Fuzzy Multi-Objective Approach for Reconfiguration of Electric Distribution Network

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Abstract – Since electric distribution network reconfiguration accounts for various operational constraints it is a combinatorial optimization problem. This paper presents a fuzzy multi-objective approach to improve the efficiency of radial electric distribution network by reducing active power loss and node voltage deviation. Multiple objectives considered are minimizing the active power loss and minimizing node voltage deviation, subject to a radial network structure in which all loads must be energized. Evaluations of imprecise nature of these two objectives are modeled with fuzzy sets. Depending on relative importance weighing factors can be assigned to each objective. The effectiveness of the proposed method is tested with IEEE 33 bus radial distribution system for minimization of system active power loss and reducing node voltage deviation.

Index Terms – Electric Distribution Network, Fuzzy Logic, Multi-objective optimization, Radial distribution System, Reconfiguration.

1. INTRODUCTION

Power distribution systems are usually configured radially, but the act of opening or closing switches or protection devices can possibly change the topology of such systems. In this context, the network is reconfigured to maintain its radial topology and also to reduce power losses at the feeders, to enhance the voltage profile for customers, and to increase the reliability levels.

A Radial distribution system is a combination of Sectionalizing switches (Normally Closed) and Tie switches (Normally Open). By performing switching actions, we can alter the topology of the network and obtain the best possible configuration. The switching action depends on the number of switches. The greater the number of switches more is the possibilities of reconfiguration. To minimize the number of switching actions, we incorporate different methods. Though there are many options for reducing losses in a distribution system viz., reconfiguration, capacitor placement, load feeder balancing etc., reconfiguration is the most preferred method because it requires no extra equipment to be installed and is cost effective.

In recent years, considerable research has been conducted for loss minimization in the area of network reconfiguration of distribution systems. Various algorithms are proposed and tested for network reconfiguration.

Merlin, et al [1], first proposed reconfiguration for distribution system. For determining minimum loss configuration he used a branch-and-bound-type optimization technique. In this method, meshed network is first formed by closing all network switches. Radial configuration is then restored by opening switches one after another. Based on the method presented by Merlin, et al [1], Shirmohammadi, et al [2], presented heuristic algorithm. In this method also, the optimum flow pattern in the network is established by closing all of the network switches and then opening it one after another. This helped overcoming many approximations of Merlin, et al [1] algorithm.

The heuristic algorithm based on power flow is proposed by Goswami, et al [3]. It has used Shirmohammadi, et al's [2] method to determine the minimum loss configuration of radial distribution networks. To determine a distribution system configuration, simplified formula is developed by Civanlar, et al [4] to calculate the loss reduction that has resulted due to load transfer between two feeders. It has considered only one objective that is power loss reduction. To obtain global optimal or, at least near global optimal solutions for reconfiguration of distribution network Chiang, et al [5,6] and Jeon, et al [7] have proposed solution techniques, using simulated annealing. But it is very time consuming. Using simulated annealing technique Jiang, et al [8] have presented an algorithm for switch reconfiguration and capacitor control of distribution system. Lee, et al [9] has proposed a performance index based approach using heuristic rule for resistive loss reduction. Aoki, et al [10] have altogether different approach for this problem. They have formulated it as a discrete optimization problem. Pattern recognizer neural networks are used by Fereidunian, et al [11] for distribution reconfiguration algorithm. Wagner, et al [12] has presented comparison of various methods which are applied to network reconfiguration for loss reduction. They have that suggested that substantial savings can be provided by heuristic approaches so these are suitable for real time implementation. Algorithms employing artificial intelligence for network reconfiguration of distribution network are proposed by Hsiao, et al [13], Jeon, et al [14], Shin, et al [15], Hsiao [16], Lin, et al [17], Das [18] and Hong, et al [19]. The disadvantage with most of the above mentioned algorithms is that they focus only power loss reduction as the objective of network reconfiguration. Few even though have considered multiple objectives; they have employed global optimization approaches such as genetic algorithms, evolutionary programming, and simulated annealing and hence are not suitable for real time implementations.

In the light of the above developments and subject to operational and electric constraints this work formulates the network reconfiguration problem as a multiple objective problem. The proposed method makes use of heuristic rules for selection of tie-switch for operation. The objectives considered for problem formulation are

1. Minimization of the system power loss.
2. Minimization of the deviations of the nodes voltage.

2. MEMBERSHIP FUNCTIONS FOR DIFFERENT OBJECTIVES

Fuzzy multi-objective method in this paper is developed by D. Das [18]. Each objective in fuzzy domain is associated with a membership function. The degree of satisfaction of the objective is indicated by the membership function. In the crisp theory, the objective is either satisfied or it is not satisfied. If satisfied, membership value is unity and in case of violation it is zero. But in fuzzy sets varying degrees of membership function values can be assigned. It can range from zero to unity. Thus, fuzzy set theory is an extended form of standard set theory.

2.1. Membership Function for Real Power Loss Reduction (μL_i)

The efficiency of distribution network can be increased by minimizing the active power loss. Therefore, the aim of this fuzzy membership function is to reduce the active power loss of the system.

$$x(i) = \frac{P_{loss(i)}}{P_{loss(0)}} \qquad for\ i = 1,2,3, \dots, N_k \tag{1}$$

where, N_k is the total number of branches in the loop including tie-branch, when i^{th} tie-switch is closed, $P_{loss(i)}$ is the total real power loss of the radial configuration of the system when i^{th} branch in the loop is opened, and $P_{loss(0)}$ is the total real power loss before network reconfiguration.

From equation (1) it can be expressed 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.

The membership function for real power loss reduction is given in Figure 1. From Figure 1, μLi can be written as

$$\mu L_i = \frac{(x_{max} - x_i)}{(x_{max} - x_{min})}\ , \quad for\ x_{min} < x_i < x_{max} \tag{2}$$

Where,

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

$\mu L_i = 0\ , \ for\ x_i \le x_{max}$

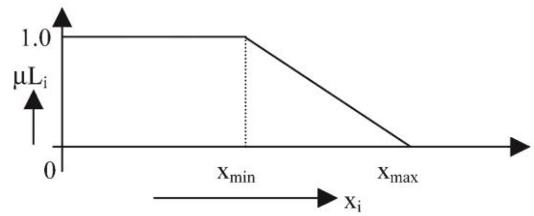

Figure 1. Membership Function for Power Loss Reduction.

In this study, it is assumed that x_{min} = 0.5 and x_{max}= 1. This indicates that if the loss is 50% or less of the $P_{loss}(0)$, the unity membership value is assigned and if the loss is 100% or more of $P_{loss}(0)$, the zero membership value is assigned.

2.2. Membership Function for Maximum Node Voltage Deviation (μV_i)

The aim of this membership function is that the deviation of node voltages should be less. Let us define

$$y_i = max\left|V_{i,j} - V_s\right|, \quad For\ i = 1,2,3, \dots, N_k$$
$$and\ j = 1,2,3, \dots, NB \tag{3}$$

where, N_k is total number of branches in the loop including the tie branch, when the i^{th} tie switch is closed; NB is total number of nodes of the system; V_s is voltage of the substation (in per unit); and $V_{i,j}$ is voltage of node corresponding to the opening of the i^{th} branch in the loop (in per unit).

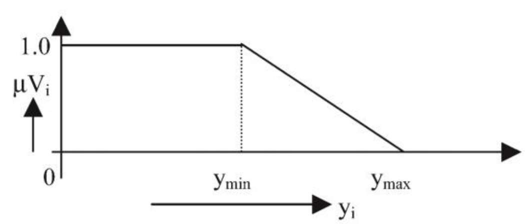

Figure 2. Member Ship Function for Maximum Node Voltage Deviation

In fuzzy environment of the research, if the maximum voltage deviation is less, then a higher membership value is assigned and if deviation is more, then a lower membership value is assigned. Figure 2 shows the membership function for maximum node voltage deviation. From Figure 2, we can write

$$\mu V_i = \frac{(y_{max} - y_i)}{(y_{max} - y_{min})}, \quad for\ y_{min} < y_i < y_{max} \quad (4)$$

Where

$\mu V_i = 1, \quad for\ y_i \le y_{min}$

$\mu V_i = 0, \quad for\ y_i \le y_{max}$

In this study, y_{min}= 0.05 and y_{max}= 0.10 have been considered. y_{min}= 0.05 means if the substation voltage is 1.0 per unit, then the minimum system voltage will be 0.95 per unit and if the minimum system voltage is greater than or equal to 0.95 p.u., the unity membership value is assigned. Similarly, if y_{max}= 0.10, the minimum system voltage will be 0.90 per unit and if the minimum system voltage is less than or equal to 0.90 per unit, the zero membership value is assigned.

3. MULTIOBJECTIVE OPTIMIZATION

In many real-world design or decision making problems Global optimization techniques are not just used for finding the maxima or minima of single functions f but they are rather applied to sets F consisting of n = $|F|$ objective functions f_i, each representing one criterion to be optimized.

$$F = \{f_i: \mathbb{X} \to Y_i : 0 < i \le n, Y_i \subseteq \mathbb{R}\} \quad (5)$$

Algorithms designed to optimize such sets of objective functions are usually named with the prefix Multi-objective,

Vilfredo Pareto, 110 years ago has laid the mathematical foundation for multi-objective optimization which considers conflicting criteria in a fair way. Pareto optimality became an important notion in economics, game theory, engineering, and social sciences. It defines the frontier of solutions that can be reached by trading-off conflicting objectives in an optimal manner. From this front, a decision maker either a human or an algorithm can finally choose the configurations that, in his opinion, suit best. The notation of optimal in the Pareto sense is strongly based on the definition of domination.

An element x_1 dominates an element x_2 if x_1 is better than x_2 in at least one objective function and not worse with respect to all other objectives.

An element $x^* \in \mathbb{X}$ is Pareto optimal and hence, part of the optimal set X^*, if it is not dominated by any other element in the problem space $\mathbb{X}$. In terms of Pareto optimization, X^* is called the Pareto set or the Pareto Frontier.

4. FUZZY MULTIOBJECTIVE OPTIMIZATION

When there are multiple objectives to be satisfied simultaneously, it is required to find Pareto Optimal solution. One solution methodology for the multi-objective optimization in fuzzy framework can be performed by using max–min principle [20-21]. It is described as follows.

1. The Membership values of all the different objectives are evaluated for each option considered. For example, when the k^{th} tie switch of a distribution system is closed, a loop is formed with N_k number of branches in the loop. Now, opening each branch in this loop is an option. After opening the i^{th} branch in this loop (radial structure is retained), the load-flow run was carried out to compute μL_i and μV_i for $i=1,2,3\ldots N_k$.

2. The degree of overall satisfaction 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", we can model it with the intersection of the fuzzy sets then it is given by

$$D_{k,i} = min\ \{w_1 * \mu Li,\ w_2 * \mu Vi\}, \quad for\ i= 1,2,\ldots N_k \quad (6)$$

Where, w_1, w_2 are weighting factors which can be used to assign relative importance to the objectives during optimization.

3. The optimal solution OS_k is the maximum of all such overall degrees of satisfaction. In the present work, the classical fuzzy set union is used and the fuzzy decision for an optimal solution is then given by

$$OS_k = max\ \{D_{k,i}\}, \quad for\ i = 1, 2, \ldots, N_k \quad (7)$$

5. ALGORITHM

The optimal switching strategies for network reconfiguration proposed by most of the researchers need to consider every candidate switch to evaluate the effectiveness of loss reduction, and extensive numerical computation is often required. 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 say δ, then this tie switch is considered first. It is expected that because of the largest voltage difference, this switching will cause maximum loss reduction, and improvement in system voltage. It will also 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 (δ), then this tie-switch operation is discarded. A complete algorithm for the proposed method of the network reconfiguration process is given below:

Step1. Read system data.

Step2. Run the load-flow program for distribution networks.

Step3. Compute the voltage difference across the open tie switches (i.e. $\Delta V_{tie}(i)\ for\ i = 1,2, \dots n^{th}\ tie$)

Step4. Identify the open tie switch across which the voltage difference is maximum and its code k (i.e.$\Delta V_{tiemax} = \Delta V_{tie}(k)$)

Step5. If $V_{tiemax} > \delta$ go to Step6 otherwise, go to Step10.

Step6. 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;

Step7. 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 μLi, μVi, using (2) and (4), respectively, and evaluate: $D_{k,i} = min\{w_1 * \mu Li, w_2 * \mu Vi\}$; Where w_1 and w_2 are weighting factors for power loss and voltage deviation which are defined by operator depending on relative importance of corresponding objectives. In proposed study same value is assigned to w_1 and w_2 which means equal importance to both objectives.

Step8. Obtain the optimal solution for the operation of tie switch "k", (i.e., $OS_k = max\{D_{k,i}\}$, for $i = 1, 2, \dots, N_k$).

Step9. Rearrange the coding of the rest of the tie switches and go to Step2.

Step10. Print output results;

Step11. Stop.

6. EXPLAINATION OF PROPOSED METHOD

Proposed algorithm is explained by using standard IEEE 33 Bus system. Consider the sample radial distribution system as shown in Fig. 3.

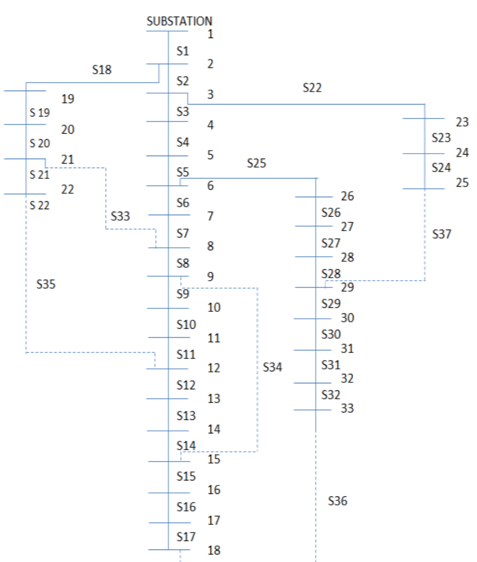

Figure 3. IEEE 33 Bus

It is assumed that every branch has a sectionalizing switch. This system has one feeder, five tie branches, and five tie switches. Initially, run the load-flow program. Now compute the voltage difference across all of the open tie-switches and detect the open tie-switch across which the voltage difference is maximum. Say the voltage difference across the open tie switch, S35 is maximum. Now check whether this voltage difference is greater than some specified value (δ) or not. Say this voltage difference is greater than δ ; therefore, this tie switch S35 will be considered first.

Now if tie S35 is closed, a loop will be formed and the total number of branches including tie branch (12–22) in this loop will be 15. These branches are 12–22, 22–21, 21–20, 20–19, 19–2, 2–3, 3–4, 4–5, 5–6, 6-7, 7-8, 8-9, 9-10, 10-11 and 11-12. Opening each branch in this loop is an option. As discussed, for each option considered, the membership values of all the objectives are evaluated. Therefore, to maintain radial structure one branch at a time in the loop is opened and the membership value of each objective is evaluated.

To explain, as tie switch S35 is closed, to maintain radial structure first open the sectionalizing switch of branch 22–21 and run the load-flow program. After that, compute μLi and μVi using (2) and (4) respectively. Now the overall degree of satisfaction for this option using (6) is

$$D_{1,1} = \min\{\ \mu L_1\ ,\ \mu V_1\ \} \quad (8)$$

Note that here loss and node voltage deviations have given equal priority so w_1 and w_2 are taken to be 1. Now close the sectionalizing switch of branch 21–20, and open the sectionalizing switch of branch 22–21 and run the load-flow program. Now, the overall degree of satisfaction for this option is computed as

$$D_{1,2} = \min\{\ \mu L_2\ ,\ \mu V_2\ \} \quad (9)$$

Similarly, $D_{1,1}, D_{1,2} \dots, D_{1,15}$ have to be computed. The optimal solution OS_1 for tie switch S35 is the maximum of all such overall degrees of satisfaction. Therefore, the optimal solution for tie switch S35can be given as

$$OS_1 = max\{\ D_{1,1}, D_{1,2} \dots, D_{1,15}\ \} \quad (10)$$

Assume, $OS_1 = D_{1,2}$, which means the optimal solution for this tie switch S35 operation can be obtained by opening the sectionalizing switch of branch 22–21 and closing the tie switch of the tie branch 22–12, and the radial structure of the network is retained. Fig. 4 shows the radial configuration of the network after the first switching operation.

Again, run the load-flow program, and the voltage difference across the remaining open tie switches (i.e S33, S34, S37 and S37) is computed and suppose the voltage difference across tie switch S34 is maximum. Now check whether the voltage difference across S34 is greater than δ or not. If it is greater than δ then tie switch S34 is closed to form a loop in this system and a similar procedure is repeated as mentioned before.

Suppose the optimal solution for this tie switch (S34) operation suggests opening the sectionalizing switch of branch 10–11 and closing the tie switch (S34) of the tie- branch 9–15. Therefore, the sectionalizing switch of branch 10–11 must be opened and the tie-switch (S34) of the tie- branch 9–15 must be closed. Fig. 5 shows the radial configuration of this network which gives optimal solution.

Again, run the load-flow program and the voltage difference across remaining tie-switches is computed. Same procedure as discussed above is repeated till all tie branches are tested.

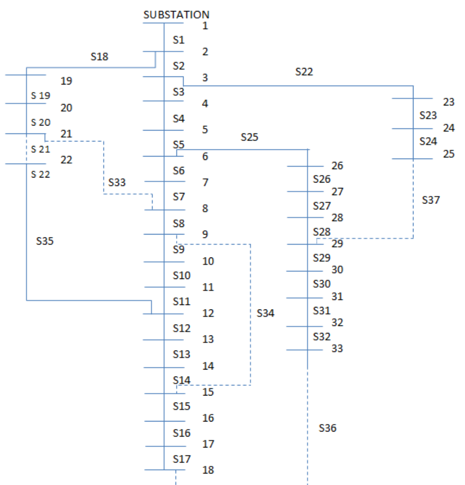

Figure 4. Reconfiguration with S35 Closed

7. RESULTS

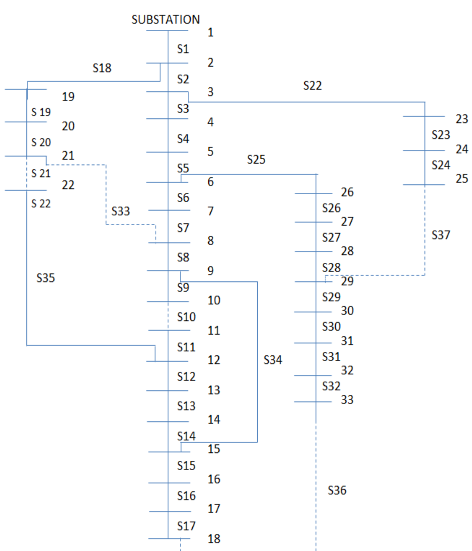

Figure 5. Reconfiguration when S34 is closed

Simulation and testing of proposed algorithm is done in MATLAB with IEEE 33 Bus system. It is radial distribution system with one feeder, having nominal voltage of 12.66kv and all loads are balanced. It has 32 sectionalizing branches and 5 tie branches. It is shown in Fig.3. Line and load data is provided in Appendix A.

Before network reconfiguration, the total real power loss of this system is 208.4 kW. The minimum node voltage is 0.91p.u. Fig. 6 shows the final radial configuration of the system. After reconfiguration, the total real power loss is 138.92kW. The minimum node voltage is 0.94p.u.

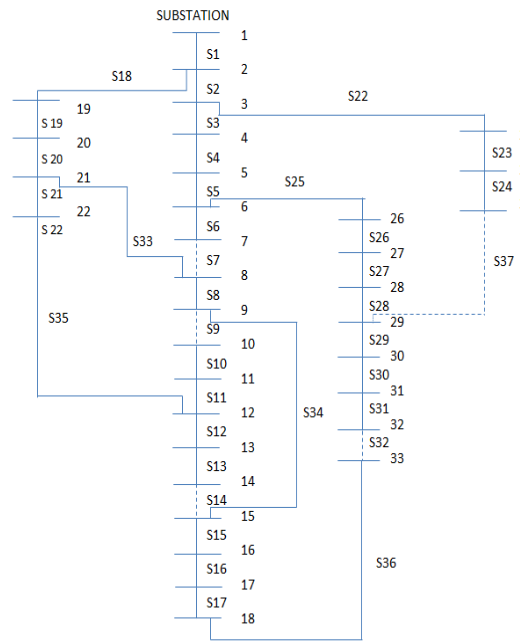

Figure 6. Bus Structure After Reconfiguration

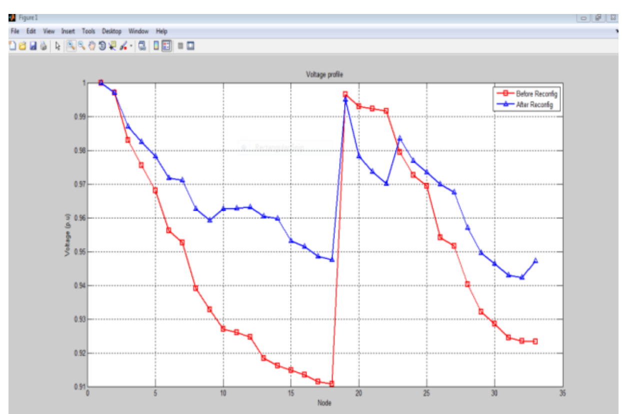

Figure 7. Voltage Profile

This clearly shows reduction of system power loss by 33.35% and improvement in node voltage deviation from 0.91pu to 0.94pu. Table 1 gives detailed result along with tie switches before and after reconfiguration. System voltage profile is shown in Fig.7

****************** SIMULATION RESULTS OF 33 BUS DISTRIBUTION NETWORK *******************

	BEFORE RECONFIGURATION	AFTER RECONFIGURATION
Tie switches:	33 34 35 36 37	7 9 14 32 37
Power loss:	208.4592 kW	138.9275 kW
Power loss reduction:	_____	33.355 %
Minimum voltage:	0.91075 pu	0.94234 pu

Table 1. Simulation Result

8. CONCLUSION

To solve network reconfiguration problem fuzzy multi-objective algorithm has been proposed in present work. The objectives considered are minimization of real power loss and minimization of the deviations of nodes voltage, subject to maintenance of the radial network structure. It is possible to consider few other objectives like minimization of branch current constraint violation and load balancing for optimization. The proposed algorithm also attempts to minimize the number of tie-switch operations which in turn reduces computational time. This simulation has proved the feasibility of the proposed algorithm. The obtained results are quite encouraging which suggests the implementation of the strategy on a large-size distribution network.

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APPENDIX

Bus No.	P_L (kW)	Q_L (kVAr)	Bus No.	P_L (kW)	Q_L (kVAr)
2	100	60	18	90	40
3	90	40	19	90	40
4	120	80	20	90	40
5	60	30	21	90	40
6	60	20	22	90	40
7	200	100	23	90	50
8	200	100	24	420	200
9	60	20	25	420	200
10	60	20	26	60	25
11	45	30	27	60	25
12	60	35	28	60	20
13	60	35	29	120	70
14	120	80	30	200	100
15	60	10	31	150	70
16	60	20	32	210	100
17	60	20	33	60	40

Table A1. Load data for 33-bus distribution system

Table A2. System data for 33-bus distribution system

Branch No.	Sending End	Receiving End	R (Ω)	X (Ω)
1	1	2	0.0922	0.0470
2	2	3	0.4930	0.2512
3	3	4	0.3661	0.1864
4	4	5	0.3811	0.1941
5	5	6	0.8190	0.7070
6	6	7	0.1872	0.6188
7	7	8	0.7115	0.2351
8	8	9	1.0299	0.7400
9	9	10	1.0440	0.7400
10	10	11	0.1967	0.0651
11	11	12	0.3744	0.1298
12	12	13	1.4680	1.1549
13	13	14	0.5416	0.7129
14	14	15	0.5909	0.5260
15	15	16	0.7462	0.5449
16	16	17	1.2889	1.7210
17	17	18	0.7320	0.5739
18	2	19	0.1640	0.1565
19	19	20	1.5042	1.3555
20	20	21	0.4095	0.4784
21	21	22	0.7089	0.9373
22	3	23	0.4512	0.3084
23	23	24	0.8980	0.7091
24	24	25	0.8959	0.7071
25	6	26	0.2031	0.1034
26	26	27	0.2842	0.1447
27	27	28	1.0589	0.9338
28	28	29	0.8043	0.7006
29	29	30	0.5074	0.2585
30	30	31	0.9745	0.9629
31	31	32	0.3105	0.3619
32	32	33	0.3411	0.5302
34	8	21	2.0000	2.0000
36	9	15	2.0000	2.0000
35	12	22	2.0000	2.0000
37	18	33	0.5000	0.5000
33	25	29	0.5000	0.5000

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