Multi-objective Distribution Feeder Reconfiguration

M. R. FAROOQI, P.K.AGARWAL, K. R. NIAZI
Electrical Engineering. Department
Malaviya National Institute of Technology
J. L. N. Marg, Jaipur 302017
INDIA

Abstract: - In the context of modern power systems the multi objective feeder reconfiguration problem has assumed significant importance. This paper presents a fuzzy set theory based approach for the multi objective network reconfiguration of distribution system. The multiple objectives which are met are feeder balancing, minimize power losses, feeder-current constraints and deviation of node voltage. The method has been applied on a medium sized distribution system and the results are presented. The implementation results of the method are promising and encouraging.

Key-Words: - **F**eeder reconfiguration, Fuzzy, Distribution network, Power-loss, Feeder-current, Node-voltage

1 Introduction

Distribution system reconfiguration has assumed significant importance. The present trend towards competitive business environment has forced modern electric utilities to operate their distribution systems as efficiently as possible by minimizing the distribution loss. 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.. 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 except [28]. This paper attempts to extend the work of Das [28] by applying some heuristic rules to improve the performance. In the light of above, this paper addresses the problem of feeder reconfiguration as multi objective feeder reconfiguration problem in fuzzy frame work. The problem formulation considers four different objectives related to:-

1) minimization of system's power loss;
2) minimization of deviation of node voltage;
3) minimization of the branch current constraint violation;
4) load balancing among various feeders.

At the same time a radial network must remain after network reconfiguration in which all loads are served. These four objectives are modelled with fuzzy sets to evaluate there imprecise nature.

2 Proposed Methodology

In the fuzzy domain, each objective is associated with a membership function. The membership function indicates the degree of satisfaction of the objective. Fuzzy sets entertain varying degrees of membership function values from zero to unity. The membership function consists of a lower and upper bound value together with a strictly monotonically decreasing and continuous function for different objectives which are described below.

2.1 Membership Function for Real Power Loss Reduction (μL_i)

The basic purpose for this membership function is to reduce the real power loss of the system.
Let us define

$$x_i = \frac{PLOSS(i)}{PLOSS^0} \quad \text{for } i = 1,2,\ldots\ldots, N_k \quad (1)$$

where

N_k is the total number of branches in the loop including tie-branch, when kth tie-switch is closed.

PLOSS(i) is the total real power loss of the radial configuration of the system when ith branch in the loop is opened.

PLOSS^0 is the total real power loss before network reconfiguration.

Equation (1) indicates that if x_i is high, power loss reduction is low and, hence, a lower membership value is assigned and if x_i is low, the power loss reduction is high and a higher membership value is assigned. (μL_i) Can be written as

$$\mu L_i = \frac{(x_{\max} - x_i)}{(x_{\max} - x_{\min})}, \qquad \text{for } x_{\min}<x_i<x_{\max}$$

$$\mu L_i = 1, \qquad \text{for } x_i \le x_{\min}$$

$$\mu L_i = 0, \qquad \text{for } x_i \ge x_{\max} \quad (2)$$

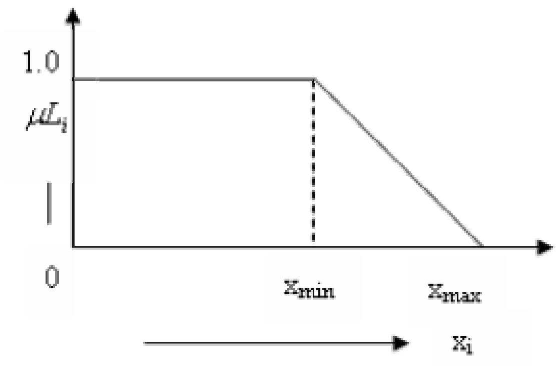

Fig. 1 Membership function for power-loss reduction.

In the present work, it has been assumed that $x_{\min} = 0.5$ and $x_{\max} = 1.0$

2.2 Membership Function for Maximum Node Voltage Deviation (μV_i)

The basic purpose of this membership function is to reduce deviation of node voltages from their nominal value.
Let us define

$$y_i = \max\left|V_{i,j} - V_s\right|, \qquad \text{for } i=1,2,\ldots\ldots\ldots N_k$$
$$j=1,2,\ldots\ldots\ldots \text{NB} \qquad (3)$$

where

N_k - total number of branches in the loop including the tie branch, when the kth tie switch is closed;

NB - total number of nodes of the system;

V_s - voltage of the substation (in per unit);

$V_{i,j}$ - voltage of node corresponding to the opening of the j_{th} branch in the loop (in per unit).

If the maximum value of nodes voltage deviation is less, then a higher membership value is assigned and if deviation is more, then a lower membership value is assigned.

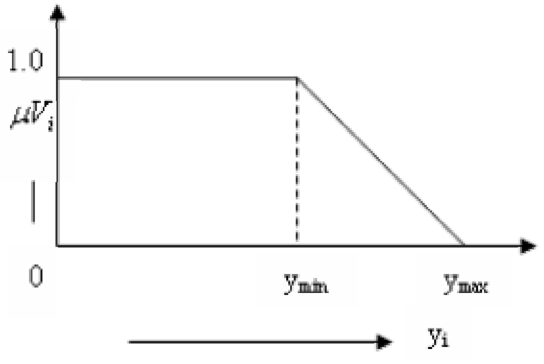

Fig.2. Membership function for maximum node voltage deviation.

From Fig. 2, we can write

$$\mu V_i = \frac{(y_{\max} - y_i)}{(y_{\max} - y_{\min})}, \qquad \text{for } y_{\min}<y_i<y_{\max}$$

$$\mu V_i = 1 \qquad \text{for } y_i \le y_{\min}$$

$$\mu V_i = 0 \qquad \text{for } y_i \ge y_{\max} \qquad (4)$$

In the present work, $y_{\min} = 0.05$ and $y_{\max} = 0.10$ have been considered.

2.3 Membership Function for Maximum Branch Current Loading Index (μA_i)

The feeder currents in the network should not violates the rated current limits. The basic purpose for this membership function is to minimize the branch current constraint violation.

Let us define

$$\text{Branch current loading index} = \frac{|I(i,m)|}{I_c(m)},$$

$$\text{for } i = 1,2,\ldots\ldots.Nk$$
$$m = 1,2,\ldots\ldots\ldots\ldots.NB-1 \qquad (5)$$

where,

N_k - total number of branches in the loop including the tie branch when the kth tie switch is closed;

I(i,m) - magnitude of current of branch-m when the ith branch in the loop is opened;

Ic(m) - line capacity of branch-m;

NB - total number of the nodes of the system.

Let us define

$$z_i = \max \frac{|I(i,m)|}{I_c(m)}, \qquad \text{for } i=1,2,\ldots\ldots.Nk$$
$$m=1,2,\ldots\ldots\ldots\ldots\ldots NB-1. \qquad (6)$$

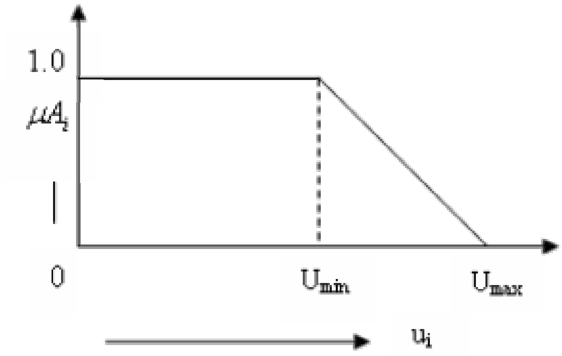

Fig. 3 Membership function for current branch current loading index

From Fig. 3, we can write

$$\mu A_i = \frac{(z_{\max} - z_i)}{(z_{\max} - z_{\min})}, \qquad \text{for } z_{\min} < z_i < z_{\max}$$

$$\mu V_i = 1, \qquad \text{for } z_i \le z_{\min}$$

$$\mu V_i = 0, \qquad \text{for } z_i \ge z_{\max} \qquad (7)$$

In this case, Z_{min} = 1.0 and Z_{max} = 1.15 have been considered.

2.4 Membership Function for Feeder Load Balancing (μB_i)

An effective strategy to increase the loading margin of heavily loaded feeders is to transfer part of their loads to lightly loaded feeders. Feeder load balancing index may be given as

$$FLB_{i,j} = \frac{(IFF_i^{\max} - IF_{i,j})}{IFF_i^{\max}} \qquad \text{for } i=1,2,\ldots\ldots\ldots N_k$$
$$j=1, 2,\ldots\ldots\ldots\ldots.NF \qquad (8)$$

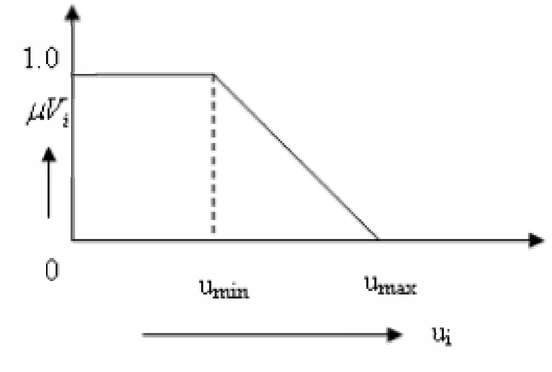

Fig. 4 Membership function for load balancing index.

where,

N_k - total number of branches including the tie branch in the loop when the kth tie switch is closed;

NF - total number of feeders;

$IF_{i,j}$ - current of feeder j corresponding to the opening of the i^{th} branch in the loop;

IFF_i(max) - is the maximum of all the feeder currents corresponding to the opening of the ith branch in the loop = max ($IF_{i,j}$) for j = 1, 2,….,NF.

Let us define

$$\mu_i = \max(FLB_{i,j}) \qquad \text{for } i = 1,2,\ldots\ldots.N_k$$
$$j = 1,2,\ldots\ldots\ldots\ldots NF. \qquad (9)$$

Equation (9) indicates that a better load balancing can be achieved if the value of μ_i is low. Fig. 4 shows the membership function for μ_i. From Fig. 4, we can write

$$\mu B_i = \frac{(u_{\max} - u_i)}{(u_{\max} - u_{\min})}, \qquad \text{for } u_{\min} < u_i < u_{\max}$$

$$\mu B_i = 1 \qquad \text{for } u_i \le u_{\min}$$

$$\mu B_i = 0 \qquad \text{for } u_i \ge u_{\max} \qquad (10)$$

In this case, u_{min} = 0.10 and u_{max} = 0.50 have been considered.

3 Solution Methodology

When there are multiple objectives to be satisfied simultaneously a compromise has to be made to get the best solution. One solution methodology for the multi objective optimization in fuzzy framework is based on the max–min principle which is described as follows.

1) For each option considered radial topology, the membership values of all different objectives are evaluated.

2) Now the degree of overall satisfaction is the minimum of all the above membership values. The fuzzy decision for overall satisfaction is then given by

$$D_{k,i} = \min\{\mu L_i, \mu V_i, \mu A_i, \mu B_i\}$$
$$\text{for } i = 1,2,\ldots\ldots\ldots\ldots N_k \qquad (11)$$

3) The optimal solution is the maximum of all such overall degree of satisfaction. The fuzzy decision for an optimal solution is then given by

$$OS_k = \max\{D_{k,i}\}, \quad \text{for } i = 1,2,\ldots\ldots\ldots N_k \qquad (12)$$

The proposed methodology essentially based on individual loop optimization. For the base case distribution network, load flow program is run to evaluate the membership values of all different objectives functions. The overall degree of satisfaction for this operation is the minimum of all the above membership values. Now, one tie switch is arbitrarily closed and the adjoining left or right branch is open to restore the radiality. The load flow program is then run to evaluate the membership values of all different objectives functions for this tie operation and the corresponding overall degree of satisfaction. When all the option of one loop has been evaluated the best option for the considered loop is the one which gives maximum value the overall degree of satisfaction. This procedure is repeated for other branches of the loop. The whole procedure is then repeated for all the remaining tie switches.

4 Heuristic rules To Improve The Performance

To improve the performance of the method and to reduce the number of tie switch option following heuristic rules are proposed.

It has been derived by Shirmohammadi et al [2], that to obtain a minimum loss radial configuration, the equivalent resistive network can be used for the purpose of identifying the on/off status of tie/sectionalizing switches. Therefore, it is proposed to convert the given network into a resistive network by replacing the impedance of the branches of the network by equivalent resistances of the same magnitude.

To minimize the number of tie-switch operations, in the first iteration, the voltage difference across the all open tie switches are calculated. The tie switch, across which the voltage is maximum, is identified . If this maximum voltage difference is greater than some specified value, say $(\varepsilon) = 0.01$ then this tie switch is considered first. It is expected that because of the largest voltage difference, this switching will cause maximum loss reduction, improve minimum system voltage, and will provide better load balancing. In the next iteration, the same procedure is repeated for the remaining tie-switches and so forth. If, in any iteration, this maximum voltage difference is less than the specified value (ε), then this tie-switch operation is discarded and automatically other tie-switch operations are discarded because the voltage difference across all other open tie switches is less than (ε).

A complete algorithm for the proposed method of the network reconfiguration process is given below:

1. read system data;
2. run the load-flow program for the base case radial distribution networks;
3. compute the voltage difference across the open tie switches(i.e., $\Delta Vtie(i)$ for i=1,2,3…….ntie);
4. identify the open tie switch across which the voltage difference is maximum and its code (i.e., $\Delta V_{tie\max} = \Delta V(k)$);
5. if $\Delta Vtie, \max > 0.01$, go to Step (6); otherwise, go to Step (10).
6. select the tie switch "k " and identify the total number of loop branches (N_k) including the tie branch when the tie-switch "k " is closed;
7. open one branch at a time in the loop and evaluate the membership value for each objective and also evaluate the overall degree of satisfaction (i.e., for i=1 to N_k, compute, $\mu L_i, \mu V_i, \mu A_i, \mu B_i$, and using (2), (4), (7), and (10), respectively, and evaluate;
8. Obtain the optimal solution for the operation of tie-switch "k," (i.e., $OS_k = \max\{D_{k,i}\}$, for i=1…… N_k);

9. $N_{tie} = N_{tie} - 1$ and rearrange the coding of the rest of the tie switches and go to (Step 2);
10. print output results;

5 Simulation and Results

The tested system is a 11-kV radial distribution system having two substations, four feeders, 70 nodes, and 78 branches (including tie branches) as shown in Fig 5. Tie switches of this system are open in normal conditions. Data for this system are given in [11]. Before network reconfiguration, the total real power loss of this system is 244.151 kW. The minimum voltage is $V_{min}=V_{67}=0.9052$ p.u. and average voltage is 0.94933 p.u.

The proposed method has been applied and the final radial configuration of the system obtained is as shown in Fig. 5.

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 better solution After reconfiguration, the total real power loss is 222.616 kW which is smaller than obtained by [28].

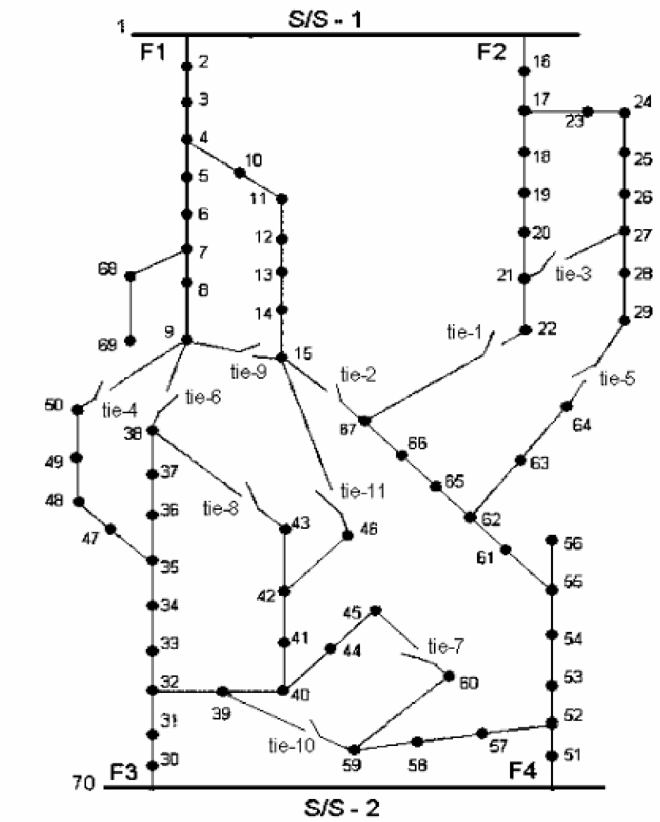

Fig.5 Tested Radial Distribution System

Table 1
Optimal Solution for Tie-Switch Operation

Tie Switch Operation (tie-k)	Optimal Solution (OS_k)
Tie-1	OS - 0.145470 (66-65)
Tie-3	OS - 0.153268 (26-27)
Tie-4	OS - 0.160180 (50-49)
Tie-6	OS - 0.153787 (09-08)
Tie-9	OS - 0.140454 (14-15)
Tie-11	OS - 0.151789 (09-15)
Tie-7	OS - 0.174534 (40-44)

The minimum system voltage is also better than that obtained by Das [28]. The voltage profiles of the reconfigured network are shown in Fig. 6.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]. As regards to load balancing, it may be observed from the proposed method gives the maximum feeder current smaller than [28] and minimum feeder current larger than [28].

Table 2
Comparison of Results

S. No.	Base case	Das [28]	**Proposed method**
Feeder1 current (A)	157.94	173.90	**151.83**
Feeder2 current (A)	109.00	131.50	**131.52**
Feeder3 current (A)	162.27	133.90	**156.08**
Feeder4 current (A)	148.79	135.10	**136.97**
Power Losses (Kw)	244.15	223.764	**222.645**
V(p.u.)	0.91	0.921704	**0.92**

4 Conclusion

In this paper a multi objective feeder reconfiguration method has been proposed in the fuzzy frame work. The objectives considered attempt to maximize the fuzzy satisfaction of the minimization of real power loss, minimization of the deviations of nodes voltage, minimization of the branch current constraint violation, and feeder load balancing subject to the radial network structure in which all loads must be energized Some heuristic rules have also been proposed to improve the performance and speed of the method. The proposed method has been applied on a 70 bus medium sized distribution network and the results are presented.

The implementation results have been compared with other established method. The implementation results of the method on medium size distribution are promising and encouraging.

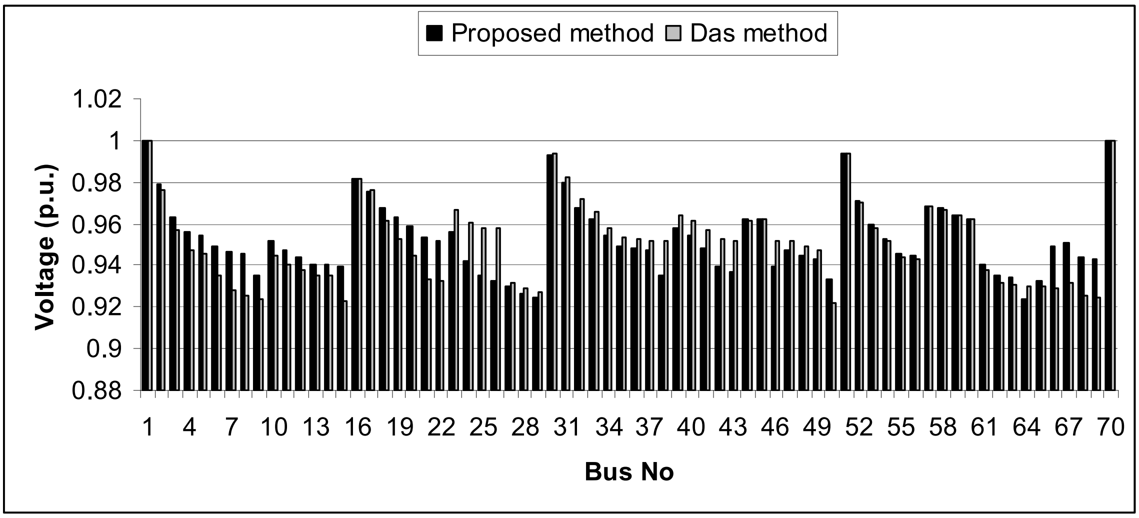

Fig. 6 Comparison of voltage profiles of the reconfigured distribution system

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