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A Heuristic Based Multi-Objective Approach for Network Reconfiguration of Distribution Systems

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Abstract

This paper presents an algorithm for network reconfiguration based on the heuristic rules and fuzzy multi-objective approach with an improved Fast Decoupled load flow algorithm. Multiple objectives are considered to minimize the real power loss, deviation in bus voltages, branch current violation and for load balancing among feeders, while subjected to a radial network structure in which all loads kept energized. These four objectives are modeled with fuzzy sets to evaluate their imprecise nature. Heuristic rules are also incorporated in the algorithm for drastically minimizing the number of tie-switch operations. An improved Fast Decoupled load flow algorithm with Single Matrix Model (FDC-SMM) has been proposed for distribution networks. The proposed algorithm is very effective in dealing with reconfiguration problems of single and multi-feeder networks

Keywords: Multi-objective approach, Reconfiguration, Fuzzy set theory, Fast decoupled load flow

1. Introduction

Network reconfiguration is one of the main functions of the distribution automation. Their configurations may be varied with switching operations so that all of the loads are supplied and reduce the power loss. The change in network configuration is performed by opening sectionalizing (normally closed) and closing tie (normally open) switches of the network. These switchings are performed in such a way that the radiality of the network. A heuristic algorithm has been presented by Shirmohammadi and Hong (1989). Here the solution procedure starts by closing all of the network switches which are then opened one after another so as to establish the optimum flow pattern in the network is maintained and all of the loads are energized. Debapriya Das (2006) presented an algorithm for network reconfiguration based on fuzzy multi-objective approach. Four multiple objectives were considered for minimization of (i) real power loss (ii) nodes voltage deviation (iii) branch current constraint violation and (iv) feeder load imbalance and were modeled by fuzzy sets. Distribution system reconfiguration for loss reduction was first proposed by Merlin and Back (1975). They have used a branch-and-bound-type optimization technique to determine the minimum loss configuration. In this method, all network switches are first closed to form a meshed network. The switches are then opened successively to restore radial configuration. Taylor and Lubkeman (1990) implemented heuristic search strategies for feeder reconfiguration. A best-first tree searching strategy, based on heuristics, was used to evaluate various alternatives. A rule based system was created to avoid exhaustive search. Civanlar et al. (1988) made use solely of heuristics to determine a distribution system configuration which would reduce line losses. Civanlar et al. made use of what is known as a “branch exchange” operation for switching operations: the opening of any switch was required to correspond to the closure of another switch, ensuring that the radial nature of the distribution system would be preserved. Baran and Wu (1989) have made an attempt to improve the method of Civanlar et al. (1988) by introducing two approximation formulas for power flow in the transfer of system loads. The power-flow equations used by Baran and Wu were defined by recursive approximation of P, Q, and V at each node. Zhou et al. (1997) have proposed two feeder reconfiguration algorithms for the purpose of service restoration and load balancing. Their methodologies combined the optimization techniques with heuristic rules and fuzzy logic for efficiency and robust performance. Taleski and Rajicic (1997) have proposed a method to determine the configuration with minimum energy losses for a given period. Borozan and Rajakovic (1997) have considered the application aspects of optimal distribution network reconfiguration. Chichani and Hackam (1991) proposed a linear programming method using transportation techniques and a heuristic search method. A comparison was presented with the previously existing optimal load flow based heuristic techniques.

In this paper a method is presented considering multiple objectives for network reconfiguration in which all loads are kept energized. Heuristic rules are also incorporated in the proposed algorithm and considers only few switches to get the optimal solution. The proposed algorithm reduces the required number of load flow runs, thereby relieving from large computational burden.

2. Membership Functions of Different Objectives

In the fuzzy domain, each objective is associated with a membership function. The membership function indicates the degree of satisfaction of the objective. In the crisp domain, either the objective is satisfied or it is violated, implying membership values of unity and zero, respectively. On the contrary, 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 x_i be defined as $$x_i = \frac{PLOSS(i)}{PLOSS^0}, \text{ for } i = 1,2,\ldots N_k. \quad (1)$$

Where N_k is the total number of branches in the newly formed loop including tie- branch when k^{th} 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, and $PLOSS^\circ$ 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.

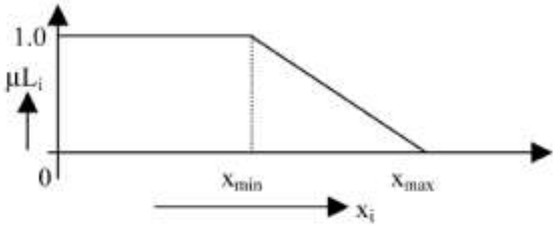


Fig. 1. Membership function for power-loss reduction.

The membership function for real power loss reduction is given in Fig.1. and μL_i can be written as

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

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

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

In this paper, it has been assumed that maximum reduction in losses is 50% and minimum reduction is 0%. Thus, x_{min}=0.5 and x_{max}=1.0. This means if the active power loss is 50% or less of the base case $PLOSS^0$, the unity membership value is assigned and if the loss is equals (100%) or more than base case $PLOSS^0$, the zero membership value is assigned. This implies that any branch opening in newly formed loop which causes higher losses need to be ignored.

2.2 Membership Function for Maximum Node Voltage Deviation (μV_i)

The basic purpose of this membership function is that the deviation of nodes voltage should be less.

Let ΔV_i be defined as $\Delta V_i = \max|V_{i,j} - V_s|$, for $i = 1,2,\ldots N_k$, $j = 1,2,\ldots NB$ (3)

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

NB is the total number of nodes in the system;

V_s is the Voltage of the substation (in per unit);

$V_{i,j}$ is the Voltage of node j corresponding to the opening of the ith branch in the newly formed 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.

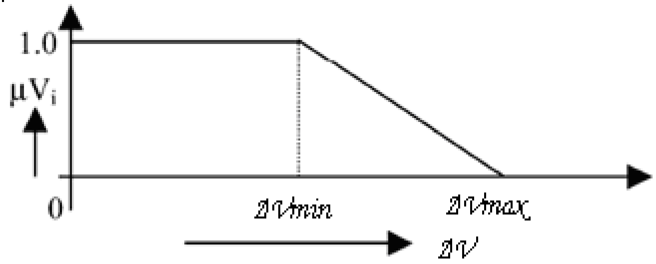


Fig. 2. Membership function for maximum node voltage deviation.

From Fig.2 it can written

$\mu V_i=(\Delta V_{max}-\Delta V_i)/(\Delta V_{max}-\Delta V_{min})$ for $\Delta V_{min}<\Delta V_i<\Delta V_{max}$

$\mu V_i=1,$ for $\Delta V_i \leq \Delta V_{min}$.

$\mu V_i=0,$ for $\Delta V_i \geq \Delta V_{max}$. (4)

In this paper, $\Delta V_{min} = 0.05$ and $\Delta V_{max} = 0.10$ have been considered. $\Delta V_{min} = 0.05$ means if the substation voltage is 1.0 p.u., then the minimum system voltage will be 0.95 p.u. and if system voltage is greater than or equal to 0.95 p.u., the unity membership value is assigned. Similarly if ΔV_{max} is 0.10, the permissible minimum system voltage will be 0.90 p.u. and if the minimum system voltage is less than or equals to 0.90 p.u., then zero membership value is assigned.

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

The basic purpose for this membership function is to minimize the branch current constraint violation. Let Branch current loading index be defined as,

$$\text{Branch current loading index} = \frac{|I(i,m)|}{I_c(m)}, \; m = 1,2,\ldots NB-1 \quad \text{for } i = 1,2,\ldots N_k \qquad (5)$$

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;

$I_c(m)$:line capacity of branch-m;

NB :total number of the nodes of the system.

$$\text{Let } z_i \text{ be defined as } \; z_i = \max\left[\frac{|I(i,m)|}{I_c(m)}\right], \text{ for } m=1,2....NB-1. \text{ for } i = 1,2,\ldots N_k \qquad (6)$$

When the maximum value of branch current loading index exceeds unity, a lower membership value is assigned and as long as it is less than or equal to unity, the maximum membership value is assigned (i.e., unity).

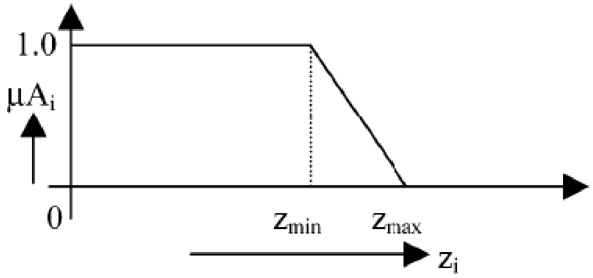


Fig.3: Membership Function For Maximum Branch Current Loading Index.

The membership function for the maximum branch current loading index is shown in Fig.3 and it can written,

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

$\mu A_i = 1$, for $z_i \le z_{\min}$.

$\mu A_i = 0$, for $z_i \ge z_{\max}$. (7)

In this case, $z_{min} = 1.0$ and $z_{max} = 1.15$ have been considered. $z_{min} = 1.0$ indicates that as long as the branch currents of the system are less than or equal to their respective line capacity, unity membership value is assigned and $z_{max} = 1.15$ indicates that 15% overloading is allowed for each branch and if in any branch, the current is greater than or equal to 1.15 times the line capacity, a zero membership value is assigned

2.4 Membership Function for Feeder Load Balancing (μB_i)

Load balancing is one of the major objectives of feeder reconfiguration. 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

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

where

N_k : total number of branches in the loop including the tie branch 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 ith branch in the loop;

IFF_i^{max}: maximum value of the feeder currents of various feeders corresponding to the opening of the ith branch in the loop = max(IF_{ij}), forj = 1,2,… NF.

Let f_i be defined as $f_i = \max(FLB_{i,j})$, for j = 1,2,…NF for i = 1,2,…N_k (9)

Equation (9) indicates that a better load balancing can be achieved if the value of f_i is low. Therefore, for lower f_i, a higher membership grade is assigned and for higher f_i, a lower membership grade is assigned.

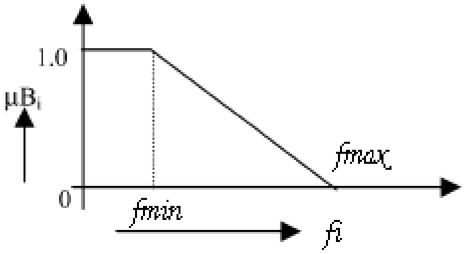


Fig.4: Membership Function For The Load Balancing Index.

From Fig. 4, we can write

$\mu B_i = (f_{max} - f_i)/(f_{max} - f_{min})$ for $f_{min} < f < f_{max}$

$\mu B_i = 1.0$, for $f_i \le f_{min}$

$\mu B_i = 0$, for $f_i \ge f_{max}$. (10)

In this case, $f_{min} = 0.10$ and $f_{max} = 0.50$ have been considered. $f_{min} = 0.10$ indicates that the maximum deviation of feeder currents will be 10% with respect to the maximum value of feeder current and if this deviation is less than or equal to 10%, the unity membership value is assigned and f_{max} = 0.50 indicates that if this deviation is greater than 50%, a zero membership value is assigned.

3. Optimization In Fuzzy Environment

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 multiobjective optimization in fuzzy framework is based on the max-min principle which is described as below.

Step 1)

Let N_{tie} be the number of tie switches in a given distribution network. Assume that kth tie switch is closed. Then N_k branches are observed in the newly formed loop. For each k^{th} tie switch closed and i^{th} branch opened, the membership values of all the different objectives are evaluated. After opening the ith branch in this loop (radial structure is retained), the load-flow run was carried out to compute μL_i, μV_i, μA_i, and μB_i, for i = 1,2,…N_k using equations (2), (4), (7) and (10) respectively. This aspect needs very large CPU time as it needs to cover N_k branches for each k-tie switch case and the same is to be repeated for N_{tie} switches.

Step 2)

The degree of overall satisfaction ($D_{k,i}$) for this option is the minimum of all the above membership values. Now, a fuzzy decision for overall satisfaction may be defined as the choice that satisfies all of the objectives and if we interpret this as a logical "and", it can be modelled with the intersection of the fuzzy sets. In this thesis work, classical fuzzy set intersection is used and the fuzzy decision for overall satisfaction is then given by $D_{k,i} = \min\{\mu L_i, \mu V_i, \mu A_i, \text{and } \mu B_i\}$, for i = 1,2,…$N_k$.

Step 3)

The optimal solution (OS_k) is the maximum of all such overall degrees of satisfaction. Now, a fuzzy decision for an optimal solution may be defined as the choice that maximizes all such overall degrees of satisfaction and if we interpret this as a logical "or" we can model it with the union of fuzzy sets. In this thesis work, the classical fuzzy set union is used and the fuzzy decision for an optimal solution is then given by $OS_k = \max\{D_{k,i}\}$, for i = 1,2,…N_k.

At the end of step 3, it will be indicating the optimal branch i to be opened with the k^{th} tie switch closed.

The above process (steps 1 to 3) is to be repeated for remaining tie-switch cases identifying the tie-switch which has maximum voltage deviation across its nodes.

4. Heuristic Rules For Minimizing The Number Of Tie-Switch Operations And Algorithm

In the present work, heuristic rules are considered which minimize the number of tie-switch operations. These heuristic rules are explained below.

In the first iteration, compute the voltage difference across all of the open tie switches and detect the open tie switch across which the voltage difference is maximum. If this maximum voltage difference is greater than some specified value (ε), 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 .

4.1 Algorithm for the Proposed Heuristic Based Fuzzy Method

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

Step 1) Read system data;

Step2) Run the SMM YY model load-flow program for radial distribution networks;

Step 3) Compute the voltage difference across the open tie switches (i.e., $\Delta V_{tie}(i)$ for i 1,2,…ntie);

Step 4) Identify the open tie switch across which the voltage difference is maximum and its code k

(i.e., $\Delta V_{tie,max} = \Delta V_{tie}(k)$);

Step 5) If $\Delta V_{tie,max} > \varepsilon$, go to Step 6); otherwise, go to Step 10);

Step 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;

Step 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 μL_i, μV_i, μA_i, and μB_i using (2), (4), (7)and (10), respectively, and evaluate: $D_{k,i}=\min\{\mu L_i, \mu V_i, \mu A_i, \text{ and } \mu B_i\}$

Step 8) Obtain the optimal solution for that operation of tie-switch "k," (i.e., $OS_k=\max\{D_{k,i}\}$, for i = 1,2,…,N_k);

Step 9) ntie = ntie – 1. If ntie>0 go to step 2;

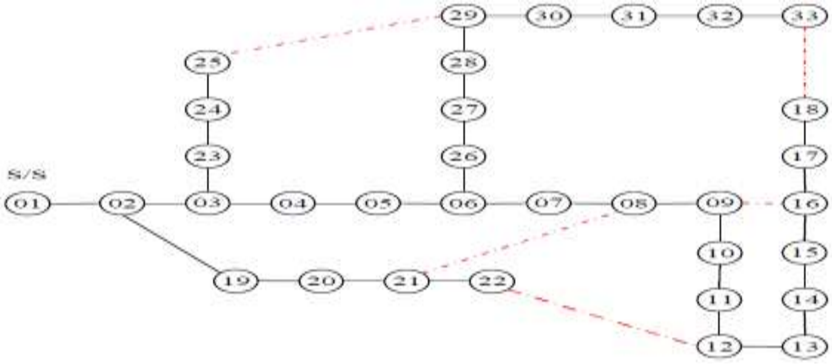
Step 10) Print output results;

Step 11) Stop

5. Test Cases

The proposed algorithm has been tested on 33, 69 and 70 bus Distribution systems. 33 bus system is having single substation with 5 – tie switches. 69 bus system also has single substation with 5-tie switches. The 70 bus system is with two substations, four feeders and 11- tie switches.

5.1 33-Bus Single Feeder Circuit (Single Substation)



----------------- Tie-switches

___________ sectionalizing switches

Fig. 5. Bus System Before Reconfiguration

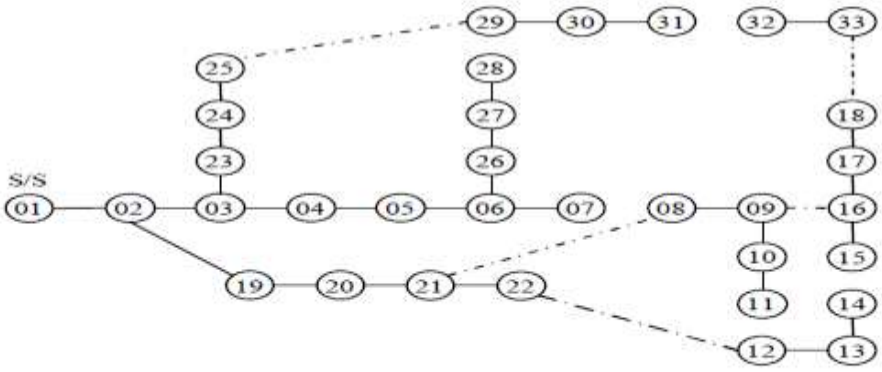


Fig.6. Bus System After Reconfiguration

5.2 69-Bus Single Feeder Circuit (Single Substation)

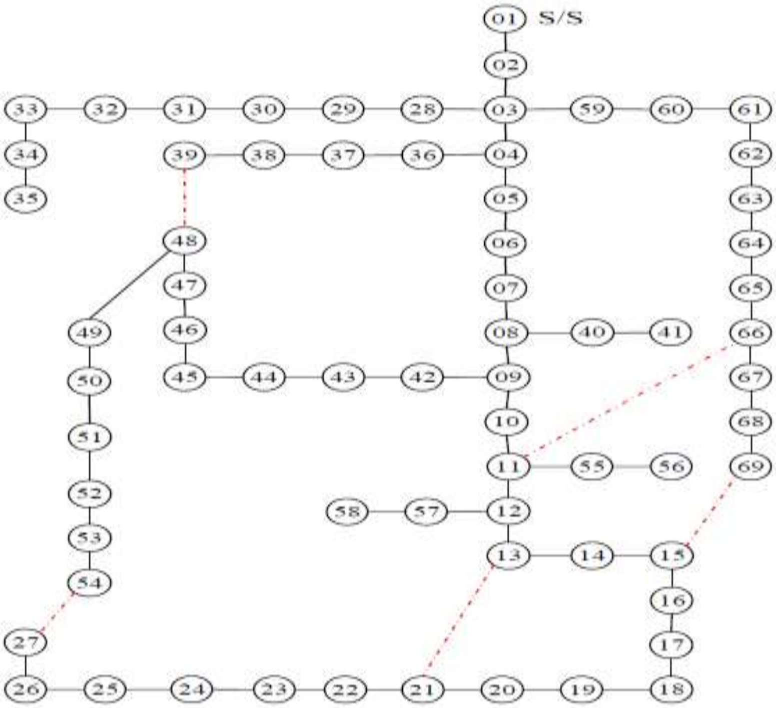


Fig.7. Bus System Before Reconfiguration

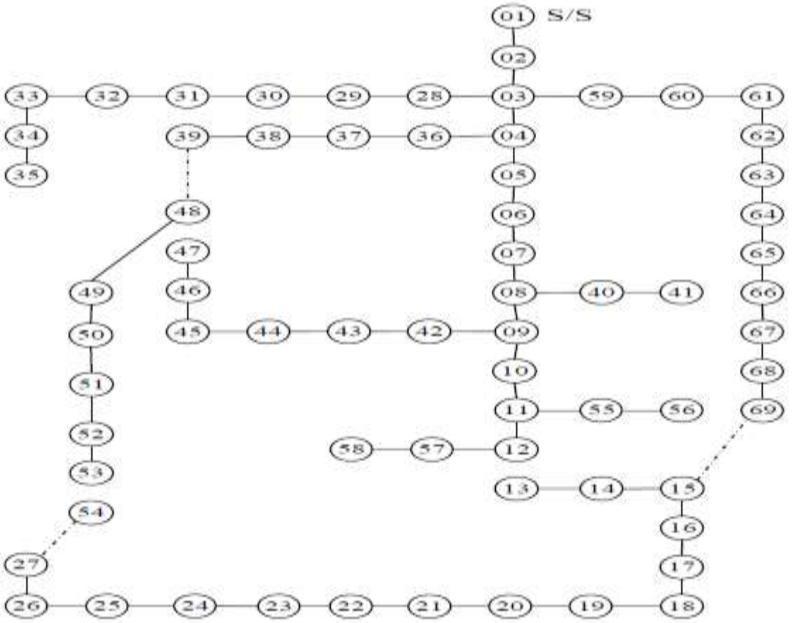


Fig.8. Bus System After Reconfiguration

5.3 Bus Four Feeder Circuit (Two Substations)

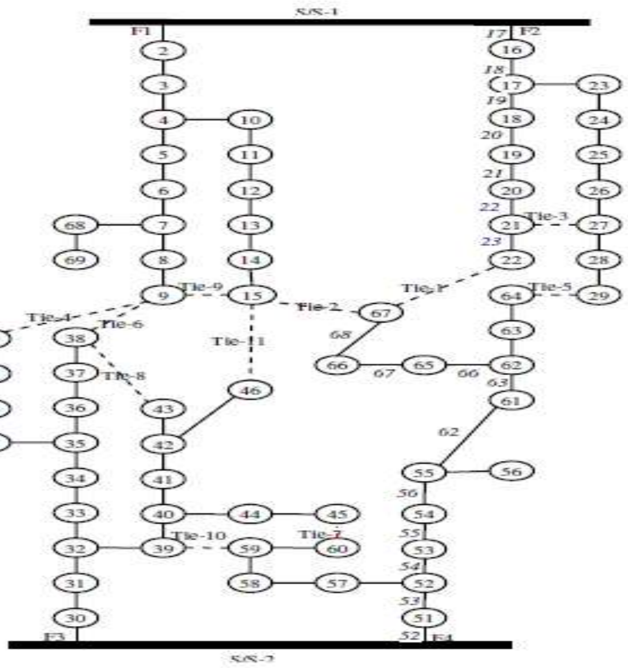


Fig.9. 70 Bus System Before Reconfiguration

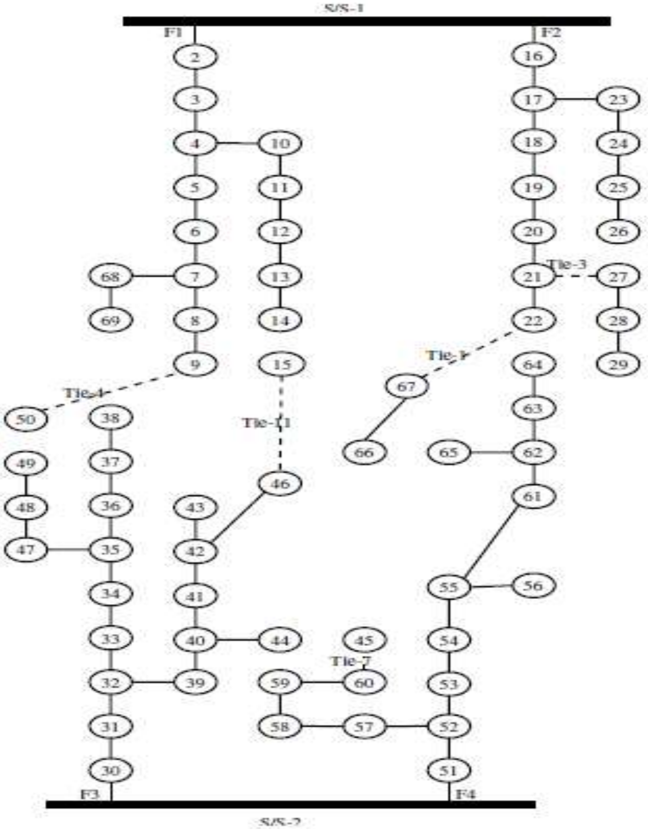


Fig.10. 70 Bus System After Reconfiguration

6. RESULTS

For a 33-Bus Single Feeder Circuit (Single Substation)

Before network reconfiguration,

The total real power loss is 373.63 KW.

The minimum voltage is $V_{min} = V_{33} = 0.877172$ p.u.

After reconfiguration,

The total real power loss is 243.99 kW.

The minimum voltage is $V_{min} = V_{32} = 0.899635$ p.u.

After network reconfiguration, the real power loss reduction is 34.7% and minimum voltage of the system has improved from 0.877172 to 0.899635 p.u.

Table1. Optimal Solution for Tie Switch Operation of 33 Bus System

Tie-Switch Operation (Tie-k)	Optimal Solution (Os_k)
tie-1	0.156802
tie-4	0.181545
tie-3	0.189632

tie-7	0.20084
tie-11	0.207366

Table 2. Feeder Currents of 33 Bus System

Feeders Current (Amp.)	
Before Reconfiguration	After Reconfiguration
IF_1 = 99.11	IF_1 = 115.87
IF_2 = 106.73	IF_2 =129.42
IF_3 =159.38	IF_3 = 131.71
IF_4 =147.34	IF_4 = 133.24

From Table 2, it is seen that the feeders current are more balanced after reconfiguration.

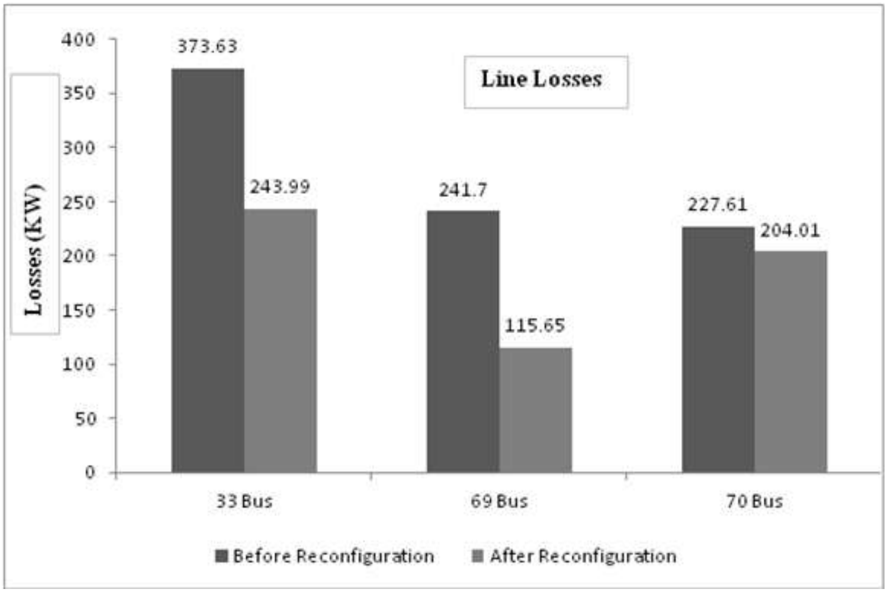


Fig.11 Line Losses of 33, 69&70 Bus Systems Before & After Reconfiguration

7. Conclusion

In this paper, a heuristic-based fuzzy multi-objective algorithm has been presented to solve the network reconfiguration problem in a radial distribution system.

The objectives considered attempt to maximize the fuzzy satisfaction of Minimization of real power loss, minimization of the deviations of nodes voltage, minimization of the branch current constraint violation and feeder load balancing among various feeders subject to the radial network structure in which all loads must be energized.

The algorithm also minimizes the number of tie-switch operations, the obtained results are quite good and they encourage the implementation of the strategy on a large-size distribution network.

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