Distribution Feeder Reconfiguration for Complex Power Loss Minimization

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***Abstract*:-** Complex power loss minimization is an important aspect of modern distribution systems. Complex power loss minimization leads to capacity reduction with improved voltage profile besides active power loss minimization under certain justified assumptions. This paper presents a simple, efficient and direct method for minimum complex power loss radial feeder reconfiguration in response to changing operating conditions. The method is based on the optimality condition, which has been derived analytically using incremental complex power concept. The method has been applied on different small to medium sized distribution systems and the results are presented. The implementation results of the method are promising and encouraging.

Key-Words: - Loss minimization, load flow, power distribution, System reconfiguration, Incremental loss, Radial network

1 INTRODUCTION

DISTRIBUTION system reconfiguration has assumed significant importance. The distribution loss for a given load depends on distribution network configuration. To improve reliability distribution network are structured meshed. However, they are normally operated in radial mode for effective coordination of their protective schemes and to reduce the fault level. The network reconfiguration is done by changing the ON/OFF status of sectionalizing/tie switches. The aim of distribution system operator is to reconfigure the distribution network in response to changing load demand or other conditions in such a fashion that distribution loss is minimum, network remains radial with all operating constraints satisfied. Since, there may be large possible switching combinations, finding an optimal switching combination is a difficult optimization problem. A lot of research work has been carried out in the area of distribution network reconfiguration. These research efforts can be broadly classified into traditional approaches and AI based approaches. The traditional approaches include heuristic optimization approaches and classical optimization approaches. Merlin et al [1] were first to report a method for distribution system reconfiguration to minimize line loss. They formulated the problem as integer mixed non-linear optimization problem which is solved through a discrete branch-and-bound technique. The solution starts with all switches closed. The switches are then opened successively to eliminate loops till radial configuration is achieved. An equivalent resistive network model is used to determine the switches to be opened. Civinlar et al [2] suggested a branch exchange type heuristic method, in which a computationally efficient formula was developed to determine change of loss due to switch exchange between two feeders. Different combinations of tie switches and sectionalizing switches are checked to see the improvement in loss reduction. Shirmohammadi et al [3] proposed a method based on [1]. The solution procedure starts with a meshed network; the switches are then opened one after another on the basis of minimum power flow. Goswami et al [4] extended the method [2] by limiting the switch exchange with in a single loop each time. The method is computationally less demanding. Baran et al [5] developed a heuristic algorithm based on the idea of branch exchange for loss minimization and load balancing. They have also developed an algebraic expression for estimating loss reduction due to branch exchange. Chen et al [6] suggested an objective function consisting system loss cost and switching operation cost to derive a long term and short term switching plan for system reconfiguration. Jin et al [7] formulated the reconfiguration and load balancing problem as a combinatorial non differentiable optimization problem with certain constraints. Aoki et al [8] used a quasi-quadratic non linear programming technique to minimize distribution loss. McDermott et al [9] proposed a heuristic constructive algorithm that starts with all operable switches open and at each step the switch that result in least increase in the objective function is closed. The objective function is defined as the ratio of incremental loss to incremental load supplied. Wagner et al [10] have presented a comparison of different methods and suggested that heuristic approaches are suitable for real time distribution system reconfiguration for loss minimization. A survey on distribution system reconfiguration was carried out by Sarfi et al [11]. A method based on network partitioning theory was proposed by Sarfi et al [12] for distribution system reconfiguration. Sarma et al [13] presented a 0 – 1 integer programming method for feeder reconfiguration and suggested that consideration of multiple switching at a time can give optimal solution for loss minimization. Gohokar et al [14] proposed a method for distribution feeder reconfiguration based on network topology approach. Schmidt et al [15] formulated the problem of feeder reconfiguration as a mixed integer non linear optimization problem, in which integer variables represent states of switches and continuous variables the current flowing through the branches. To solve the optimization problem, a best search algorithm was used to determine the values of integer variables. Gomes et al [16] presented an optimal power flow based heuristic method for feeder reconfiguration for loss minimization. Morton et al [32] proposed a brute-forced exhaustive search algorithm for the solution of network reconfiguration problem for loss minimization. The method provides global optimum solution under certain assumptions. However, the method is computationally demanding.

The traditional approaches are by and large iterative and therefore are not suitable for on line feeder reconfiguration for loss minimization. In the area of AI based approaches, Nara et al [17] used Genetic Algorithm (GA) for loss minimum distribution system reconfiguration. Lin et al [18] and Zhu [19] proposed refined GAs for feeder reconfiguration. Ramos et al [20] proposed a GA approach which involves path based network modeling. Alexandre et al [21] proposed a genetic algorithm, which incorporates a new tree encoding based on graph chain, for optimal feeder reconfiguration. A fuzzy mutated GA was proposed by Prasad et al [22]. An integrated fuzzy genetic algorithm was explored by Hong et al [23] for multi objective feeder reconfiguration. Lin et al [24] presented application of immune algorithm for distribution system reconfiguration for loss minimization and load balancing in feeders and transformers. Artificial neural network based method was first proposed by Kim et al [25] for on line feeder reconfiguration. Salazar et al [30] extended this approach by using a clustering type neural network which require a smaller training set and can be trained with better generalization capability.

Hsiao et al [26] presented the application of evolutionary programming for multi objective feeder reconfiguration. Ant colony search algorithm has also been exploited for distribution system reconfiguration for loss minimization [27]. Das [28] suggested a fuzzy multi-objective approach for feeder reconfiguration which incorporates a heuristic rule base. Jeon et al [29] presented the application of simulated annealing for large distribution network reconfiguration. Recently Chuang et al [31] suggested a Rule Expert Knowledge based Petri Net approach for temperature adoptive feeder reconfiguration under the conditions of feeder over load / faults. The AI techniques can handle broader objectives but are computationally demanding, except ANN approaches. The ANN approaches are, although, suitable for on line application need rigorous off line computation for all the possible operating conditions to achieve generalization.

So far attempts have been made to minimize active power loss by reconfiguring the distribution feeder in response to changing operating conditions. However, complex power loss minimization is an equally important aspect. It leads to capacity reduction with improved voltage profile as well as active power loss reduction under certain justified assumptions. Capacity reduction means overall economy in the generation, transmission and distribution. In this paper, a simple method is developed for distribution system reconfiguration for complex power loss minimization. The proposed method is based on the optimality conditions derived in section II. The implementation results of the method on three small to medium distribution systems are presented in section III. Finally conclusions drawn from the study are presented in section IV.

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2. FORMULATION OF THE PROPOSED METHOD

In this section the reconfiguration method is developed based on the incremental complex power loss approach. Let us consider a radial feeder as shown in Fig 1, having n substations. The complex power loss $S_{(loss)}$ in the feeder is given by

$$\begin{aligned} S_{(\mathrm{loss})} &= VI^* - \sum_{i=1}^{n} S_i \\ &= VI^* - \sum_{i=1}^{n-1} S_i - S_n \end{aligned}$$

Where, V is the complex voltage at the feeding point, I, is the current delivered by the feeding point and $S_{i,}$ is the load at ith substation. If a small load ∂S_n, is added at the tail end of the feeder, i.e., at n th substation; the increase in power loss $S_{(loss)}$ is then given by

$$\partial S_{(loss)} = V(\partial I)^* - \partial S_n$$

$$= V\sum_{i=1}^{n-1}(\partial I_i)^* + V(\partial I_n)^* - \partial S_n \qquad (1)$$

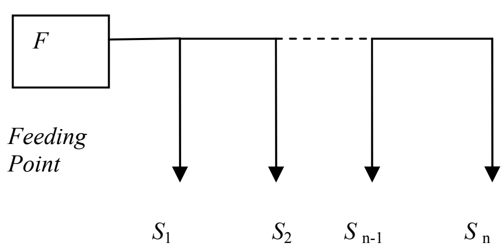

Fig.1 : Radial feeder

Now assume that the added load ∂S_n is sufficiently small such that the change in voltages at all substation buses is negligible. This assumption leads to the conclusion that the current drawn by each substation, except the nth substation, will not change appreciably, i.e., ∂I_i $i=1,2...n-1$ is zero. .Substituting in (1)

$$\partial S_{(loss)} = V(\partial I)^* - \partial S_n \qquad (2)$$

The load at nth substation S_n is given by

$$S_n = V_n I_n^*$$

Therefore, the added load ∂S_n at the substation is

$$\partial S_n = V_n(\partial I_n)^* + I_n^* \partial V_n$$

Neglecting ∂V_n, implies that

$$(\partial I_n)^* = \left(\frac{\partial S_n}{V_n}\right) \qquad (3)$$

Substituting the value of $(\partial I_n)^*$ in (2)

$$\partial S_{(loss)} = V\left(\frac{\partial S_n}{V_n}\right) - \partial S_n$$

Therefore the incremental loss $\left(\frac{\partial S_{(loss)}}{\partial S_n}\right)$ is given by

$$= V\sum_{i=1}^{n}(\partial I_i)^* - \partial S_n$$

$$\left(\frac{\partial S_{(loss)}}{\partial S_n}\right) = \left(\frac{V}{V_n}\right) - 1 \qquad (4)$$

2.1 Derivation of Optimality Conditions

If Let us now consider an interconnected distribution system having two feeding points F_1 and F_2 is shown in Fig 2. In the interconnected system, one of the sub-stations will be receiving power from both side Let the, m^{th}, substation be receiving power from both sides. Let us consider a hypothetical situation that the load at this substation be split into $Sm1$ and S_{m2} by opening a hypothetical tie switch. The system is now converted into two radial feeders. The total load at m^{th} substation

$$S_m = S_{m1} + S_{m2}$$

The total system loss is given by the expression,

$$S_{(loss)} = S_{(loss)1} + S_{(loss)2}$$

The aim is now to minimize $S_{(loss)}$ by appropriately choosing the values of S_{m1} and S_{m2}

Therefore, the optimization problem becomes

Minimize $S_{(loss)} = S_{(loss)1} + S_{(loss)2}$

Subject to the constraint $S_m = S_{m1} + S_{m2}$

Using Lagrange multiplier approach to solve the problem, the modified unconstrained objective function becomes

$$F = S_{(loss)1} + S_{(loss)2} + \mu * (S_m - S_{m1} - S_{m2}) \qquad (5)$$

Therefore, the minimum loss conditions are

$$\left(\frac{\partial F}{\partial S_{m1}}\right) = 0 \quad \text{and} \quad \left(\frac{\partial F}{\partial S_{m2}}\right) = 0 \qquad (6)$$

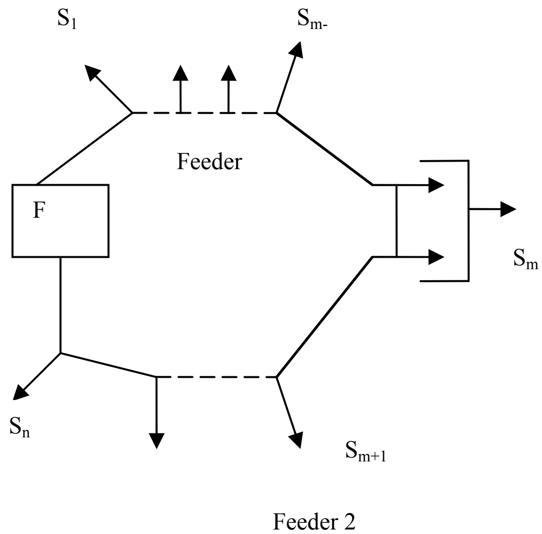

Fig. 2: Two feeder interconnected system

Substituting the value of F from (5) in (6)

$$\left(\frac{\partial S_{(loss)1}}{\partial S_{m1}}\right) - \mu = 0 \text{ and } \left(\frac{\partial S_{(loss)2}}{\partial S_{m2}}\right) - \mu = 0$$

Resulting in the condition of optimality as

$$\left(\frac{\partial S_{(loss)1}}{\partial S_{m1}}\right) = \left(\frac{\partial S_{(loss)2}}{\partial S_{m2}}\right) \tag{7}$$

If the voltages at load busses $m1$ and $m2$ of m th substation are V_{m1} and V_{m2} respectively and the voltage at the feeding points is V_{m1}; using equation (4), equation (7) can be expressed as

$$\left(\frac{V}{V_{m1}}\right) - 1 = \left(\frac{V}{V_{m2}}\right) - 1 \tag{8}$$

Resulting in the condition of optimality as

$$V_{m1} = V_{m2} \tag{9}$$

The interpretation of equation (9) is that an interconnected network can be converted into radial networks with minimum complex power loss if the complex voltages at the two end of the switch are equal. Under this condition the obtained radial networks are optimally configured from complex power point of view.

2.2 Evaluation of Minimum Complex Power Loss Radial Configuration

As already proved the power loss occurring in a system is optimal when the system is in the interconnected mode. If the system is operated in radial mode by opening any feeder section the losses are bound to increase. The aim of this section is identify the feeder section which should be opened so that the system can be operated in radial mode with a minimum possible increase in power loss. In order identify such a feeder section the system let the system be connected in interconnected mode by closing the tie switch. By performing the load flow study one can easily identify the substation m which is being fed from two feeding points. The bus at this substation can be split into two hypothetical buses m_1 and m_2 connected through hypothetical tie-line switch carrying zero current by dividing the load S_m between the hypothetical buses in accordance with power received from the two sides. It is assumed that the load at these buses be S_{m1} and S_{m2} and the corresponding voltages be V_{m1} and V_{m2} such that

$$S_m = S_{m1} + S_{m2} \quad \text{and}$$

$$V_m = V_{m1} = V_{m2} .$$

As no current flows through the tie-switch it can be opened without causing any change in the bus voltages or power flows. Thus, the system is converted into two radial feeders. When the hypothetical tie-switch is opened the power losses $S_{(loss)1}$ and $S_{(loss)2}$ in feeders 1 and 2, are given respectively by

$$S_{(loss)1} = \sum_{i=1}^{m1} I_{bi}{}^2 Z_i \tag{10}$$

$$S_{(loss)2} = \sum_{i=m2}^{n} I_{bi}{}^2 Z_i \tag{11}$$

The sum of the two gives total complex power loss under reconfigured condition and it is optimal.

Since hypothetical switch can not be opened to operate the system in radial mode, the hypothetical tie-switch is assumed to be closed and any one of sectionalizing switches on either side is opened. The opening of the sectionalizing switch will transfer tail end load of one feeder to another feeder.

The change in losses of the two feeders when the tail end load S_{m2} is transferred from feeder 2 to feeder 1 can be calculated from the following equations:

$$\partial S_{(loss)1} = \sum_{i=1}^{m1}\left\{ I_{bi} + \left|\frac{S_{m2}^{\ *}}{V_m^{\ *}}\right| \right\}^2 Z_i - \sum_{i=1}^{m1} I_{bi}^{\ 2} Z_i \quad (12)$$

$$\partial S_{(loss)2} = \sum_{i=m2}^{n}\left\{ I_{bi} - \left|\frac{S_{m2}^{\ *}}{V_m^{\ *}}\right| \right\}^2 Z_i - \sum_{i=m2}^{n} I_{bi}^{\ 2} Z_i \quad (13)$$

Simplifying (12)

$$\partial S_{(loss)1} = 2\left|\frac{S_{m2}^{\ *}}{V_m^{\ *}}\right| \sum_{i=1}^{m} I_{bi} Z_i + \left|\frac{S_{m2}^{\ *}}{V_m^{\ *}}\right|^2 \sum_{i=1}^{m} Z_i$$

$$= 2\left|\frac{S_{m2}^{\ *}}{V_m^{\ *}}\right| \left|V - V_m\right| + \left|\frac{S_{m2}^{\ *}}{V_m^{\ *}}\right|^2 \sum_{i=1}^{m} Z_i \quad (14)$$

Where $\sum_{i=1}^{m} I_{bi} Z_i$ represents the total voltage drop $\left|V - V_m\right|$ Similarly it can be proved

$$\partial S_{(loss)2} = -2\left|\frac{S_{m2}^{\ *}}{V_m^{\ *}}\right| \left|V - V_m\right| + \left|\frac{S_{m2}^{\ *}}{V_m^{\ *}}\right|^2 \sum_{i=m2}^{n} Z_i \quad (15)$$

Thus, the increase in power loss due to transfer of load S_{m2} from feeder to 2 to feeder 1 is

$$\partial S_{(loss)} = \partial S_{(loss)1} + \partial S_{(loss)2} = \left|\frac{S_{m2}^{\ *}}{V_m^{\ *}}\right|^2 \sum_{i=1}^{n} Z_i \quad (16)$$

It can be similarly proved that the increase in power loss due transfer of load S_{m1} from feeder 1 to feeder 2 is

$$\partial S_{(loss)} = \left|\frac{S_{m1}^{\ *}}{V_m^{\ *}}\right|^2 \sum_{i=1}^{n} Z_i \quad (17)$$

From (16) and (17) it is clear that for operating the system in radial mode, the increase in complex power loss is a function of load to be transferred from one feeder to another.

Hence to obtain minimum loss radial configuration the sectionalizing switch out of the sectionalizing switches on either side of the hypothetical switch which carries less complex power should be selected for opening.

With little mathematics and under the assumptions that (a) all the feeder sections have the same R/X ratio, (b) all the loads have same power factor and (c) transfer of load from one feeder to another does not change voltage at substation buses appreciably, it can be proved that the derived optimality condition holds for real power minimization also. The algorithm of the proposed method is as follows

1. Read system data and switch data.
2. Close all normally open switch to form an interconnected network
3. Perform load flow study and obtain results.
4. Identify the nodes which are receiving power from more than one source.
5. Compare the complex power flows toward the each individual identified node. Open the line section(s) feeding less complex power to individual identified node.
6. Print the resulting minimum complex power loss radial configuration.

3. IMPLEMENTATION RESULTS

A. Example-1

The system is a 23 kV three feeders distribution system of Civanlar [2] having 13 normally closed sectionalizing switches and 3 normally open tie switches. The data of the system is given in [2, 27] on 100 MVA base. In the original configuration all the tie switch (line section 5-11, 10-14 and 7-16) are open and the total distribution losses for the initial radial configuration are 511.436 KW, 590.367 KVAR and 781.01KVA with minimum voltage of 0.969266 at bus 12. When all the open switches are closed and load flow program is run, three buses, namely 7, 8 and 9, are found to receive complex power from two lines as shown in Table 1. At node seven the incoming line 7-16 carries less complex power at node eight the incoming line 8-10 carries less complex power and at node nine the incoming line 9-11 carries less complex power

Table 1: Identification of switches to be opened

Bus receiving power from two or more than two sides	Incoming lines	Complex Power	Open the line
7	7-6 **7-16**	0.72268 + j 1.02673 **0.77732 + j 0.17327**	7-16
8	8-2 **8-10**	10.82184 + 2.06099 **0.49885 + j 0.38850**	8-10
9	9-8 **9-11**	7.27650 + j 0.31128 **2.24284 +j 0.43788**	9-11

Therefore, network is reconfigured by opening the line section 7-16, 8-10 and 9-11. The total active power loss, reactive power loss and complex power loss after reconfiguration are found to be 466.127 KW, 544.899 and 717.07 KVA respectively. The minimum voltage is found to be V12=0.971575 p.u., which is more than the initial configuration voltage. The same results are obtained by other established methods [2, 27]

B. Example-2

The system is 12.66 KV distribution system of Baran and Wu [5] having 33 buses, 37 lines including 5 tie lines.

Under normal operating conditions all the tie switches are open. The data for the system are given in [5]. The initial system loss is 195.690 KW. The minimum system voltage is 0.916084 put., at bus number, 33. When all the open switches are closed and load flow program is run, five buses are found to receive complex power from two lines and therefore incoming line at each bus, which carries less complex power, is open. The application results of the proposed method as well as other methods are summarized in Table 2. From the Table 2, it can be seen that the proposed method nearly give the optimum solution but with minimum system voltage slightly improved. The voltages of different buses of the reconfigured system are shown in Fig. 1. From this figure it may be observed that voltage profiles are slightly better in case of proposed method and the minimum system voltage is also improved. It has been found that out of 33 buses, the voltages at 19 buses are found to be better than or equal to the voltages obtained by optimal search method [32]. From the Table 2, it may also be seen than when the initial configuration of the system is changed by closing the normally open switches 21-8 and 25-29 and opening the switches 3-4 and 6-7, all the method give the same configuration except [4]. Thus, the method [4] is dependent on initial configuration while the proposed method is independent of initial configuration.

Table 2: Comparative results of the proposed method and other methods

Radial network	Initial network	Goswami [4]	Goswami [4] When initial configuration is changed	Optimal By brute search [32] & Zhu[19]	**Proposed**
Open Lines	8-21, 9-15 12-22, 18-33 25-29	7-8, 9-10 14-15, 32-33 25-29	7-8, 9-10 14-15, 32-33 25-29	7-8, 9-10 14-15, 32-33 25-29	**7-8, 12-11 14-15, 28-29 32-33**
Active Power Loss (KW	195.690	139.344	143.404	139.344	**139.431**
Reactive Power Loss(KVAR)	134.572	102.274	103.964	102.274	**105.6**
Complex Power Loss(KVA	237.5	172.849	177.125	172.849	**174.906**
Minimum Voltage (P.U.)	V_{33}=0.916084	V_{32}=0.937254	V_{32}=0.939754	V_{32}=0.937254	**V_{32}=0.941287**

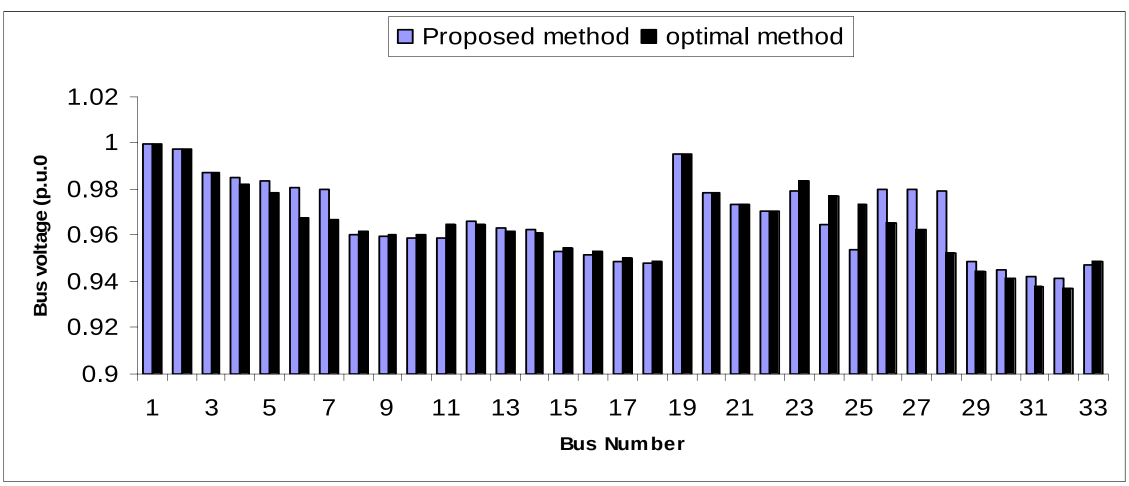

Fig. 3 : Comparison of voltage profiles of the reconfigured distribution system

C. Example-3

The system is 11KV radial system having two substations, 70 buses and 78 lines including 11 tie switches. Under normal operating conditions, all tie switches are assumed to be open. The system data is taken from [28].

The results of the initial radial configuration, the method [28] and the proposed method are summarized in Table 3. From the table it may be observed that the proposed method gives best solution for complex loss minimization. There is around 8.5 % reduction in the complex power loss from the initial configuration and around 2.42 % improvement in the minimum system voltage. The minimum system voltage is also better than that obtained by Das [28], which takes into account the voltage deviation constraints. As regards to the active power loss, the proposed method provides nearly the same result as obtained by [28]. The voltage profiles of the reconfigured network are shown in Fig. 2. It has also been found that out of 70 nodes, 41 nodes have voltages greater than or equal to that obtained by the method [28]. This improvement in voltage profile is due to the optimization of complex power. The method [28] encompasses broader objectives including node voltage deviation, branch current constraints and load balancing. The load balancing aspect will help to reduce the loss. Therefore, this method should give better result than the result obtained by proposed method.

Table. 3: Result comparison of the two methods

Radial network	Open lines	Loss (KW)	Loss (KVAR)	Loss (KVA)	Min. Voltage
Initial network	9-50,9-38 15-46,22-67 29-64,45-60, 43-38,39-59 21-27,15-9 67-15.	244.314	221.617	329.85	V_{67}=0.905179
Das [28]	26-27, 67-15 49-50, 44-45 38-37, 14-15, 65-66, 64-29 9-38, 39-59, 15-46.	223.870	212.127	308.408	V_{50}=0.921678
Proposed	**8-9, 9-15 , 21-27, 37-38 59-39 ,40-44, 49-50, 63-64 66-65, 15-67, 42-46.**	**224.512**	**201.810**	**301.882**	**V_{64}=0.924139**

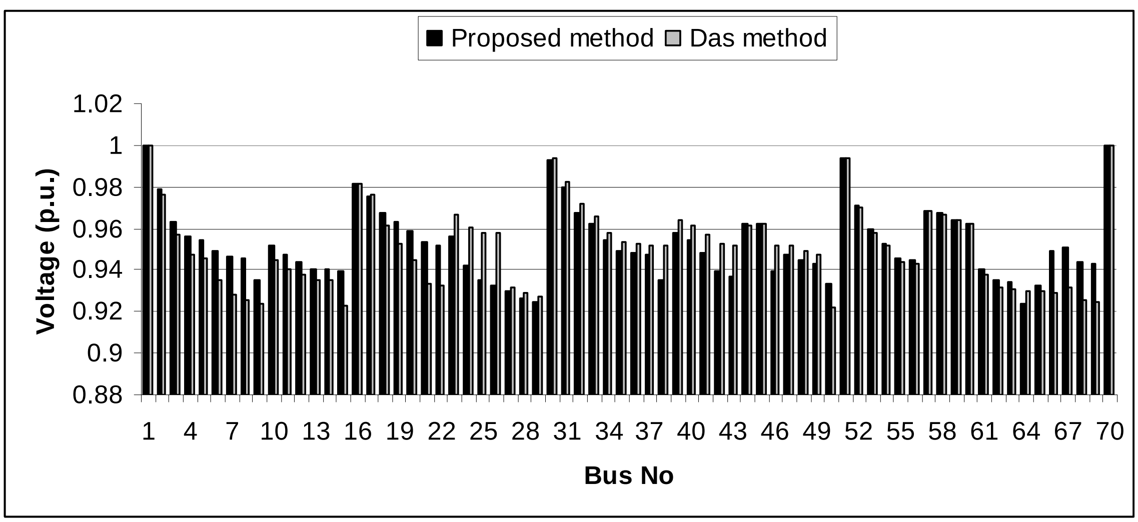

Fig. 4 : Comparison of voltage profiles of the reconfigured distribution system

4. CONCLUSION

In this paper a fast method for distribution system reconfiguration for complex power loss minimization has been developed. The condition of optimality for feeder reconfiguration has been derived for complex power loss minimization. Under certain justified assumption the derived condition holds for active power loss minimization also. The method has been applied on three different distribution systems having unequal R/X ratios and unequal power factors of the loads. The results of the application show that the method is reasonably accurate even under the conditions of unequal R/X ratios and unequal power factors of the loads for active power minimization in addition to complex power minimization. Due to optimization of complex power the voltages of reconfigured networks are, in some cases, better than previously reported work. In modern distribution systems, the assumptions of equal R/X ratios and same power factor of all the loads are nearly true due standardization and strict regulation for maintaining constant power factor. Therefore, the method is promising in the context of modern distribution systems for minimizing both the active power loss and complex power loss. The reduction of complex power loss has added advantages of capacity reduction and improved voltage profiles. The method does not require any search technique and computation of switch operation is also very fast as it requires only one or two load flow runs to identify the optimal radial configuration for loss minimization. Therefore, method has the potential to be used for on line feeder reconfiguration to minimize complex power. The implementation results of the method on medium size distribution are promising and encouraging.

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