TECHNICAL NOTE

A MULTI-OBJECTIVE METHOD FOR NETWORK RECONFIGURATION

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Abstract This paper presents an algorithm based on multi-objective approach for network reconfiguration. Multiple objectives are considered for reduction in the system power loss, deviations of the nodes voltage and transformers loading imbalance, while subject to a radial network structure in which all the loads must be energized and no branch current constraint is violated. These three objectives are integrated into an objective function through weighting factors and the configuration with minimum objective function value is selected for each tie-switch operation. Heuristic rule is also incorporated in the algorithm for selecting the sequence of tie-switch operation. The effectiveness of the proposed method is demonstrated through examples.

Keywords Distribution System, Network Reconfiguration, Multi-Objective Optimization

چکیده این مقاله الگوریتمی بر پایه رویکرد چندهدفی برای شکل‌دهی مجدد شبکه را ارائه می‌کند. چندین هدف برای کاهش افت توان سیستم بررسی شده، انحراف‌های ولتاژ گره‌ها و عدم توازن بارگذاری ترانسفورمرها دنبال می‌شود، در حالی‌که ساختار شبکه شعاعی مدنظر است که در آن تمام بارها باید انرژی‌گذاری شوند و از مرز هیچ‌یک از حدود(محدودیت‌های) جریان شاخه‌ای تجاوز نمی‌شود. این سه هدف با ضرایب وزنی در یک تابع هدف جمع شده‌اند و کمترین تابع هدف برای عملکرد هر tie-switch انتخاب‌شده‌است. در الگوریتم انتخاب ترتیب عملکرد tie-switch از قانونی ابتکاری استفاده شده است. کارایی روش پیشنهادی با مثال‌هایی اثبات شده است.

1. INTRODUCTION

Distribution networks are generally built as meshed networks but they are operated radially. Their configuration may be varied with manual or automatic switching operations to transfer loads from one feeder to the other. Network reconfiguration is the process of changing the topology of distribution system by altering the status of sectionalizing (normally closed) and tie (normally open) switch in such a way that the radiality of the network is maintained and all the loads are supplied. It reduces power loss, increases system security, enhances power quality and relieves the overloading of the network components. As there are many candidate-switching combinations in the distribution system, network reconfiguration is a complicated combinatorial, non-differentiable constrained optimization problem.

During the last few years, extensive research has been carried out for loss minimization in the area of network reconfiguration of distribution systems. Distribution system reconfiguration for loss reduction was first proposed by Merlin, et al [1], using 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 one after another to restore radial configuration. Shirmohammadi, et al [2] have proposed a heuristic algorithm based on the method presented by Merlin, et al [1]. In this method also, 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. Many approximations of the method of Merlin, et al [1] have been overcome in this algorithm.

Civanlar, et al [3] have developed a simplified formula to calculate the loss reduction as a result of load transfer between two feeders which is used to determine a distribution system configuration. The algorithm considers only power loss reduction as the objective. Goswami, et al [4] reported a power flow based heuristic algorithm for determining the minimum loss configuration of radial distribution networks based on Shirmohammadi, et al [2]. Jiang, et al [5] have presented a comprehensive algorithm for distribution system switch reconfiguration and capacitor control employing simulated annealing technique. Chiang, et al [6,7] and Jeon, et al [8] have proposed solution techniques based on simulated annealing algorithm to obtain global optimal or, at least near global optimal solutions for network reconfiguration. These algorithms being based on simulated annealing have the disadvantage that they are time consuming. Wagner, et al [9] has presented a comparison of various methods applied to feeder reconfiguration for loss reduction. They have suggested that heuristic approaches can provide substantial savings and are suitable for real-time implementation. Lee, et al [10] has proposed a heuristic rule and performance index based approach for resistive loss reduction. Aoki, et al [11] have formulated minimization of losses in a distribution system as a discrete optimization problem. Fereidunian, et al [12] presented a distribution reconfiguration algorithm using pattern recognizer neural networks. Lin, et al [13], Hsiao, et al [14], Jeon, et al [15], Shin, et al [16], Hsiao [17], Hong, et al [18], and Das [19,20] have proposed artificial intelligence based applications for network loss configuration. The disadvantage with most of the above mentioned algorithms is that some of them consider only power loss reduction [3-11] as the objective of network reconfiguration, while some others, even though consider multiple objectives, global optimization approaches such as genetic algorithms, evolutionary programming, and simulated annealing [13-18] are used for obtaining the resulting configuration and hence they are not suitable for real time implementations.

In the light of the above developments, this work formulates the network reconfiguration problem as a multiple objective problem subject to operational and electric constraints. The proposed method also incorporates a heuristic rule for selection of tie-switch for operation. The problem formulation proposed herein considers three objectives related to:

1. Minimization of the system power loss.
2. Minimization of the deviations of the nodes voltage.
3. Minimization of transformers loading imbalance.

2. DEFINITIONS OF DIFFERENT INDICES AND OBJECTIVE FUNCTION

Multi-objective optimization problems have many objectives and trade-off between the objectives exist and we never have a situation in which all the objectives can be simultaneously satisfied in the best possible way. The three objectives, described as follow are integrated into an objective function through appropriate weighting factors.

2.1. Real Power Loss Reduction Index Real power loss reduction index may be defined as:

$$X_i = \frac{Ploss(i)}{Ploss^0} \quad \forall\, i = 1, 2, ..., N_k \tag{1}$$

Equation 1 indicates that if X_i is low then power loss reduction is high. The value of X_i should be less than unity for reduction of losses. During iterative process, if X_i is greater than unity, value of objective function is set to very high value of 10000000.

2.2. Maximum Voltage Deviation Index Maximum voltage deviation index may be defined as:

$$Y_i = \max\left| V_s - V_{i,j} \right| \quad \forall\, i = 1, 2, ..., N_k \quad \forall\, j = 1, 2, ..., NB \tag{2}$$

In this case, if the value of Y_i is low, the system has better voltage profile. For example if the substation voltage is 1.0 pu and system minimum voltage constraint is set to V^s_{min} = 0.9 pu, then Y_i = Y_{max} = 0.10. Therefore, it is desirable that during iterative process, Y_i must be less than 0.10. If the value of Y_i is greater than 0.10, the value of objective function is set to very high value of 10000000.

2.3. Transformer Load Balancing Index

Transformer load balancing index is defined as:

$$Z_i = \max\left(\frac{ITr^{Opt}_{i,j} - ITr_{i,j}}{ITr^{Opt}_{i,j}}\right) \quad \forall i = 1, 2, ..., N_k \quad \forall j = 1, 2, ..., N_t \qquad (3)$$

Equation 3 indicates that a better transformer load balancing can be achieved if the value of Z_i is low. In this case a limit is imposed on Z_i, i.e., Z_i = Z_{max} = 0.20. Z_{max} = 0.20 indicates that the maximum deviation of transformer currents will be 20 % with respect to the optimum transformer current. During iterative process, if Z_i is greater than 0.20, the objective function value is set to very high value of 10000000.

The three different indices described above are combined through appropriate weighting factors to form the objective function as follows:

$$J_i = w_1 X_i + w_2 Y_i + w_3 Z_i \qquad \forall i = 1, 2, ..., N_k \qquad (4)$$

In the deregulated scenario, it is important that in addition to real power loss reduction, the reconfiguration algorithm considers improvement of system voltage and that transformers in the distribution system are almost balanced based on their kVA rating so that the distribution system can take care of any sudden change in load demand (to enhance security) which is very common. Hence, in the present work, the weights of the objective functions are selected in such a way that all the three objectives mentioned above are given equal weighage. The selection of weighting factors has been done based on the maximum value that each objective can achieve without violation of their respective constraints. The maximum value of X_i with reduction in power loss is less than 1.0. Let the value of w_1 be 1.0. The maximum value of the voltage deviation index Y_i without violation of voltage constraint is less than 0.1. Hence, we have selected w_2 as 10, so that w_2Y_i will get almost equal weightage as that of w_1X_i. The maximum value of the transformer load balancing index, Z_i with the constraint that all the transformer currents are within 20 % of their respective optimum currents to be shared, is less than 0.2. Hence, we have selected w_3 as 5, so that w_3Z_i will get almost equal weightage as that of w_1X_i and w_2Y_i. Thus, in the present work, the weighting factors selected are w_1 = 1 and w_2 =10 and w_3 = 5.

3. HEURISTIC RULE AND EXPLANATION OF THE PROPOSED TECHNIQUE

In order to obtain optimal switching strategy for network reconfiguration, one needs to consider every candidate switch. In the present paper, all the tie-switches are considered and a heuristic rule is incorporated for selecting the tie-switch one at a time. This heuristic rule is explained below.

In the first iteration, voltage difference across all the open tie-switches is computed by running a load flow and the open tie-switch across which maximum voltage difference has occurred is identified. The reason for selecting the tie-switch across which voltage difference is maximum is that currents will be more at lower voltages (and therefore power loss also will be more) and if we operate such a tie-switch, it is expected that there will be greater improvement in the system voltage profile. Hence, it will cause maximum loss reduction, minimum branch current constraint violation and better transformer load balancing. In the next iteration, the same procedure is repeated for the remaining tie-switches and so on.

For the purpose of explanation of the proposed algorithm, consider the sample radial distribution system as shown in Figure 1. It is assumed that every branch has a sectionalizing switch. This system has three substations, three feeders, four tie branches, and four tie-switches.

First, run the load flow program to compute the voltage difference across all 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, tie-4 (Figure 1) is maximum, and then this tie-switch (tie-4) will be considered first.

Now, if tie-4 is closed, a loop will be formed (Figure 2) and the total number of branches including tie branch (24-13) in this loop will be 10. These branches are 13-12, 12-11, 11-10, 10-26, 27-18, 18-19, 19-22, 22-23, 23-24, and 24-13. Opening of each branch in this loop is an option. For each option considered, value of objective function is evaluated. Say in this loop, first open sectionalizing switch of branch 13-12 (radial structure is retained) and run the load flow program. Now compute X_1, Y_1, and Z_1 using Equations 1-3 and then the objective function value J_1 is evaluated using Equation 4, i.e.,

$$J_1 = w_1 X_1 + w_2 Y_1 + w_3 Z_1 \tag{5}$$

Similarly, close the sectionalizing switch of branch 13-12 and open the sectionalizing switch of branch 12-11 (radial structure is retained) and run the load flow program. Now the objective function value J_2 for this option is computed as:

$$J_2 = w_1 X_2 + w_2 Y_2 + w_3 Z_2 \tag{6}$$

Similarly, J_3, J_4,…,J_{10} have to be computed. The optimal solution OS_1 for this tie-switch (tie-4) operation is the minimum of all such values of J_i. Thus the optimal solution for this tie-switch (tie-4) operation can be obtained as:

$$OS_1 = \min\{J_1, J_2, ..., J_{10}\} \tag{7}$$

Suppose $OS_1 = J_2$, which means that optimal solution for this tie-switch operation (tie-4) can be obtained by opening the sectionalizing switch of branch 12-11 and closing the open tie-switch, tie-4 of the branch 24-13 and the radial structure of the network is retained. Figure 3 shows the radial configuration of the network after the first switching operation.

Again, run the load flow program and compute the voltage difference across the remaining open tie-switches (tie-1, tie-2 and tie-3). Suppose, the voltage difference across tie-switch, tie-1 is maximum. Now this tie-switch (tie-1) is closed and a loop will be formed as shown in Figure 4. The total branches in this loop including tie branch (6-14) is 14. These branches are 25-1, 1-2, 2-3, 3-4, 4-5, 5-6, 6-14, 14-13, 13-24, 24-23, 23-22, 22-19, 19-18, 18-27. Again by opening sectionalizing switches one by one, objective function values J_1, J_2, J_3,…,J_{14} are evaluated. Now the optimal solution for the tie-switch operation (tie-1) can be

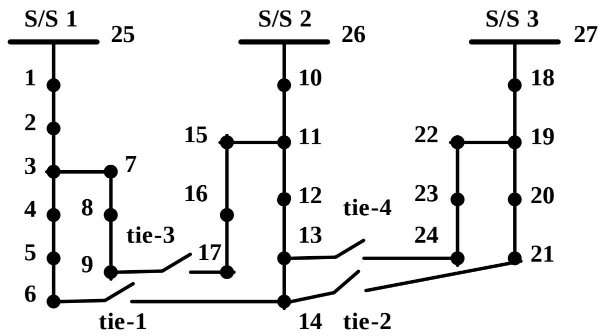

Figure 1. Sample distribution network with four tie branches

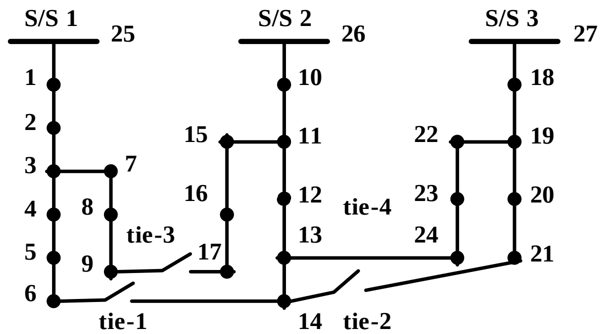

Figure 2. Distribution system with tie-switch, tie-4 closed

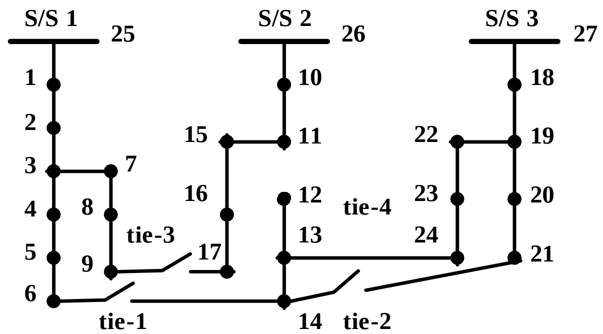

Figure 3. Radial configuration after the first switching operation

obtained as:

$$OS_2 = \min\{J_1, J_2, ..., J_{14}\} \qquad (8)$$

Say $OS_2 = J_8$, then, the optimal solution for tie-switch (tie-1) can be obtained by opening sectionalizing switch of branch 14-13 and closing this tie-switch (tie-1) of the branch 6-14. Figure 5 shows the radial configuration of the network after the second switching operation. The same procedure is repeated till all tie-switches are considered.

In the present work, a load flow algorithm developed in [21] for solving the radial distribution network has been used. A complete algorithm for the proposed network reconfiguration technique is given below.

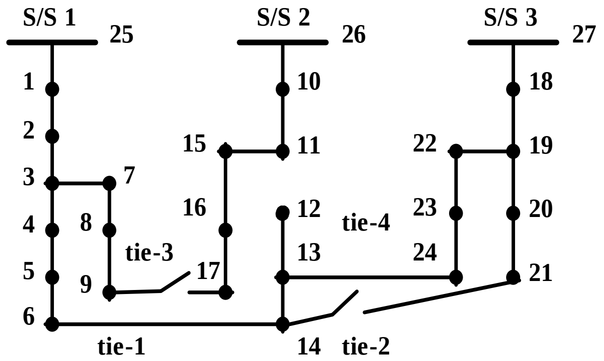

Figure 4. Distribution system with tie-switch, tie-1 closed.

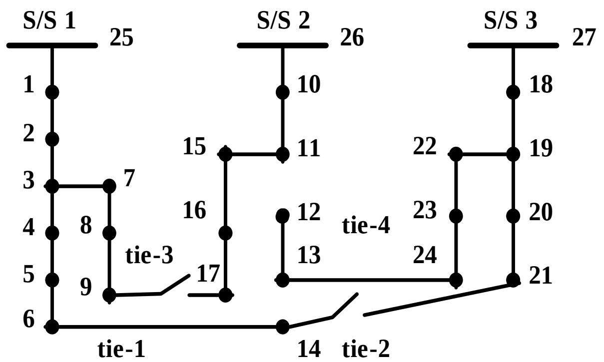

Figure 5. Radial configuration after the second switching operation

4. ALGORITHM

Step 1. Read system data.

Step 2. Run the load flow program for radial distribution network.

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

Step 4. Identify the open tie-switch across which the voltage difference is maximum and its code is k, i.e., $\Delta V_{tie,max} = \Delta V_{tie}(k)$.

Step 5. 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 6. Open one branch at a time in the loop and evaluate the value for each objective, i.e., for i = 1 to N_k, compute X_i, Y_i, and Z_i using Equations 1-3, respectively and then compute J_i using Equation 4.

Step 7. Obtain the optimal solution for the operation of tie-switch ‘k’, i.e., $OS_k = \min\{J_i\}$ for i = 1, 2,…,N_k which do not violate the branch current constraints. If $OS_k = OS_{k-1}$ for k>1, retain the configuration obtained with the previous tie-switch operation.

Step 8. n tie = n tie-1.

Step 9. Check whether n tie = 0. If yes go to Step 11 otherwise go to Step 10.

Step 10. Rearrange the coding of the rest of the tie-switches and go to Step 2

Step 11. Print output results

Step 12. Stop.

5. NUMERICAL EXAMPLES

5.1. Radial Distribution System with 72 Nodes

The proposed algorithm is tested with an 11 kV radial distribution system having four substations, 72 nodes and 78 branches including eleven tie branches which are open under normal operating conditions as shown in Figure 6. Data for this system are given in Appendix. Results of load flow before reconfiguration are given in Table 1. It can be seen that the real power loss is 298.36 kW,

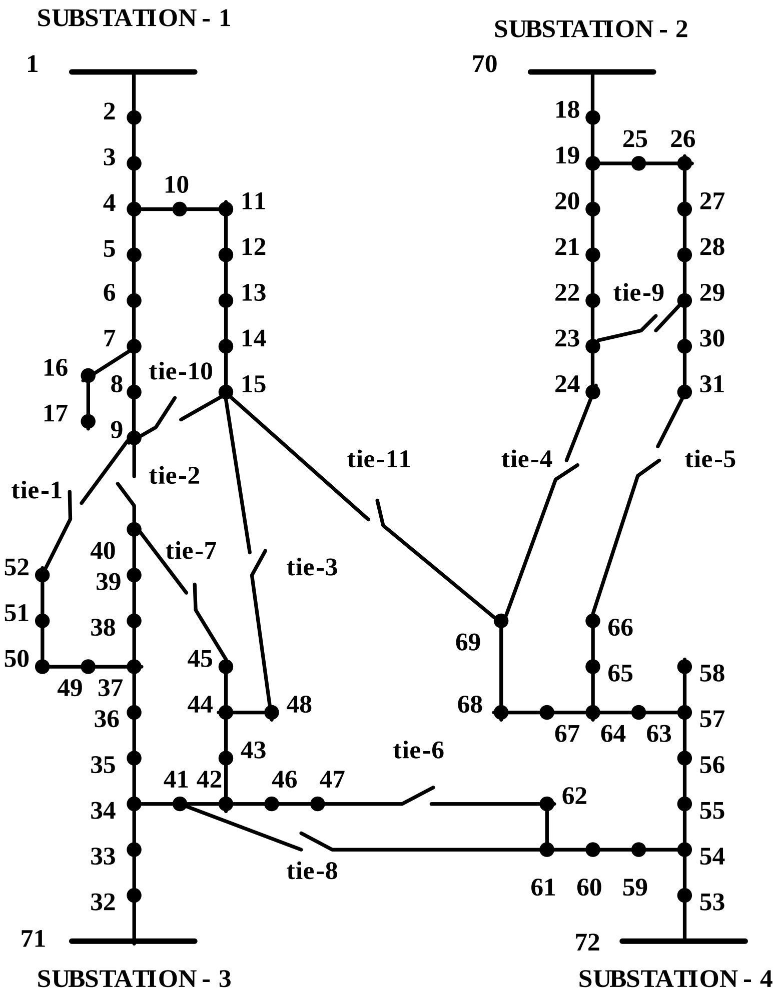

Figure 6. Distribution system with 11 tie-switches before reconfiguration

TABLE 1. Load Flow Results before Reconfiguration

Power Loss (kW)	Minimum System Voltage V_{min} (pu)	Loading Ratio of Transformer TLR_j^b (%)
298.36	$V_{min} = V_{69} = 0.8889$	$TLR_1^b = 62.97$ $TLR_2^b = 59.96$ $TLR_3^b = 85.42$ $TLR_4^b = 80.56$

minimum system voltage is $V_{min} = V_{69} = 0.8889$ pu and the transformer loading ratios before reconfiguration at substations 1, 2, 3 and 4 are 62.97 %, 59.96 %, 85.42 % and 80.56 %, respectively.

Table 2 shows the results for various cases after reconfiguration. For Case-1a, all the objectives as given in Equations 1-3 are considered. From Table 2 it is seen that power loss is 263.66 kW. This means reduction of power loss is 34.7 kW, i.e., 11.63 %. Minimum system voltage is $V_{min} = V_{31} = 0.9162$ pu, i.e., minimum system voltage has improved from 0.8889 pu to 0.9162 pu. It can be seen that the minimum voltage before reconfiguration occurs at node no. 69 and that after reconfiguration occurs at node no. 31. The loading ratios of the transformers at substations 1, 2, 3 and 4 are 72.43 %, 74.87 %, 72.69 % and 71.83 %, respectively. Loading ratios of transformers are more or less balanced after reconfiguration as compared to that obtained before reconfiguration (Comparing the results of Table 2 with Table 1). Changes in configuration during different tie-switch operations are given in Table 3. Change of branches is also highlighted in Table 3. Final configuration of the distribution system is given in Figure 7.

For Case 1b, only power loss reduction index is considered in the objective function, i.e. $w_1 = 1$ and $w_2 = w_3 = 0$. From Table 2, it can be seen that power loss is 261.07 kW. This means power loss reduction is 37.29 kW, i.e., 12.49 % loss reduction. The minimum system voltage has improved from $V_{min} = V_{69} = 0.8889$ pu to $V_{min} = V_{31} = 0.9247$ pu.

TABLE 2. Load Flow Results after Reconfiguration

Different Cases	Power Loss (kW)	Minimum System Voltage V_{min} (pu)	Loading Ratio of Transformer TLR_j^a (%)
Case 1 (w_1=2,w_2=10,w_3=1,w_4=1)	263.97	$V_{min} = V_{31} = 0.9157$	$TLR_1^a = 72.43$ $TLR_2^a = 74.87$ $TLR_3^a = 71.86$ $TLR_4^a = 72.66$
Case 2 (w_1=1,w_2=0,w_3=0,w_4=0)	261.07	$V_{min} = V_{31} = 0.9247$	$TLR_1^a = 61.65$ $TLR_2^a = 82.16$ $TLR_3^a = 80.38$ $TLR_4^a = 66.73$

TABLE 3. Configuration Changes (Case 1a)

Changes in Configuration		Objective Function Value (OS_i)
Branches out	Branches in	
64 – 67	24 – 69	2.5061
51 – 52	9 – 52	2.4092
15 – 48	15– 48	2.4092
15 – 69	15 – 69	2.4092
23 – 29	23 – 29	2.4092
46 – 47	47 – 62	2.2350
9 – 15	9 – 15	2.2350
39 – 40	40 – 45	2.2345
9 – 40	9 – 40	2.2345
30 – 31	31 – 66	1.7753
41 –61	41 – 61	1.7753

The loading ratios of the transformers at four substations are 61.65 %, 82.16 %, 80.38 %, and 66.73 %, respectively and they are not balanced after reconfiguration as compared to Case-1a. Changes in configuration for Case 1b during different tie-switch operations are given in Table 4. Change of branches is also highlighted in Table 4. The final configuration is given in Figure 8.

As the proposed method is not similar to that of other methods, a direct comparison is not possible, however, the proposed method has been compared with two other existing methods [11,15] for w_1 =1, w_2 = 10, and w_3 = 5 the results are nearly the same as shown in Table 3. However, the proposed method takes much less CPU time as compared to the two other existing methods. Table 5 gives the comparison of CPU time.

5.2. Radial Distribution System with 152 Nodes

In this example, a 152 node radial distribution system having four substations (data for this system can be obtained from the corresponding author) as shown in Figure 9 is considered. The system has 21 tie-switches which are normally open. The eight transformers in this distribution system are denoted as T_1-T_8. The rating of transformers T_3 and T_8 is 2.5 MVA and all other transformers are rated at 2 MVA. The results of the load flow before reconfiguration is given in Table 6. It can be seen from Table 6 that the total real power loss of the distribution system is 467.27 kW, the minimum system voltage is $V_{min} = V_{101} = 0.8889$ pu and the transformer loading ratios of the eight transformers T_1-T_8 are 62.97 %, 47.81 %, 58.22 %, 55.79 %, 76.70 %, 69.08 %, 56.51 %, and 80.56 %, respectively. Thus, the transformer loading ratios vary from 47.81 % to 80.56 %.

The results of reconfiguration for various cases are shown in Table 7. For Case 2a, all the three objectives are considered. It can be seen from Table 7 that the real power loss after reconfiguration is 420.83 kW and minimum system voltage for Case 2a is $V_{min} = V_{101} = 0.9131$ pu. There is a reduction of 46.44 kW (9.9 % of 467.27 kW) in the real power loss. The transformer loading ratios of T_1-T_8 are 61.87 %, 62.74 %, 63.62 %, 61.23 %, 62.60 %, 61.16 %, 66.06 %, and 66.97 %, respectively. It can be seen that the transformers are more or less balanced after reconfiguration. The variation of transformer loading ratios after reconfiguration is from 61.16 % to 66.97 % as compared to a variation from 47.81 % to 80.56 % before reconfiguration. The changes in configuration with different tie-switch operations are tabulated in Table 8. The variation of objective function value OS_i with tie-switch operations is given in Figure 10.

For Case 2b, only power loss reduction index is considered in the objective function, i.e. $w_1 = 1$ and $w_2 = w_3 = 0$. From Table 7, it can be seen that for Case 2b, real power loss has reduced from 467.27 kW to 412.01 kW. The minimum system voltage is $V_{min} = V_{101} = 0.9131$ pu. The transformer loading ratios of T_1-T_8 are 58.60 %, 73.88 %, 62.50 %, 54.96 %, 58.45 %, 61.16 %, 70.6 2 %, and 65.91 %, respectively. It can be seen that the transformers are not balanced as compared to Case 2a. The changes in configuration with different tie-switch operations are tabulated in Table 8. The variation of objective function value OS_i with tie-switch operations is given in Figure 11.

5.3. Radial Distribution System with 69 Nodes

In this example, a 12.66 kV radial distribution system having 69 nodes and 73 branches including tie-branches as shown in Figure 12 is considered (Baran, et al [22]). This example demonstrates the effectiveness of the proposed network reconfiguration algorithm. As seen from Figure 12, the system has five tie-branches 11-43, 13-21, 50-59, 27-65, and 15-46, which are normally open. The real power loss of the system before reconfiguration is 224.95 kW and the minimum system voltage is $V_{min} = V_{65} = 0.9092$ pu.

Reconfiguration considering real power loss reduction as objective has resulted in a real power loss of 99.59 kW and minimum system voltage of $V_{min} = 0.9483$ pu. The open branches after reconfiguration are 11-43, 13-21, 57-58, 63-64, and 14-15. The results obtained are tabulated in Table 9 and are compared with three other existing methods. It can be seen from Table 9 that proposed method resulted in a real power loss of 99.59 kW, whereas with Shirmohammadi, et al [2], real power loss is 106.17 kW. Goswami, et al [4] obtained a real power loss of 108.63 kW. Reconfiguration algorithm implemented by Jiang, et al [5] using simulated annealing resulted in a real power loss of 119.91 kW.

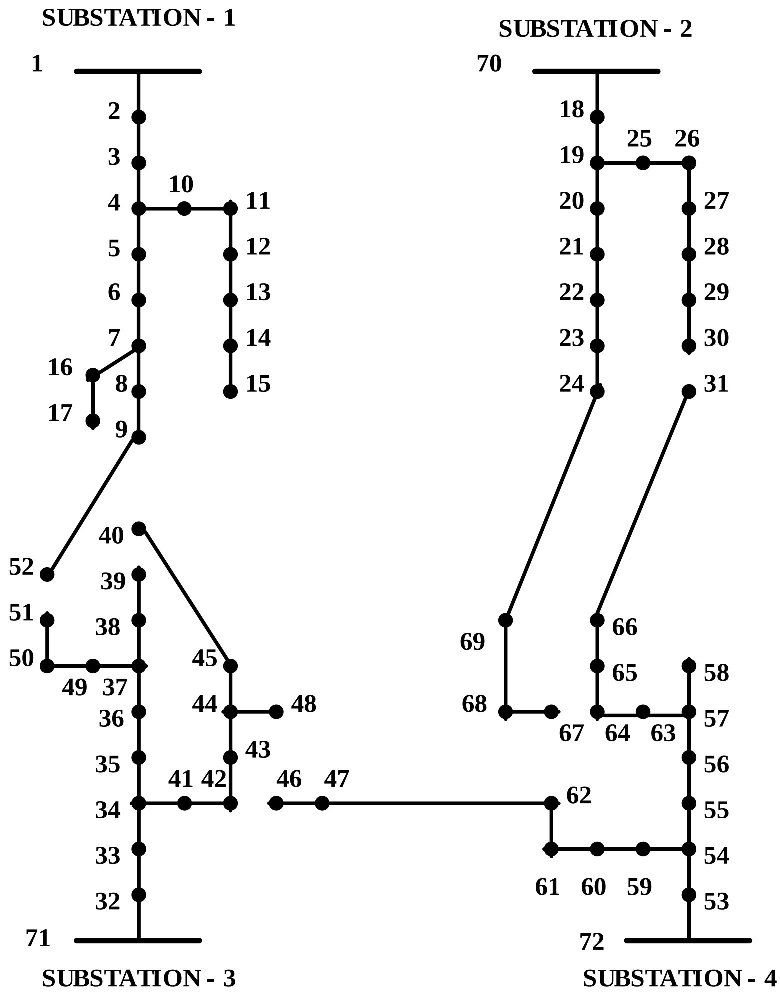

Figure 7. Distribution system after reconfiguration (Case 1a)

TABLE 4. Configuration Changes (Case 1b)

Changes in Configuration		Objective Function Value (OS_i)
Branches out	Branches in	
64 – 67	24 – 69	0.8992
51 – 52	9 – 52	0.8857
14 – 15	15 – 48	0.8845
42 – 46	47 – 62	0.8751
23 – 29	23 – 29	0.8751
9 – 15	9 – 15	0.8751
15 – 69	15 – 69	0.8751
31 – 66	31 – 66	0.8751
41 – 61	41 – 61	0.8751
44 – 45	40 – 45	0.8750
9 – 40	9 – 40	0.8750

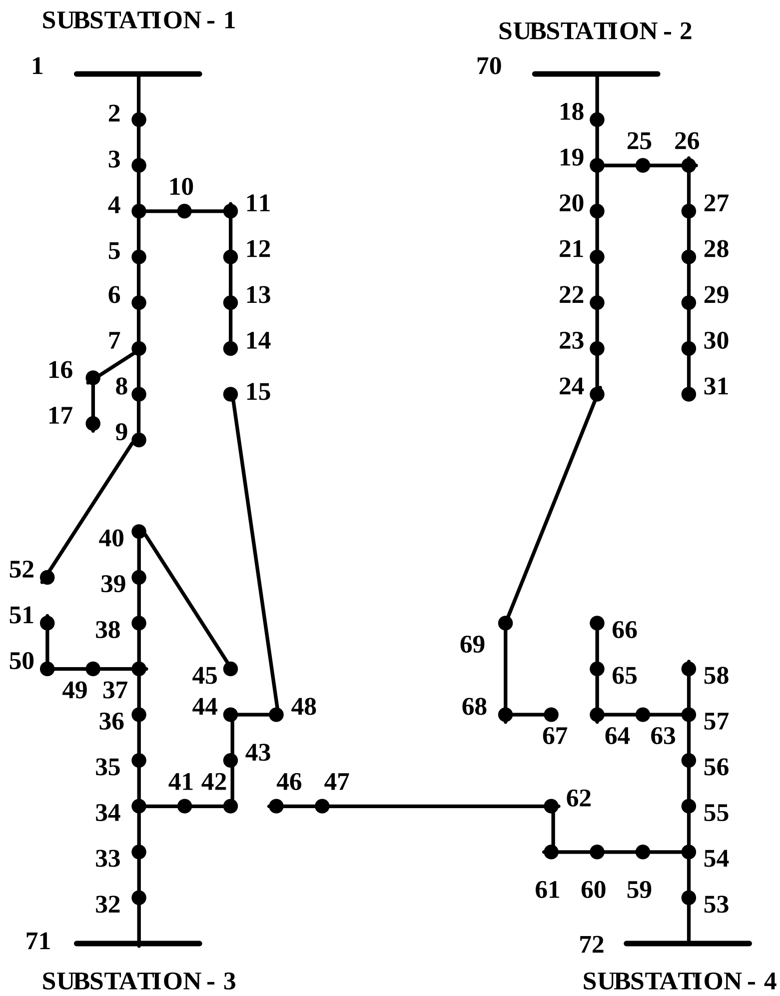

Figure 8. Distribution system after reconfiguration (Case 1b)

TABLE 5. Comparison of the CPU Time

Methods	CPU Time (s)
Proposed Method	2.5
Method proposed in [11]	12.1
Method proposed in [15]	14.6

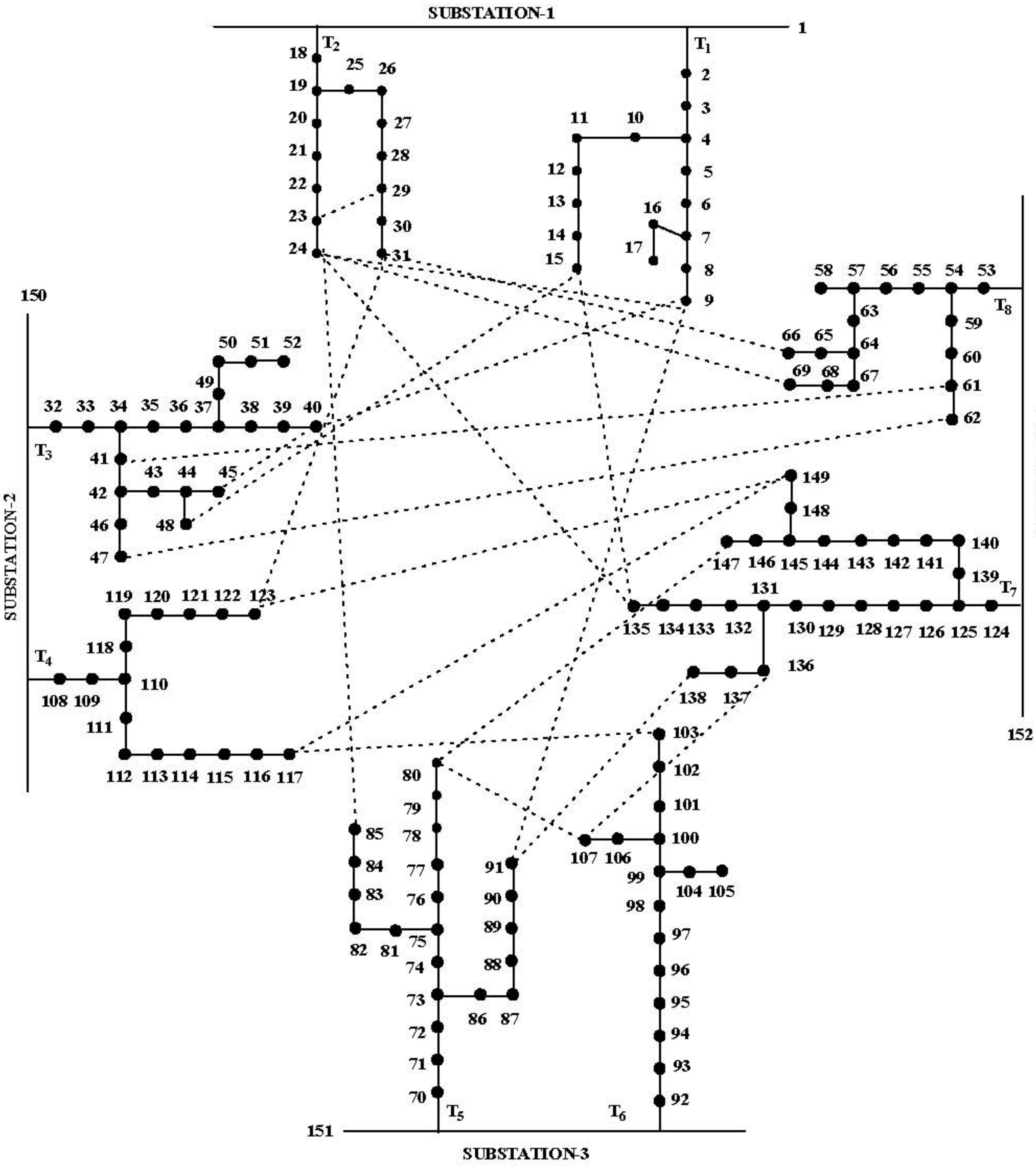

Figure 9. Radial distribution system with 152 nodes, 21 tie-lines

6. CONCLUSIONS

In the present work, a heuristic-based multi-objective algorithm has been proposed to solve the network reconfiguration problem in a radial distribution system. The objectives considered attempt to reduce the real power loss, reduce the deviations of nodes voltage, and reduce transformers

TABLE 6. Load Flow Results before Reconfiguration

Power Loss (kW)	Minimum System Voltage V_{min} (pu)	Loading Ratio of transformer TLR_j^b (%)
467.27	$V_{min} = V_{69} = 0.8889$	$TLR_1^b = 62.97$ $TLR_2^b = 47.81$ $TLR_3^b = 58.22$ $TLR_4^b = 55.79$ $TLR_5^b = 76.70$ $TLR_6^b = 69.08$ $TLR_7^b = 56.51$ $TLR_8^b = 80.56$

TABLE 7. Load Flow Results after Reconfiguration

Different Cases	Power Loss (kW)	Minimum System Voltage V_{min} (pu)	Loading Ratio of transformer TLR_j^a (%)
Case 2a (w_1=1,w_2=,w_3=5)	420.83	$V_{min} = V_{101} = 0.9131$	$TLR_1^a = 61.87$ $TLR_2^a = 62.74$ $TLR_3^a = 63.62$ $TLR_4^a = 61.23$ $TLR_5^a = 62.60$ $TLR_6^a = 61.16$ $TLR_7^a = 66.06$ $TLR_8^a = 66.97$
Case 2b (w_1=1,w_2=0,w_3=0)	412.01	$V_{min} = V_{101} = 0.9131$	$TLR_1^a = 58.60$ $TLR_2^a = 73.88$ $TLR_3^a = 62.50$ $TLR_4^a = 54.96$ $TLR_5^a = 58.45$ $TLR_6^a = 61.16$ $TLR_7^a = 70.62$ $TLR_8^a = 65.91$

TABLE 8. Configuration Changes

Changes in Configuration							
Case 2a				Case 2b			
Branches out		Branches in		Branches out		Branches in	
64	67	24	69	64	67	24	69
100	106	107	136	100	106	107	136
101	102	103	117	101	102	103	117
76	77	80	147	76	77	80	147
15	48	15	48	14	15	15	48
91	138	91	138	90	91	9	91
24	85	24	85	116	117	117	149
90	91	9	91	80	107	80	107
15	135	15	135	84	85	24	85
8	9	9	40	24	135	24	135
117	149	117	149	46	47	47	62
40	45	40	45	9	24	9	24
123	149	123	149	137	138	91	138
24	135	24	135	9	40	9	40
30	31	31	66	31	66	31	66
31	123	31	123	123	149	123	149
23	29	23	29	44	45	40	45
9	24	9	24	23	29	23	29
80	107	80	107	41	61	41	61
41	61	41	61	31	123	31	123
47	62	47	62	134	135	15	135

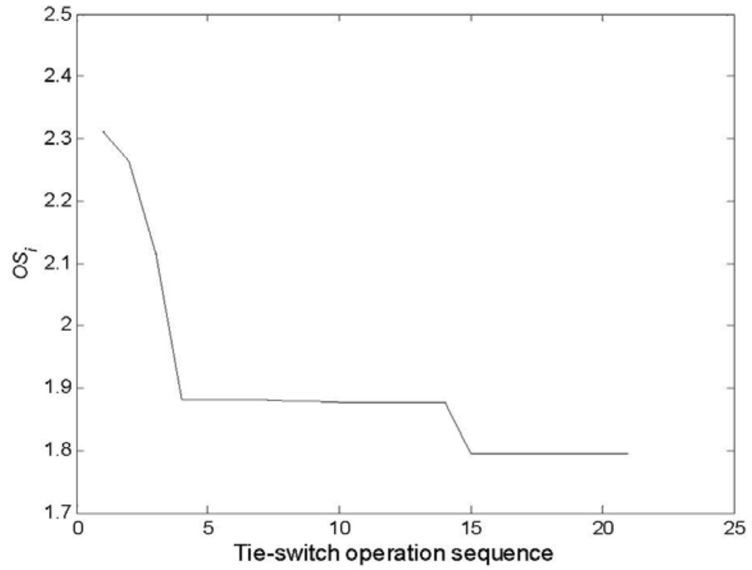

Figure 10. Objective function vs tie-switch operation (Multi-objective)

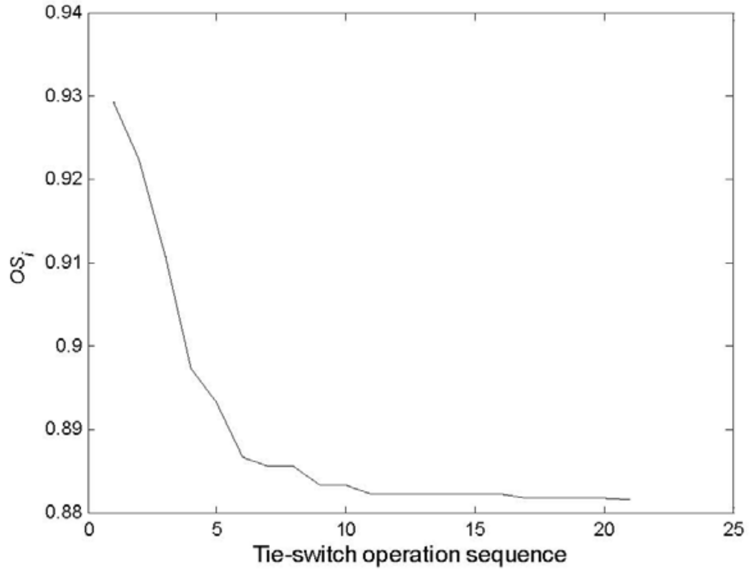

Figure 11. Objective function vs tie-switch operation (only real power loss)

load imbalance subject to the radial network structure in which all loads are energized and the branch current constraints are not violated. It was observed that, with the proposed method, all the objectives are satisfied including the load balancing of transformers having different ratings as compared to those before reconfiguration. The simulation studies on a medium size distribution network have proved the feasibility of the proposed approach and obtained results are quite good. Comparison of the results of the proposed method with two other existing methods also shows the superiority of the proposed algorithm.

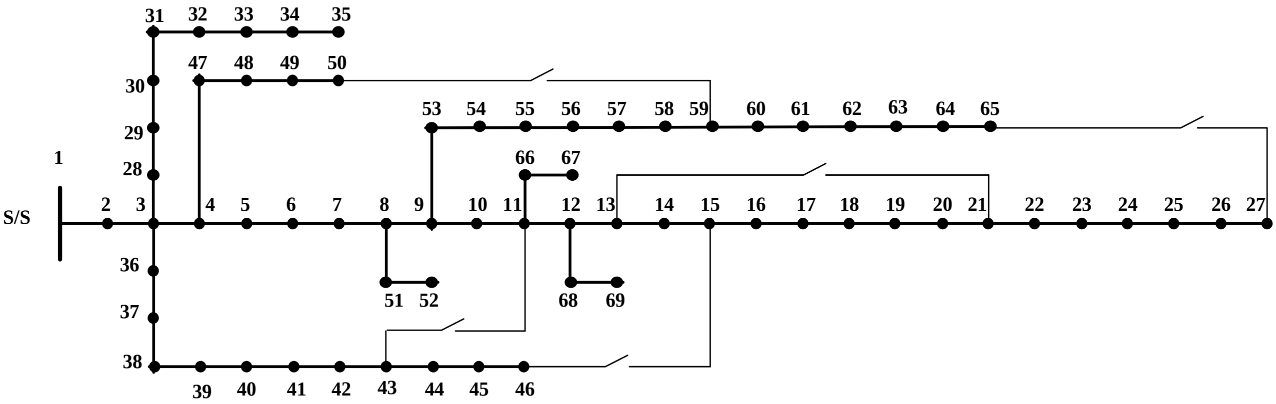

Figure 12. 69 node radial distribution system with 5 tie-switches

TABLE 9. Comparison of Results for 69 Node Radial Distribution System

Method	Real Power Loss (kW)	V_{min} (pu)	Loss Reduction (%)
Proposed Method	99.59	0.9483	55.72
Shirmohammadi, et al [2]	106.17	0.9458	52.80
Goswami, et al [4]	108.63	0.9440	51.71
Jiang, et al [5]	119.91	0.9410	46.69

7. NOMENCLATURE

V_s Voltage at the substation (in pu)

NB Total number of nodes in the system.

N_k Total number of branches in the loop including tie branch, when k^{th} tie-switch is closed.

$V_{i,j}$ Voltage of node j corresponding to the opening of the i^{th} branch in the loop (in pu)

Ploss (i) Total real power loss when i^{th} branch in the loop is opened

$Ploss^0$ Total real power loss in the network before reconfiguration.

|I(i,m)| Magnitude current of branch-m when the i^{th} branch in the loop is opened.

$I_c(m)$ Line capacity of branch-m.

kVA_j kVA rating of j^{th} transformer

$ITr_{i,j}$ Current of j^{th} transformer when the i^{th} branch in the loop is opened.

N_t Total number of transformers

$ITr_{i,j}^{Opt}$ Optimal value of the current to be shared by the j^{th} transformer when the i^{th} branch in the loop is opened
$= \dfrac{kVA_j}{\sum_j kVA_j} \sum_j ITr_{i,j}$, $j=1,2,...,N_t$

ITr_j^b Current of j^{th} transformer before reconfiguration.

ITr_j^a Current of j^{th} transformer after reconfiguration.

ITr_j^{Rated}	Rated current of j^{th} transformer
TLR_i^b	Loading ratio of j^{th} transformer before reconfiguration ($j=1,2,\ldots,N_t$) $= \frac{ITr_j^b}{ITr_j^{Rated}}$
TLR_i^a	Loading ratio of j^{th} transformer after reconfiguration ($j=1,2,\ldots,N_t$) $= \frac{ITr_j^a}{ITr_j^{Rated}}$
w_1, w_2, w_3, w_4	Weighting factors for the indices of system power loss, deviations of the nodes voltage, branch current constraint violation and transformers loading imbalance, respectively.

8. APPENDIX

TABLE a1. Line and Load Data

Branch Number jj	Sending end node IS(jj)	Receiving end node IR(jj)	R(Ω)	X(Ω)	PL(IR(jj)) (kW)	QL(IR(jj)) (kVar)
1	1	2	1.0970	1.0740	100.0	90.0
2	2	3	1.463	1.432	60.0	40.0
3	3	4	0.731	0.716	150.0	130.0
4	4	5	0.366	0.358	75.0	50.0
5	5	6	1.828	1.790	15.0	9.0
6	6	7	1.097	1.074	18.0	14.0
7	7	8	0.731	0.716	13.00	10.00
8	8	9	0.731	0.716	16.00	11.00
9	4	10	1.080	0.734	20.00	10.00
10	10	11	1.620	1.101	16.00	9.00
11	11	12	1.080	0.734	50.00	40.00
12	12	13	1.350	.9170	105.00	90.00
13	13	14	0.810	0.550	25.00	15.0
14	14	15	1.944	1.321	140.0	125.0
15	7	16	1.080	0.734	100.00	60.00
16	16	17	1.620	1.101	40.00	30.00
17	70	18	1.097	1.074	60.00	30.00
18	18	19	0.366	0.358	40.0	25.0
19	19	20	1.463	1.432	15.00	9.0
20	20	21	0.914	0.895	13.00	7.00
21	21	22	0.804	0.787	30.00	20.00
22	22	23	1.133	1.110	90.0	50.0
23	23	24	0.475	0.465	50.0	30.0
24	19	25	2.214	1.505	60.0	40.0
25	25	26	1.620	1.110	100.0	80.0
26	26	27	1.080	0.734	80.0	65.0
27	27	28	0.540	0.367	100.0	60.0
28	28	29	0.540	0.367	100.0	55.0
29	29	30	1.080	0.734	120.0	70.0
30	30	31	1.080	0.734	105.0	70.0
31	71	32	0.366	0.358	80.0	50.0
32	32	33	0.731	0.716	160.00	140.00

	33	33	34	0.731	0.716	13.00	8.00
	34	34	35	0.804	0.787	46.0	39.0
	35	35	36	1.170	1.145	150.0	130.0
	36	36	37	0.768	0.752	40.0	28.0
	37	37	38	0.731	0.716	60.00	40.00
	38	38	39	1.097	1.074	40.00	30.00
	39	39	40	1.463	1.432	30.00	25.0
	40	34	41	1.080	0.734	150.0	100.0
	41	41	42	0.540	0.367	60.0	35.0
	42	42	43	1.080	0.734	120.0	70.0
	43	43	44	1.836	1.248	90.0	60.0
	44	44	45	1.296	0.881	18.0	10.0
	45	42	46	1.188	0.807	16.0	10.0
	46	46	47	0.540	0.367	100.0	50.0
	47	44	48	1.080	0.734	60.0	40.0
	48	37	49	0.540	0.367	90.0	70.0
	49	49	50	1.080	0.734	85.0	55.0
	50	50	51	1.080	0.734	100.0	70.0
	51	51	52	1.080	0.734	140.0	90.0
	52	72	53	0.366	0.358	60.0	40.0
	53	53	54	1.463	1.432	20.00	11.0
	54	54	55	1.463	1.432	80.00	60.0
	55	55	56	0.914	0.895	36.0	24.0
	56	56	57	1.097	1.074	130.00	120.00
	57	57	58	1.097	1.074	43.00	30.00
	58	54	59	0.270	0.183	80.0	50.0
	59	59	60	0.270	0.183	240.0	120.0
	60	60	61	0.810	0.550	125.0	110.0
	61	61	62	1.296	0.881	125.0	110.0
	62	57	63	1.188	0.807	10.0	5.0
	63	63	64	1.188	0.807	150.0	130.0
	64	64	65	0.810	0.550	50.0	30.0
	65	65	66	1.620	1.101	30.0	20.0
	66	64	67	1.080	0.734	130.0	120.0
	67	67	68	0.540	0.367	150.0	130.0
	68	68	69	1.080	0.734	25.0	15.0
Tie-branches	69	9	52	0.908	0.726	--	--
	70	9	40	0.381	0.244	--	--
	71	15	48	0.681	0.544	--	--
	72	24	69	0.254	0.203	--	--
	73	31	66	0.254	0.203	--	--
	74	47	62	0.254	0.203	--	--
	75	40	45	0.454	0.363	--	--
	76	41	61	0.454	0.363	--	--
	77	23	29	0.454	0.363	--	--
	78	9	15	0.681	0.544	--	--
	79	15	69	0.454	0.363	--	--

Other Data: Current carrying capacity of all tie branches are 234.0 A. The current carrying capacity of branches 1-8, 17-23, 31-39 and 52-57 is 270 A. For branches 9 -16, 24-30, 40-51 and 58-68, it is 208 A. The ratings of the transformers of Substation 1, 2, 3 and 4 are 2 MVA, 2 MVA, 2.5 MVA and 2.5 MVA, respectively.

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