract- **Network reconfiguration in distribution system is realized by changing the status of sectionalizing switches, and is usually done for the purpose of loss reduction. Loss reduction can result in substantial benefits for a utility. Other benefits from loss reduction include increased system capacity, and possible deferment or elimination of capital expenditures for system improvements and expansion. There is also improved voltage regulation as a result of reducing feeder voltage drop. Research work included by this paper focuses on using branch exchange method to minimize losses and solve the problems over different radial configuration. Solution's algorithm for loss minimization has been developed based on two stages of solution methodology. The first stage determines maximum loss-reduction loop by comparing the size of circles for every loop. In a distribution system, a loop is associated by a tie-line and hence there are several loops in the system. To obtain the maximum loss-reduction loop, size of modified zero loss-change circles are compared, and the loop within the largest circle is identified for maximum loss-reduction. The second stage determines the switching operation to be executed in that loop to reach a minimum loss network configuration by comparing the size of the loop circle for each branch-exchange. The smallest circle is to be identified for the best solution; the size of the loop circle is reduced when the losses are minimized. The performance of the proposed branch exchange method is tested on 16-bus distribution systems.**

I. INTRODUCTION

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 radiality 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 formulas 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. The higher voltage drop side of the tie-switch is called *low voltage side* and the lower voltage drop side of the tie switch is called *high voltage side* of the loop. The low voltage side and high voltage side are denoted by l and h respectively. It is noted that no transformer is considered inside the loop. A number of papers have appeared on the general topic of feeder reconfiguration as it applies to normal operating conditions. An early work on loss reduction through network reconfiguration was presented by Civanlar et al. [1], which described a formula to estimate the loss changes for a particular switching option between two feeders. This is done through the closing of a single tie switch and the opening of a single sectionalizing switch. Shirmohammadi et al. [2], described a technique for the reconfiguration of distribution networks to decrease their resistive line losses and included results pertaining to large scale system examples. Baran and Wu [3] developed a formula following the solution approach proposed by Civanlar et al. The formula has been used in the loops of the network to determine the switching option for loss minimization. The authors showing that is possible to perform a branch exchange where a switching on the higher voltage side results in a positive loss reduction. Goswami et al. [4], presented a heuristic algorithm for the reconfiguration of feeders. Broadwater et al. [5], applied the Civanlar's method and Huddleston's quadratic loss function and multiple switching pair operation method to solve the minimum loss reconfiguration problem. Borozan et al. [6], proposed an algorithm for calculating Z_{loop} matrix using the ordered network elements. Taleski et al. [7], proposed a method to determine the network reconfiguration with minimum energy losses for a given period. Kashem et al. [8], are based on branch-exchange technique for reconfiguration to minimize distribution losses. A geometrical method for the network reconfiguration based loss minimization problem is developed and presented by Kashem et al.[9], in this method, each loop in a network is represented as a circle, which is derived from the relationship between the change of loss due to the branch-exchange and the power flows in the branches. In this paper, a proposed algorithm is compared with that in [1]. The comparison is achieved regarding Load Flow, Time required, Number of searches, and Branch-exchange. The results discussed in section VII.

II. RADIAL DISTRIBUTION SYSTEM

In Figure 1, there are two types of switches in the system. Normally closed switches connecting the line switches (SW1-

SW13) and normally open switches on the tie lines connecting (SW31-SW33).Distribution systems are normally operated as radial networks. However, changing the state of some sectionalizing switches changes configuration.

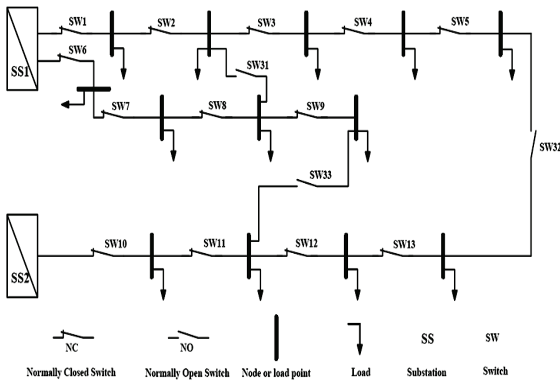

Figure 1. Schematic diagram of a distribution system.

The base radial network shown in Figure 1 can be reconfigured by first closing an open tie-switch, say switch 32. This tie-switch makes a loop in the system, which comprises of branches 1, 2, 3, 4, 5, 32, 13, 12, 11 and 10. To re-establish the radial structure again, a branch in the loop having a sectionalizing switch has to be opened, say switch 3. The effect of this switching operation is that the loads between branches 3 and 5 are shifted from one feeder to another. The network reconfiguration is made

a) To reduce the system power loss.
b) To relieve the overloads in the network.

III. Formulation of The Problem

In this section, the network reconfiguration problem for loss minimization is discussed in detail. To simplify the presentation, we will represent the system on a per phase basis and the load along a feeder section as constant P, Q loads placed at the end of the lines as shown in Figure 2. It is assumed that every switch is associated with a line in the system.

A. Power Flow Equations

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

$$P_{i+1} = P_i - r_i \frac{p_i^2 + Q_i^2}{V_i^2} - P_{Li+1} \tag{1}$$

$$Q_{i+1} = Q_i - x_i \frac{p_i^2 + Q_i^2}{V_i^2} - Q_{Li+1} \tag{2}$$

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

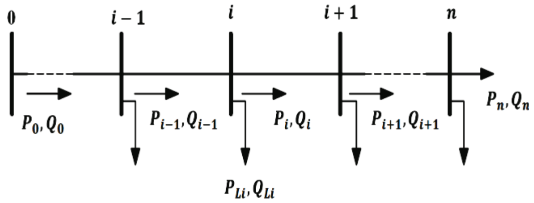

Figure 2. One line diagram of a radial network.

Dist Flow branch equations can be written in backward, by using the real power P, reactive power Q, voltage at the receiving end of a branch to express the same quantities at the sending end of the branch as:

$$P_{i-1} = P_i + r_i \frac{p_i'^2 + Q_i'^2}{V_i^2} + P_{Li} \tag{4}$$

$$Q_{i-1} = Q_i + x_i \frac{p_i'^2 + Q_i'^2}{V_i^2} + Q_{Li} \tag{5}$$

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

where, $p_i' = P_i + P_{Li}$ $\quad Q_i' = Q_i + Q_{Li}$

r, x are resistance and reactance of the branch respectively.

IV. Estimation of Power Loss Reduction due to a Branch Exchange.

As given in Kashem et al.[9], the loss reduction formula due to this branch exchange can be rewritten as follows

$$\begin{aligned} \Delta LP_{tm} = 2P_m \left(\sum r_l P_l - \sum r_h P_h\right) \\ + 2Q_m \left(\sum r_l Q_l - \sum r_h Q_h\right) \\ - (P_m^2 + Q_m^2) r_{loop} \end{aligned} \tag{7}$$

If the incremental power loss reduction due to branch exchange $\Delta LP_{tm} > 0$, i.e. positive loss reduction indicate that losses are reduced and $\Delta LP_{tm} < 0$, i.e. negative loss reduction indicate that losses are increased. (P_m, Q_m are real power and reactive power flow in branch *m*).

Eq. (7) can be rearranged as shown below to be represented by a circle:

$$\left[P_m - \frac{A}{C}\right]^2 + \left[Q_m - \frac{B}{C}\right]^2 = \frac{A^2 + B^2}{C^2} - \frac{\Delta LP_{tm}}{C} \tag{8}$$

where, $\quad A = \sum r_l P_l - \sum r_h P_h$,

l and h refer to low and high voltage sides respectively.

$B = \sum r_l Q_l - \sum r_h Q_h \qquad C = r_{loop}$

This is called *loop circle*. The center of the loop circle is $\left(A/_C\ ,\ B/_C\right)$ and its radius is

$$\left[\frac{A^2+B^2}{C^2}-\frac{\Delta LP_{tm}}{C}\right]^{1/2}$$

Zero loss change loop circle is that one which gives zero change in loss (ΔLP_{tm} =0). It can be represented as follows

$$\left[P_m-\frac{A}{C}\right]^2+\left[Q_m-\frac{B}{C}\right]^2=\frac{A^2+B^2}{C^2} \qquad (9)$$

Hence, radius of the loop circle for zero loss change (i.e. ΔLP_{tm} =0) is $\left[\left(\frac{A^2+B^2}{C^2}\right)\right]^{1/2}$

It is decreased if loss-reduction occurs in the loop.

A. Determination of Maximum Loss Reduction Loop

Maximum loss reduction loop formula is derived by rearrangement of equation (8) which can be rewritten in the following form

$$\Delta LP_{tm}=\left(\frac{A^2+B^2}{C}\right)-C\left\{\left(P_m-\frac{A}{C}\right)^2+\left(Q_m-\frac{B}{C}\right)^2\right\} \qquad (10)$$

From Eq. (9), it is evident that the change in loss, ΔLP_{tm} will be maximum when

$P_m=\frac{A}{C}$ and $Q_m=\frac{B}{C}$

Therefore, the maximum value of ΔLP_{tm} in a loop is

$$\Delta LP_{tm\ loop}=\left(\frac{A^2+B^2}{C}\right) \qquad (11)$$

By rearranging Eq. (9), the modified zero-loss change circle can be expressed as

$$\left[P_m^{'}-\frac{A}{\sqrt{C}}\right]^2+\left[Q_m^{'}-\frac{B}{\sqrt{C}}\right]^2=\frac{A^2+B^2}{C} \qquad (12)$$

where,

$P_m^{'}=\sqrt{C}P_m$ and $Q_m^{'}=\sqrt{C}Q_m$

The radius of the above circle is

$$\left(\frac{A^2+B^2}{C}\right)^{1/2}$$

By using Eq.(12) for all loops in the system, the largest circle will give the maximum loss reduction loop among all the circles drawn for all the loops in the network. Reduced or increased loss cannot be shown by Eq.(11) because it is always positive. Therefore, to ensure that the largest circle gives the maximum loss reduction, *nominal branch* is considered. The nominal branch is the first adjacent branch to the tie branch on the *lv*-side of the loop and the *nominal loss* is the loss which occurs by exchanging the open branch with the nominal branch. If the nominal loss is negative, then there is no branch in the loop that can be a candidate for branch exchange (Kashem et al. [9].

Eq. (8) can be rewritten for nominal branch exchange as

$$\Delta LP_{tk}=\left(\frac{A^2+B^2}{C}\right)-C\left\{\left(P_k-\frac{A}{C}\right)^2+\left(Q_k-\frac{B}{C}\right)^2\right\} \qquad (13)$$

where, P_k and Q_k are the power flow in the nominal branch (*k*). By using Eq. (13), the nominal loop circle can be drawn for nominal branch exchange and it can be compared with the zero loss change circle drawn by using Eq. (9) in the respective loop. If the nominal loop circle is reduced in size, then the nominal loss is positive and the branch exchange in the loop gives the maximum loss-reduction. Otherwise the next largest circle is considered and checked as above.

B. Determination of Switching Option for Loss Reduction

Branch-exchange is identified in the loop that would give maximum loss-reduction. Sizes of various circles which are obtained by using Eq. (8) are compared for all branches in the *lv*-side of the loop. The size of circle depends on the value of ΔLP_{tm}. When ΔLP_{tm} is positive for branch-exchange, the corresponding circle becomes smallest one. Therefore, the smallest circle will give best solution and the corresponding branch exchange will give maximum loss-reduction. The best branch-exchange is made by determining and comparing the radii of the loop circles Eq.(8) starting from the nominal branch (*k*) and moving backward in the *lv*-side of the selected loop until the radius of the circle is found minimum with all constraints satisfied.

V. ALGORITHM

Figure 3 shows a flow chart of the technique that will be used to deal with the Branch Exchange Method. The algorithm is used to determine maximum loss reduction loop which is supposed to be the largest loop circle. Data will be collected in the first place, necessary parameters will be calculated, and after running power flow using PSAT software, some refinements will be needed to approach a stable and acceptable system. A number of searches will be applied till last reconfiguration obtained to get the optimal loss reduction.

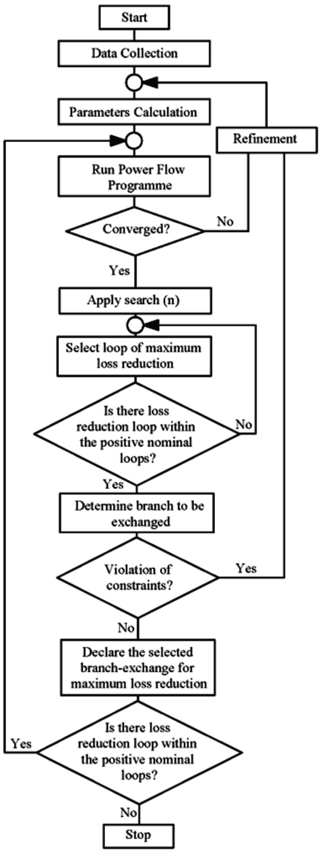

Figure 3 Flow chart of the proposed technique.

VI. Civanlar et al.'s Model of 16-Bus Distribution System [1]

Civanlar et al.'s proposed Feeder Reconfiguration technique to determine network configuration which would reduce losses. Feeder reconfiguration is performed by opening/closing two types of switches, *tie* and *sectionalizing* switches. A whole feeder, or part of a feeder, may be powered from another feeder by closing a tie switch linking the two while an appropriate sectionalizing switch must be opened to maintain radial structures. Figure 4 represents a schematic diagram of the suggested 16-bus network.

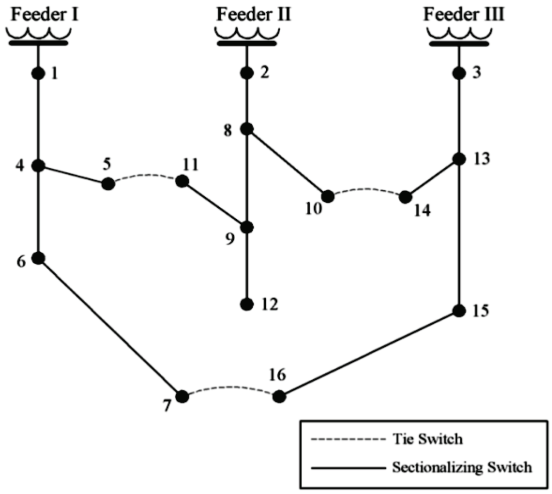

Figure 4 Schematic diagram of 16-bus network.

The test system is a hypothetical 23 kV radial distribution system. There are three tie lines (looping branches) in the system which yields to three loops, and sectionalizing switch on every branch of the system; the total load of the system is 28700 kW and 17300 kVAR; the proposed technique has been implemented by using PSAT Simulink blocks. In this example, the optimal loss reduction has been reached with *three* search loops. Figure 5 shows the schematic diagram for the 16-bus network reconfiguration for the optimal loss reduction.

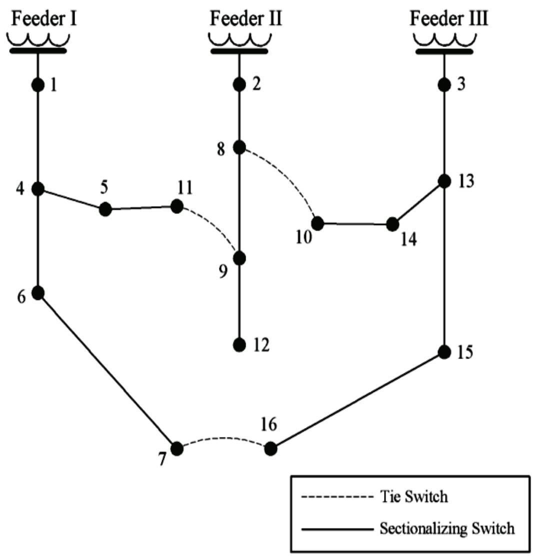

Figure 5 Schematic diagram for optimal loss.

C. Total Loss Reduction in Civanlar et. al.'s Model

Comparing the results of search 1 and search 3 within PSAT generated reports, it is obviously seen that real power losses have been decreased from 651.2 kw to 601.7 kw by using network reconfiguration technique which means that the main goal of this study has been achieved within the 16-bus distribution network.

VII. Comparison between the proposed method and Civanlar et al.'s method based on 16-bus distribution system network results.

There are some similarities and differences between the results obtained by applying the proposed technique on 16-bus distribution system network and those obtained in [1]. Those points of similarity and difference can be summarized as follow:

A. Load Flow: Civanlar et al.'s method requires three search levels, and 30 load flow solutions are required to get the optimal network configuration, while in the proposed method, three search levels with only one load flow solution for each search are required which means that a total of 3 load flow are only required to achieve the optimal loss reduction.

B. Time required: with the 30 load flow solutions, Civanlar et al.'s method takes longer time to identify the branch to be exchanged because it considers the switching exchanges of all the loops at each search-level and calculates the loss reduction for each selected switching-option by using load flow solution, while with three load flow solution required by the proposed method, the time can be significantly saved. Methods involved with a large number of load flow solutions, some times, seem exhaustive and unrealistic especially for larger systems, due to excessive computational time.

C. Number of searches: both methods required the same number of search-level to achieve the optimal reduction loss**.**

D. Branch-exchange: it is found that both techniques determined the same branch that is to be exchanged for each search-level.

VIII. CONCLUSION

Radial structure of distribution network was achieved by placing numbers of sectionalizing switches in the network, which were used to open loops that would exist while reconfiguration of the network was done for reduction of losses. These switches together with tie switches in feeders were used to reconfigure the network whenever it is needed. Loss minimization problem addressed in this paper determines the open/close states of tie and sectionalizing switches in order to achieve maximum reduction in power losses. Change in losses can be easily estimated from two power flow solutions, before and after feeder reconfiguration. The proposed method estimated loss reduction of the network from switching operation by considering several loops in a distribution system. Two stages expressed for the solution algorithm method, the first stage presented the sizes of the modified zero-loss change circles. The second stage determined the branch exchange in the selected loop. 16-bus distribution network has been chosen to apply the technique of loss reduction using reconfiguration. In this example, the optimal loss reduction has been reached with *three* search loops. The proposed technique has been applied on Civanlar et al.'s model of 16-bus distribution system network and the results obtained have been compared with those obtained in [1]. The comparison showed the advantages of applying the proposed method especially in saving the numbers of load flow solution which needs time and computational efforts especially with large distribution system.

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