Radial distribution systems reconfiguration considering power losses cost and damage cost due to power supply interruption of consumers

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Abstract: Distribution system reconfiguration problem is a complex optimization process to find a structure with minimum losses in which the satisfaction of both sides, that is consumers and distribution system companies, need to be met. One of the most significant parameters in this regard is to increase the reliability of system. This parameter, on one hand, increases the satisfaction of power consumption and on the other hand, improves the economic benefits of distribution companies. Distribution system reconfiguration, considering the reliability parameters, seems to make the attempts to solve the problem of optimization difficult. In this paper, a new heuristic approach for distribution system reconfiguration in order to decrease the power losses cost and damage cost due to power supply interruption of consumers has been presented. Radial network construction and all energized nodes constraints are the most important ones that should be considered in distribution system reconfiguration problem. Hence, in this paper a new codification is proposed which is computationally efficient and guarantees to generate only feasible radial topologies all times. In order to illustrate the performance of proposed heuristic method, modified 33-bus and 119-bus distribution networks have been employed which have led to the desired results.

Keywords: Damage cost due to power supply interruption, heuristic algorithm, new codification, power losses cost, reconfiguration, reliability.

1. Introduction

Distribution network reconfiguration refers to the change of operation configuration by altering the topological state of open/closed of some electric lines. Network reconfiguration is just feasible for those networks which are meshed. In a distribution network the numbers of lines “in operation” and “out of service” are determined. The states of these sets of lines, subjected to maintaining the radial structure, can change. These changes ought to lead to objective function improvement which, of course in this regard, operating and consumption power constraints should be taken in to account.

Paper [1] has employed load transfer from a feeder to neighbor feeder, using a series of formulas to assess power losses variation without calculating the power flow. In [2] searching techniques is presented which are based on “branch exchange” strategy. Modified Tabu Search has been utilized for distribution system reconfiguration [3]. An optimum power flow concept for active power losses minimization is used in paper [4] and the same concept is applied in order to minimize the energy losses [5]. A heuristic approach to find structure with minimum losses as well as a random walks-based technique in order to losses prediction has been suggested [6]. In order to reduce losses, considering distributed generation, a method has been used [7].

Considering reliability related issues in the reconfiguration process is a new approaching manner in the technical literature, with studies approaching different aspects. In [8], a reconfiguration approach to reduce the interruption numbers for a distribution network has been proposed. In [9], network reconfiguration problem, considering network reliability and power losses has been solved. Reconfiguration models that minimize a weighted sum of

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reliability index (SAIDI, SAIFI and MAIFI), the expected interruption cost (ECOST) and energy not supplied (ENS) are developed in [10], [11] and [12] respectively. The main goal of the distribution electrical networks operation activity is to maintain an appropriate operation state of the network elements to secure the supply of all consumers. Structural and operational transformations of the actual power systems have established a competitive framework where the economic aspects are of increased importance. In this context, the economical and reliable operation of power systems becomes primordial.

To solve the reconfiguration problem of large-sized or real distribution systems, many researchers have proposed different codification for meta-heuristic techniques to maintain the radiality constraint.

In [13], Medoza et al. used loop vectors to ensure the generation of feasible individuals throughout the genetic evolution. This drastically reduces the search space. However, it will produce infeasible individuals especially while solving the reconfiguration problem of large-sized real distribution network and this method fails to search the isolation of principal interior nodes of the distribution networks and therefore requires mesh checks which is a time consuming approach. In [14], Romero et al., in order to generate radial configuration, proposed a method based on concept called path-to-node. This method consists of identifying paths linking between each bus and substation which is an exhaustive approach. In [15], Abdelaziz et al. presented an algorithm in order to distinguish between feasible and infeasible individuals with the help of bus incidence matrix 'A'. They suggested that the value of the 'determinant of A' is either 0 or ±1 for unfeasible and feasible radial topologies respectively. If the individual is infeasible the correction algorithm is very exhaustive as it replaces each switch subsequently with all the switches of the network. This algorithm looks very handy but for medium and large-sized distribution networks CPU time will increase directly. In [16], Delbem et al., using concepts of graph theory, developed an integral proposal to deal with the problem of generating radial topologies efficiently. However in this approach, only the mutation operator was used and the recombination operator was discarded as it usually generates infeasible individuals.

In this paper, in order to recognize network radial configuration, a new codification has been presented which its implementation is simple, quick and precise. Also, a new heuristic approach for distribution system reconfiguration in order to decrease power losses cost and damage cost due to power supply interruption of consumers has been presented which achieves desired results.

2. Mathematical Model

The mathematical model of the reconfiguration optimization problem has the following general form:

$$Optim\{f\} \tag{1}$$

Subject to:

$$V_{\min} \le V_i \le V_{\max}, I_j \le I_j^{\max} \tag{2}$$

$$\psi(n) = 0 \tag{3}$$

Eq. (1) corresponds to the objective function to be optimized. Eq. (2) considers voltage constraints for each node of network and current limit for each branch of network. Eq. (3) deals with the radial topology constraint (if network is radial, so $\psi = 0$, otherwise $\psi = 1$).

In this paper, the objective function is f that should be optimized, therefore the Eq. (1) becomes:

$$Min[LC + CIC] \tag{4}$$

3. Objective function evaluation

The objective function is a combination of two criteria: losses cost (*LC*) and consumer interruption cost (*CIC*). The details related to these two criteria are explained in the next sections.

A. Evaluation of losses cost

The power losses can be identified by several components, of which the most important is given by the technical losses and two of the components can be identified in this category: power losses and energy losses [17]. The active power losses for a three-phase electrical line *i*, flowing on the line is:

$$P_{loss,i} = 3R_i I_i^2 \tag{5}$$

And the energy losses is given by:

$$W_{loss,i} = P_{loss,i} . T \tag{6}$$

So LC for line *i* is obtained by:

$$LC_i = c_{pl} P_{loss,i} + c_{wl} W_{loss,i} \tag{7}$$

Then the total losses cost (*LC*) for all network branches is:

$$LC = \sum_i LC_i \tag{8}$$

B. Interruption cost evaluation

First of all, in order for define the terms “successful” and “unsuccessful” for consumers supply connected to a distribution network after fault occurrence in network, we need to be aware of switching equipment.

Switching equipment are defined as follow [17]:

- Sectionaliser: is a switching equipment that has been designed to normal switch on/off a line circuit or to separate two circuits in case of low line load.
- Circuit breaker: is a switching equipment which is capable of interrupting normal or fault currents or establishing a connection to close a circuit.

The radial restriction of the operation topology of the distribution network causes any consumer to be connected through a certain and unique set of lines to the supplied source. Additionally, supplying power from more than one source is impossible. Therefore, to reach a successful state of the supplying a consumer, all the line sections situated on the path between the consumer and the source need to be “in service”. Also all line sections that directly connected to this path and are not able to be separated from it, have to be in service.

Unsuccessful state and fault path definitions are very complex. Based on current switching equipment in the network, we face with different states related to interruption time and affected areas by fault (cause to interruption).

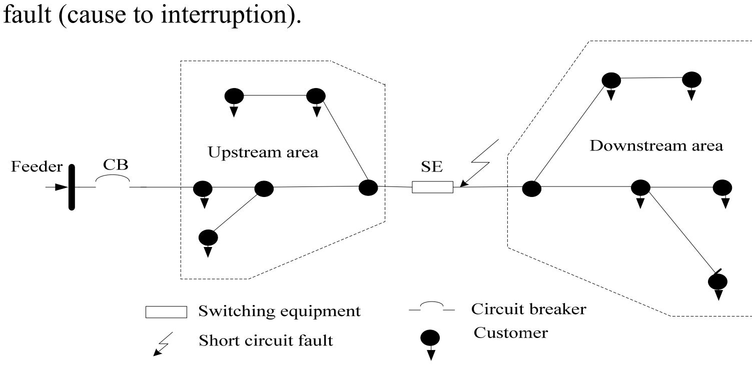


Figure 1. A radial distribution network.

Figure 1 illustrates an occurred short circuit fault in network which leads to power supply interruption in downstream consumers. Supply restoration can be handled using different ways. One of these ways is repairing the fault element of the system and resupplying through the same path. Another way is to isolate the fault and connect one of the downstream consumers to the same source of energy via back-up path or to connect to another source of energy. For the upstream consumers the consequences of fault and the energy interruption time depends on switching equipment SE.

If SE is a sectionaliser, the first equipment that operates after fault is CB which is situated on the ongoing section line from the source. The upstream consumers could be resupplied after the switching of SE.

Should SE is a circuit breaker, after fault occurrence, it itself will eliminate the short circuit. As a result, the upstream consumers will remain supplied without experiencing an interruption, although they could be affected in different ways by the transient voltage oscillations.

A branch between two nodes includes an electrical line or a transformer and two switching equipment at the nodes which they are each either sectionaliser or circuit breaker.

A branch *l* between the nodes *i* and *j* is characterized by two reliability indices (Figure 2):

- λ_{ij} failure rate (failure/year)
- r_{ij} failure duration (h)
-

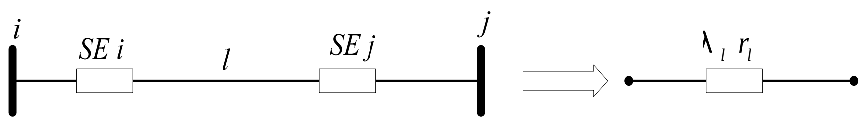


Figure 2. Equivalent reliability parameters for a branch.

The failure rate of each branch is calculated in terms of the failure rates of the component elements, considered as being series connected.

Fault occurrence in a branch affects the consumption nodes differently. During the fault clearance, there are four main steps which are explained as follow: [18]

1. Locating the fault and isolating it
2. Resupplying consumers which are not in the fault area from source
3. Load transfer to other feeders or energized nodes through closing switching equipment that are normally open
4. Repairing the equipment and resupplying the interrupted consumers through the path before fault

Steps 1, 2 and 4 are done after any fault; however, doing step 3 depends on lines capacity and network structure.

As a result, the reliability parameters of branch *l* are [19]:

$$\lambda_l = \lambda_{SEi} + \lambda_{0l} L_l + \lambda_{SEj} \quad (9)$$

$$U_l = \lambda_{SEi} r_{SEi} + \lambda_{0l} r_{0l} + \lambda_{SEj} r_{SEj} \quad (10)$$

$$r_l = \frac{U_l}{\lambda_l} \quad (11)$$

For each consumption node, three primary reliability parameters are calculated so that interruption duration of consumption nodes can be obtained.

For the power interruption at a consumption node, which connected to the feeder through first-order cut sets, one of the components of this cut sets must fail. Consequently, the components of a second or higher order cut set are effectively connected in parallel and the unavailability of a cut set is the product of unavailability of components in that cut set, assuming the failure events of the components are to be independent of each other. In addition, the consumption node fails if failure of any one of the cut sets occurs, and consequently, each cut set is effectively connected in series with all other cut sets.

Details of evaluating the reliability at the consumption node for cut sets of different orders are described here. The unavailability at the consumption node is given by:

$$U_e = \bigcup_l U_l \tag{12}$$

First-Order Cut Sets: Figure 3 shows a set of first-order cut sets between the feeder and the consumption node. The unavailability at the consumption node due to outage of elements belonging to one or more first-order cut sets is given by:

$$U_e^I = \bigcup_{l=1}^{N^I} U_l^I \tag{13}$$

Second-Order Cut Sets: Figure 4 reveals a number of second order cut sets between the feeder and the consumption node. The power interruption at a consumption node due to the failure of a second-order cut set occurs when both components in the cut set fail, since they are connected in parallel.

The unavailability at the consumption node due to outage of elements belonging to one or more second-order cut sets is given by:

$$U_e^{II} = \bigcup_{l=1}^{N^{II}} U_l^{II} \tag{14}$$

A second-order cut set can cause a power interruption only when both of its components fail. Hence

$$U_l^{II} = U_{l1}^{II} \bigcap U_{l2}^{II} \tag{15}$$

Similarly, one can calculate the unavailability at the consumption node for third and higher order cut sets.

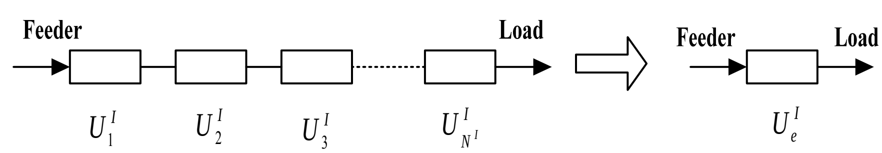


Figure 3. First-order cut sets between feeder and the consumer.

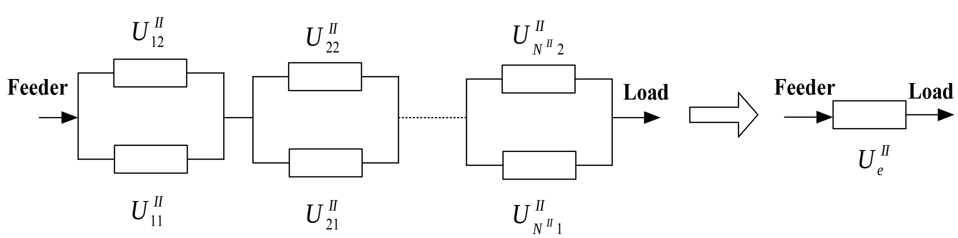


Figure 4. Second-order cut sets between feeder and the consumer.

The supply restoration of consumption node *i*, through node A, for each fault at any of branches between nodes A and *i* is accomplished after the fault repair. These set of branches are called *Rep* for node *i*. For a fault at one of the branches between nodes *i* and n, supply restoration of node *i* is performed after the fault isolation. These set of branches is identified as *Isol* for node *i*. As the network is considered radial, there is no possibility to restore the supply of node *i* by transferring it to other feeders.

The equivalent reliability parameters of the consumption node *i,* are given by:

$$\lambda_{ei,rep} = \sum_{j \in \mathrm{Re}p} \lambda_j \;, \lambda_{ei,isol} = \sum_{j \in Isol} \lambda_j \;, \lambda_{ei} = \lambda_{ei,rep} + \lambda_{ei,isol} \tag{16}$$

$$U_{ei,rep} = \sum_{j \in \mathrm{Re}p} \lambda_j r_{j,rep} \;, U_{ei,isol} = \sum_{j \in Isol} \lambda_j r_{j,isol} \;, U_{ei} = U_{ei,rep} + U_{ei,isol} \tag{17}$$

$$r_{ei} = \frac{U_{ei,rep}}{\lambda_{ei,rep}} + \frac{U_{ei,isol}}{\lambda_{ei,isol}} \tag{18}$$

So consumer interruption cost is:

$$IC_i = \lambda_{ei} \left[c_p(r_{ei}) + c_w(r_{ei}) r_{ei} \right] P_{l,i} \tag{19}$$

Hence, the consumers' interruption cost (*CIC*) for all *n* consumption nodes is given by:

$$CIC = \sum_{i=1}^{n} IC_i \tag{20}$$

The expected energy not supplied (EENS) and system average interruption duration index (SAIDI) are of the widely used reliability indices in the recent works on addressing the reliability issues while reconfiguring the distribution networks. The EENS and SAIDI may be defined as:

$$EENS = \frac{\sum_i P_{l,i} U_{ei}}{\sum_i N_i} \quad [\frac{\text{KWh}}{\text{consumer.year}}] \tag{21}$$

$$SAIDI = \frac{\sum_i N_i \lambda_{ei} r_{ei}}{\sum_i N_i} \quad [\frac{\text{hours}}{\text{consumer.year}}] \tag{22}$$

4. Proposed Codification

The radial configuration, in which the distribution network operates, should not posses any closed path with all loads energized.

Exploring the solution of distribution network reconfiguration problem using some meta-heuristic technique, the initial population may be obtained through the random selection of N_{tie} number of candidate switches out of total number of switches of the distribution network. Most of the time, it generates infeasible individuals, particularly in the case of medium or large-sized distribution networks. This certainly leads to increased computational burden to create initial population. In distribution network reconfiguration problem, one of the most important conditions at first is to generate the new configuration which meets both radial and all node energized criteria.

In the proposed codification, to avoid create infeasible individuals, some graph theory-based rules have been framed. Before framing these rules, the following terms must be defined: Consider a network with *n* nodes and *m* branches and *K* substation in which:

- A is matrix of the order $n \times 1$ that the element a_{i1} of the matrix A is equal to the number of branches which directly are connected to the *i*th node (the tie lines are ignored).

- B is matrix of the order $n \times n$. The element b_{ij} of the matrix B can be 1 or 0 as defined below:
  - b_{ij} =1 *if i=j*
  - b_{ij} = 1 *if node i and node j be connected together directly.* (23)
  - b_{ij} = 0 *Otherwise*.
- C is matrix of order $n \times n$. The element c_{ij} of the matrix C can be 1 or 0 as defined below:
  - c_{ij} =1 *for; j=1,2,…,n; if node i is substation.*
  - c_{ij} =0 *for j=1,2,…,n; Otherwise.* (24)
- D is matrix of order $n \times n$ where $D(i,j) = C(i,j) * B^n(i,j)$ (25)

It is assumed that the summation of all elements of matrix A for initial condition (with no loop in network and all nodes energized) and after any changes in switches states of the network are equal to a_1 and a_2 respectively. Now, for new arrangement of switches, the network remains radial topology and with no any node islanded, as long as all of the following rules are respected:

- Rule 1: Non of A matrix elements must equal to zero.
- Rule 2: a_1=a_2.
- Rule 3: The column summation of D matrix must not have any zero elements.

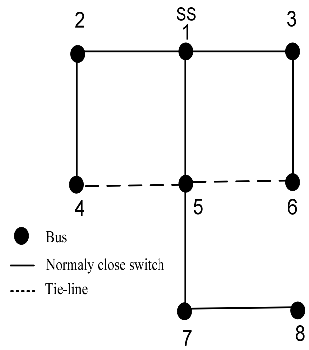
These rules guarantee to prevent producing individuals with infeasible radial topologies. Thus, are necessary to dictate meta-heuristic techniques throughout the evolution processes without involving boring mesh checks.

Now, the distribution system in Figure 5 is used to illustrate how the proposed codification works. For initial condition of Figure 5.1 the A, B, C matrixes and a_1 are:

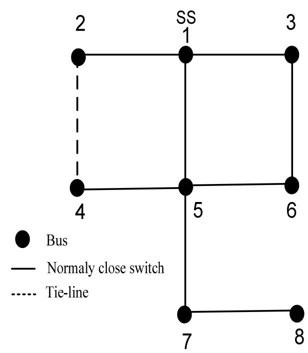
$$A = [3\ 2\ 2\ 1\ 2\ 1\ 2\ 1]'$$

$$B = \begin{bmatrix} 1 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

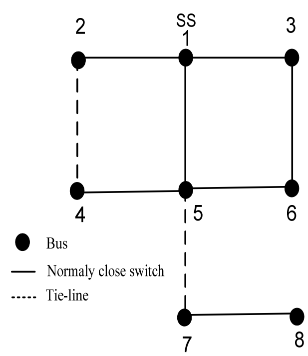
a_1=14;



(a)



(b)



(c)

Figure 5. Single-line diagram of a sample test system.
(a) Initial configuration (b) The system with a loop
(c) The system with a loop and two islanded nodes

Case 1: In case 1, which is shown in Figure 5.2, the test system has a loop and this structure does not meet criteria for distribution network operation. According to proposed codification, the rule 2 is not satisfied, because a_2 =16 and it is not equal to a_1. As a result, case 1 has been rejected.

Case 2: In case 2, which is shown in Figure 5.3, indicates a test system which contains a loop and two islanded nodes. Now Let us compute column summation of D matrix for network configuration in case 2. The column summation of D matrix is equal to:
[1508 1520 2696 1473 3336 2677 0 0]

As it can be seen, there are two zeros in column summation of D matrix at column 7 and 8. It means that nodes 7 and 8 are islanded. According to proposed codification, rule 3 is not met, as a result this structure can be rejected.

With regard to aforementioned cases (cases 1 and 2), this codification can easily recognize the jurisdiction of a structure.

This codification is also very easy to be coded in a programming environment. In this paper, this codification is used to determine merit of the new structures established for distribution network reconfiguration.

5. Proposed Heuristic Algorithm

Before explaining proposed heuristic algorithm for reconfiguration, the terms node-power (*np*), node-lp (*nl*) and tie-switch loop (*tie-loop*) should be explained.

In distribution network, based on radial configuration, each bus is connected to substation through a specified set of branches. This set of branches is unique for each bus. It is assumed that the unique set of line which connect node *i* to corresponding substation is L_i. So, *np*(*i*) and *nl*(*i*) are obtained by:

$$np(i) = \sum_{k \in L_i} R_k (P_k^2 + Q_k^2) \tag{26}$$

$$nl(i) = \lambda_{ei,rep} . p_{l,i} \tag{27}$$

Also tie-line loop (*tie-loop*) for each tie-line in the network is a set of lines which, if the tie-line is closed, forms a loop.

A. Application of proposed algorithm to find a structure with minimum losses cost

In this section, the objective function *f* that should be minimized is *LC*. To apply the proposed algorithm in the distribution network reconfiguration, the following steps should be repeated:

Step 1: Define the input data: In this step, the input data including the network configuration, lines and loads data, the tie lines (*tie-lines* vector), *tie-loop* for each tie line, number of tie lines (N_{tie}), discarded tie-lines vector ($DTV = \varnothing_{N_{tie} \times 1}$) and k=0.

Step 2: Evaluating of objective function (f_1): in this step the value of the objective function (*LC*) is evaluated using results of the power flow based on the existing tie lines (*tie-lines*).

Step 3: Computing Δnp : The node-power difference ($[\Delta np_{tie}]$, for $tie = 1,2,...,N_{tie}$) across all of the open tie lines (*tie-lines*) are computed.

Step 4: If k=N_{tie}, then finish the algorithm and print the value of objective function (f_1) and the tie lines vector (*tie-lines*), otherwise go to step 5.

Step 5: The node-power difference ($[\Delta np_{tie}]$) across such open tie lines which belong to *DTV* are ignored.

Step 6: Switching operation: such open tie line which has the maximum node-power difference in vector Δnp_{tie} is detected and considered first. Also one ends of nodes of this tie line is detected that has the highest *np*. The status of switches of both sides of this node must be changed. The detected tie line is changed in to closed and its neighbor line in corresponding *tie-loop* will change to open and create the new arrangement of tie lines (*tie-lines-new*).

Step 7: Constrains checking: in this step, the constraints related to nodes voltage, branches current and radiality constraint of the network are checked. If any constraint is violated, then k=k+1 and such tie line which is selected to switching operation (in step 6), add to *DTV* vector and return to step 4, otherwise go to step 8.

Step 8: Evaluating of objective function (f_2): in this step the new value of the objective function (f_2) is evaluated using results of the power flow based on the new status of tie lines (*tie-lines-new*). If $f_2 \leq f_1$, then go to step 9, otherwise k=k+1 and such tie line which is selected to switching operation (in step 6), add to *DTV* vector and return to step 4.

Step 9: In this step, the switching operation is accepted (*tie-lines*=*tie-lines-new*), all members of *DTV* vector are cleared ($DTV = \varnothing_{N_{tie} \times 1}$), k=0, f_1=f_2 and go to step 3.

B. Application of proposed algorithm to find a structure with minimum damage cost due to power supply interruption

In order to find an optimal configuration with minimum damage cost due to power supply interruption of consumers for the network, the algorithm uses the same process as mentioned in the previous section with little changes. Here, *np* and Δnp are replaced with nl and Δnl (node-lp difference) respectively and the objective function is changed to minimization of *CIC.*

C. Application of proposed algorithm in order to find a structure with minimum losses cost and damage cost due to power supply interruption

Here, the algorithm employs a combination of both above mentioned processes (sections 5.1 and 5.2). In order to find an optimal switching operation, in each iteration, the algorithm selects a switching operation from both switching operations, one which has caused minimum losses cost (according to section 5.1) and another which has caused minimum damage cost due to power fault at consumption nodes (according to section 5.2), which will lead to minimum total amount of losses cost and damage cost due to power supply interruption.

The flow chart of the proposed reconfiguration algorithm is presented in Figure 6.

6. Case Study

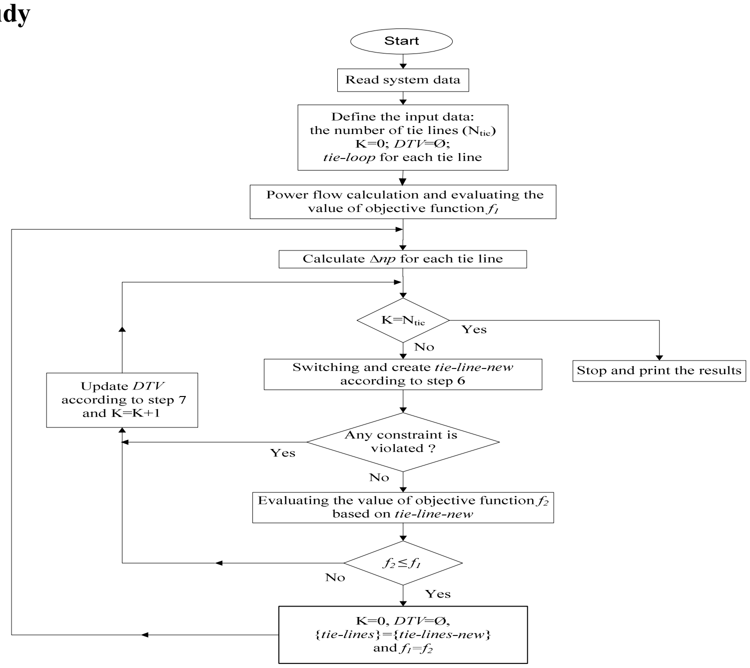


Figure 6. Flow chart of the proposed algorithm

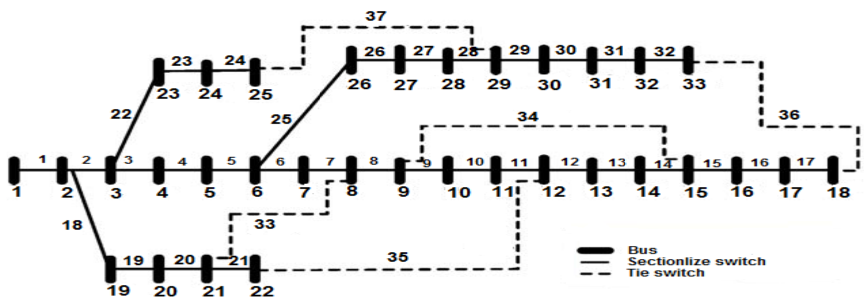


Figure 7. The IEEE 33-bus test distribution system

Efficiency of proposed method in this paper for multi criteria reconfiguration is first applied on a modified 33-bus distribution system which shown in Figure 7. The detailed data for this system is given in Appendix A. This system work at the nominal voltage of 12.66 kV and the base apparent power is 10 MVA. Also, the maximum current limit of the system branches is selected to be 255 A. The proposed method is programmed in MATLAB on a PC Pentium IV, 2.8-GHz computer with 512 MB of RAM.

In this paper, in restoration supply to power interrupted consumers processes, the possibility of load transferring to another feeder has been taken into account.

In this network, it has been assumed that there are three circuit breaker (on branch 1-2, at node 1, on branch 6-26, at node 6 and on branch 2-19, at node 19). The other existing switching equipment in the network are sectionaliser. The reliability parameters used in calculations have been illustrated in Table 1. Coefficients value of losses and interruption cost are as follows:

C_{pl}=10 \$/kw, C_{wl}=0.2 \$/kwh, C_p=5 \$/kw, C_w=1 \$/kwh.

Table 1. Reliability data of component.

Parameter / Component	Failure rate λ (*f/year*)	Repair time r_{rep} (h)	Isolation time r_{isol} (h)
Line (1 km)	0.128	45	2
Circuit breaker	0.036	16	2
Sectionalaiser	0.003	17	2

The study period (*T*) is taken on a year bases. The maximum capability of lines and the time of load transferring from one feeder to another are 650 kw and 5 hours respectively.

The results of network reconfiguration, considering LC criterion, CIC criterion and both LC and CIC criteria at the same time have been provided in Table 2.

In order to better understand of the results, Figure 8 indicates the final values of cost losses and damages cost resulted from power interruption of consumers for LC, CIC and LC+CIC criteria.

Table 2. Reconfiguration results for LC, CIC and LC+CIC minimization for modified 33-bus distribution system

Item	Initial condition	f=Min[LC]	f=Min[CIC]	f=Min[LC+CIC]
Tie-lines	33-37	7,14,9,32,37	7,13,11,31,24	7, 14, 9, 31, 28
LC (\$)	358481	246987	319372	254712
CIC (\$)	142839	118937	83959	91172
LC+CIC (\$)	501320	365924	403331	345884
EENS (kwh/consumer.y)	2.15	1.96	1.35	1.63
SAIDI (h/consumer.y)	59.61	56.16	42.29	60.34
CPU time (s)	-	0.417	1.943	3.623

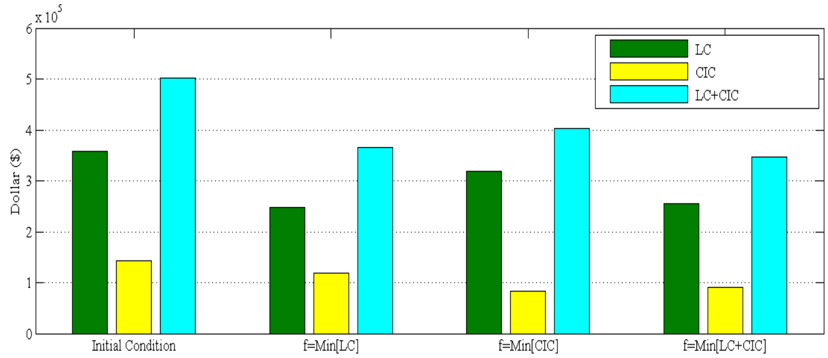


Figure 8. Comparative results for reconfiguration process
(Modified 33-bus distribution system).

The proposed method is also applied on the modified IEEE 119-node test feeder. This test system is a 11 kV distribution system with 118 sectionalizing switches and 15 tie switches as shown in Figure 9. The detailed data for this modified test system is given in Appendix A. The test results for the modified IEEE 119-node test feeder are shown in Table 3. In this case, it has been assumed that there are twelve circuit breaker (on branch 1, at node 1, on branch 5, at node 4, on branch 12, at node 11, on branch 18, at node 11, on branch 30, at node 30, on branch 38, at node 30, on branch 66, at node 68, on branch 78, at node 67, on branch 86, at node 82, on branch 89, at node 68, on branch 101, at node 105 and on branch 115, at node 119). The other existing switching equipment in the network are sectionaliser. The optimal values of LC, CIC and LC+CIC of reconfiguration for minimum losses cost, minimum damages cost resulted from power interruption of consumers and minimum losses cost and damages cost of power interruption of consumers are shown in Figure 10.

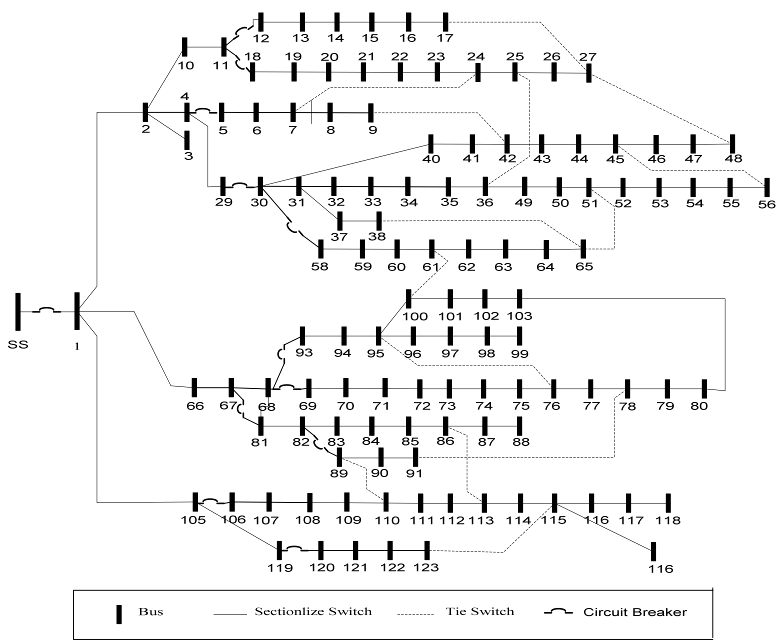


Figure 9. The modified 119-bus test system

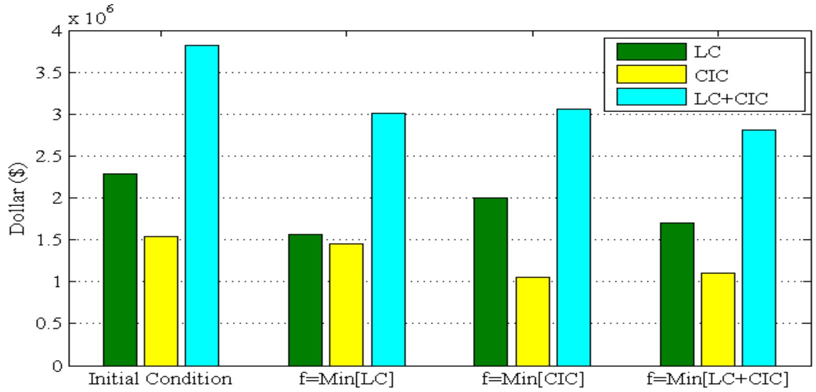


Figure 10. Comparative results for reconfiguration process
(Modified 119-bus distribution system).

Table 3. Reconfiguration results for LC, CIC and LC+CIC minimization for modified 119-bus distribution system.

Item	Initial condition	f=Min[LC]	f=Min[CIC]	f=Min[LC+CIC]
Tie-lines	119-133	43,120,24,51,49, 62,40,126,72,74, 77,83,131,110,35	44,120,121,54,123, 37,40,96,71,128, 77,108,131,109,25	46,25,121,54,49, 59,40,96,71,128, 77,130,86,110,133
LC ($)	2287233	1563790	1997510	1697800
CIC ($)	1534249	1450480	1056270	1106060
LC+CIC ($)	3821482	3014270	3053780	2803860
EENS (kwh/consumer.y)	11.13	10.94	9.13	9.42
SAIDI (h/consumer.y)	622.43	695.27	505.25	561.74
CPU time (s)	-	3.121	37.502	63.252

7. Conclusion

Distribution reconfiguration considering achieving a structure with minimum losses and energy not supplied is a complex optimization process. Various factors including the location and types of switch equipment, the capacity of lines and network structure are effective in reducing the damage cost of power interruption of consumers.

In this work, a multi objective reconfiguration problem in power distribution systems is studied. This multi objective problem was formulated taking into account two objectives to be minimized: the losses cost and damage cost resulted from power interruption of consumers. Additionally, this paper has presented a new heuristic approach in order to solve this multi objective problem. Also a new codification has been presented which avoids the creation of unconnected branches and the formation of closed loops when the proposed algorithm is searching for new configuration for the network.

In most presented articles in this regard, the possibility of load transferring to the neighbor feeders in power supply restoration to not supplied consumers process has been ignored. However, in this study, this possibility has been taken into account. The proposed method is successfully applied on modified 33-bus and 119-bus distribution networks.

List of symbols

CIC	the consumers interruption cost ($)	r_{ij}	failure duration for a line between node *i* and *j* (h)
c_{pl}	power losses cost($/kw)	$SAIDI$	system average interruption duration (h/consumer.year)
c_{wl}	energy losses cost ($/kw.h)	T	time interval (h)
C_p	cost of the interrupted power ($/kw)	*tie-loop*	set of lines which forms a loop
C_w	cost of the energy not supplied ($/kw.h)	U_e	unavailability at the consumption node (failure.h/year)
DTV	vector of discarded tie lines	U_{ei}	unavailability at the consumption node *i* (failure.h/year)
$EENS$	the expected energy not supplied (kwh/consumer.year)	$U_{ei,isol}$	unavailability at the consumption node *i* resulted from branch set *Isol* (failure.h/year)
I_j	current in the *j*th branch (pu)	$U_{ei,rep}$	unavailability at the consumption node *i* resulted from branch set *Rep* (failure.h/year)
$I_j^{\max}$	maximum current limit of the *j*th branch (pu)	U_e^I	unavailability at the consumption node due to outage of elements belonging to one or more first-order cut sets
IC_i	interruption cost of *i*th consumer ($)	U_e^{II}	unavailability at the consumption node due to outage of elements belonging to one or more second-order cut sets
LC	losses cost ($)	U_l	unavailability of the branch *l* (failure.h/year)
N_{tie}	number of tie lines	U_l^I	the unavailability of the *l*th first-order cut set (failure.h/year)
N_i	the number of consumers connected to node *i*	U_l^{II}	unavailability of the *l*th second-order cut set (failure.h/year)
N^{I}	the total number of first-order cut sets	V_i	voltage of the sending end node of the *i*th branch (pu)
N^{II}	the total number of second-order cut sets	V_{max}	maximum specified system node voltage (pu)
nl	node-lp (kw.failure/year)	V_{min}	minimum specified system node voltage (pu)
np	node-power (pu)	$W_{loss,i}$	energy losses for electrical line *i* (kw.h)
$P_{l,i}$	the loads which connected to node *i* (kw)	λ_{0l}	failure rate of electrical line *l* (failure/year)
P_i	active power at sending end of branch *i* (pu)	λ_{ei}	failure rate at the consumption node *i* (failure/year)
$P_{loss,i}$	active power losses for electrical line *i* (pu)	$\lambda_{ei,rep}$	failure rate at the consumption node *i* resulted from branch set *Rep* (failure/year)
Q_i	reactive power at sending end of branch *i* (pu)	$\lambda_{ei,isol}$	failure rate at the consumption node *i* resulted from branch set *Isol* (failure/year)
R_i	resistance of the *i*th branch (pu)	λ_l	failure rate of the branch *l* (failure/year)
r_{ei}	interruption duration of supply at consumption node *i* (h)	λ_{SEi}	failure rates of the switching equipment at nodes *i* (failure/year)
r_{0l}	restore times of supplying for a fault on the line of the branch *l* (h)	λ_{ij}	failure rate for a line between node *i* and *j* (failure/year)
r_l	restore times of supplying of the branch *l* (h)	$\psi(n)$	radial constraint for the *n*th topology
r_{SEi}	restore times of supplying for a fault at the switching equipment from the nodes *i* (h)	Δnp	node-power difference (pu)

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Appendix A.

System data for modified 33-bus distribution network

Line #	Node *i*	Node *j*	R (Ω)	X(Ω)	Length (m)	Load at node *i*		Line #	Node *i*	Node *j*	R (Ω)	X (Ω)	Length (m)	Load at node *i*	
						P(kw)	Q(kw)							P(kw)	Q(kw)
1	1	2	0.0922	0.047	100	-	-	20	20	21	0.4095	0.4784	400	90	40
2	2	3	0.493	0.2512	500	100	60	21	21	22	0.7089	0.9373	700	90	40
3	3	4	0.3661	0.1864	350	90	40	22	3	23	0.4512	0.3084	450	90	40
4	4	5	0.3811	0.1941	350	120	80	23	24	25	0.8980	0.7091	900	90	50
5	5	6	0.8190	0.7070	800	60	30	24	24	25	0.8980	0.7071	900	420	200
6	6	7	0.1872	0.6188	200	60	20	25	6	26	0.2031	0.1034	200	420	200
7	7	8	0.7115	0.2351	700	200	100	26	26	27	0.2842	0.1474	300	60	25
8	8	9	1.0299	0.7400	1000	200	100	27	27	28	1.0589	0.9338	1000	60	25
9	9	10	1.044	0.7400	1000	60	20	28	28	29	0.8043	0.7006	800	60	20
10	10	11	0.1967	0.0651	200	60	20	29	29	30	.5074	0.2585	500	120	70
11	11	12	0.3744	0.1298	350	45	30	30	30	31	0.9745	0.9629	950	200	100
12	12	13	1.4680	1.1549	1500	60	35	31	31	32	0.3105	0.3619	300	150	70
13	13	14	0.5416	0.7129	550	60	35	32	32	33	0.3411	0.5302	350	210	100
14	14	15	0.5909	0.5260	600	120	80	33	25	29	0.5000	0.5000	250	60	40
15	15	16	0.7462	0.5449	750	60	10	34	8	21	2.0000	2.0000	2000	-	-
16	16	17	1.2889	1.7210	1300	60	20	35	12	22	2.0000	2.0000	2000	-	-
17	17	18	0.7320	0.5739	700	60	20	36	9	15	2.0000	2.0000	2000	-	-
18	2	19	0.1640	0.1565	150	90	40	37	18	33	0.5000	0.5000	500	-	-
19	19	20	1.5042	1.3555	1500	90	40	-	-	-	-	-	-	-	-

System data for modified 119-bus distribution network

Line #	Node *i*	Node *j*	R (Ω)	X(Ω)	Load at node *i*		Length (km)	Line #	Node *i*	Node *j*	R (Ω)	X(Ω)	Load at node *i*		Length (km)
					P (kw)	Q (kw)							P (kw)	Q (kw)	
1	0	1	0	0	0	0	0.001	68	70	71	0.504	0.3303	52.814	25.257	1.68
2	1	2	0.036	0.01296	133.84	101.14	0.12	69	71	72	0.4	0.1461	66.89	38.713	1.353
3	2	3	0.033	0.01188	16.214	11.292	0.11	70	72	73	0.962	0.761	467.5	395.14	3.207
4	2	4	0.045	0.0162	34.315	21.845	0.15	71	73	74	0.165	0.06	594.85	239.74	0.55
5	4	5	0.015	0.054	73.016	63.602	0.05	72	74	75	0.303	0.1092	132.5	84.363	1.01
6	5	6	0.015	0.054	144.2	68.604	0.05	73	75	76	0.303	0.1092	52.699	22.482	1.01
7	6	7	0.015	0.0125	104.47	61.725	0.05	74	76	77	0.206	0.144	869.79	614.775	0.687
8	7	8	0.018	0.014	28.547	11.503	0.06	75	77	78	0.233	0.084	31.349	29.817	0.777
9	8	9	0.021	0.063	87.56	51.073	0.07	76	78	79	0.591	0.1773	192.39	122.43	1.97
10	2	10	0.166	0.1344	198.2	106.77	0.553	77	79	80	0.126	0.0453	65.75	45.37	0.42
11	10	11	0.112	0.0789	146.8	75.99	0.373	78	67	81	0.559	0.3687	238.15	223.22	1.863
12	11	12	0.187	0.313	26.04	18.687	0.623	79	81	82	0.186	0.1227	294.55	162.47	0.62
13	12	13	0.142	0.1512	52.1	23.22	0.473	80	82	83	0.186	0.1227	485.57	437.92	0.62
14	13	14	0.18	0.118	141.9	117.5	0.6	81	83	84	0.26	0.139	243.53	183.03	0.867
15	14	15	0.15	0.045	21.87	28.79	0.5	82	84	85	0.154	0.148	243.53	183.03	0.513
16	15	16	0.16	0.18	33.37	26.45	0.533	83	85	86	0.23	0.128	134.25	119.29	0.767
17	16	17	0.157	0.171	32.43	25.23	0.523	84	86	87	0.252	0.106	22.71	27.96	0.84
18	11	18	0.218	0.285	20.234	11.906	0.727	85	87	88	0.18	0.148	49.513	26.515	0.6
19	18	19	0.118	0.185	156.94	78.523	0.393	86	82	89	0.16	0.182	383.78	257.16	0.533
20	19	20	0.16	0.196	546.29	351.4	0.533	87	89	90	0.2	0.23	49.64	20.6	0.667
21	20	21	0.12	0.189	180.3	164.2	0.4	88	90	91	0.16	0.393	22.473	11.806	0.533
22	21	22	0.12	0.0789	93.167	54.594	0.4	89	68	93	0.669	0.2412	62.93	42.96	2.23
23	22	23	1.41	0.723	85.18	39.65	4.7	90	93	94	0.266	0.1227	30.67	34.93	0.887
24	23	24	0.293	0.1348	168.1	95.178	0.977	91	94	95	0.266	0.1227	62.53	66.79	0.887
25	24	25	0.133	0.104	125.11	150.22	0.443	92	95	96	0.266	0.1227	114.57	81.748	0.887
26	25	26	0.178	0.134	16.03	24.62	0.593	93	96	97	0.266	0.1227	81.292	66.526	0.887
27	26	27	0.178	0.134	26.03	24.62	0.593	94	97	98	0.233	0.115	31.733	15.96	0.777
28	4	29	0.015	0.0296	594.56	522.62	0.05	95	98	99	0.496	0.138	33.32	60.48	1.653
29	29	30	0.012	0.0276	120.62	59.117	0.04	96	95	100	0.196	0.18	531.28	224.85	0.653
30	30	31	0.12	0.2766	102.38	99.554	0.4	97	100	101	0.196	0.18	507.03	367.42	0.653
31	31	32	0.21	0.243	513.4	318.5	0.7	98	101	102	0.1866	0.122	26.39	11.7	0.622
32	32	33	0.12	0.054	475.25	456.14	0.4	99	102	103	0.0746	0.318	45.99	30.392	0.249
33	33	34	0.178	0.234	151.43	136.79	0.593	100	1	105	0.0625	0.0265	100.66	47.572	0.208
34	34	35	0.178	0.234	205.38	83.302	0.593	101	105	106	0.1501	0.234	456.48	350.3	0.5

35	35	36	0.154	0.162	131.6	93.082	0.513	102	106	107	0.1347	0.0888	522.56	449.29	0.449
36	31	37	0.187	0.261	448.4	369.7	0.623	103	107	108	0.2307	0.1203	408.43	168.46	0.769
37	37	38	0.133	0.099	440.52	321.64	0.443	104	108	109	0.447	0.1608	141.48	134.25	1.49
38	30	40	0.33	0.194	112.54	55.134	1.1	105	109	110	0.1632	0.0588	104.43	66.024	0.544
39	40	41	0.31	0.194	53.963	38.998	1.033	106	110	111	0.33	0.099	96.793	83.647	1.1
40	41	42	0.13	0.194	393.05	342.6	0.433	107	111	112	0.156	0.0561	493.92	419.34	0.52
41	42	43	0.28	0.15	326.74	278.56	0.933	108	112	113	0.3819	0.1374	225.38	135.88	1.273
42	43	44	1.18	0.85	536.26	240.24	3.933	109	113	114	0.1626	0.0585	509.21	387.21	0.542
43	44	45	0.42	0.2436	76.247	66.562	1.4	110	114	115	0.3819	0.1374	188.5	173.46	1.273
44	45	46	0.27	0.0972	53.52	39.76	0.9	111	115	116	0.2445	0.0879	918.03	898.55	0.815
45	46	47	0.339	0.1221	40.328	31.964	1.13	112	115	117	0.2088	0.0753	305.08	215.37	0.696
46	47	48	0.27	0.1779	39.653	20.758	0.9	113	117	118	0.2301	0.0828	54.38	40.97	0.767
47	36	49	0.21	0.1383	66.195	42.361	0.7	114	105	119	0.6102	0.2196	211.14	192.9	2.034
48	49	50	0.12	0.0789	73.904	51.653	0.4	115	119	120	0.1866	0.127	67.009	53.336	0.622
49	50	51	0.15	0.0987	114.77	57.965	0.5	116	120	121	0.3732	0.246	162.07	90.321	1.244
50	51	52	0.15	0.0987	918.37	1205.1	0.5	117	121	122	0.405	0.367	48.785	29.156	1.35
51	52	53	0.24	0.1581	210.3	146.66	0.8	118	122	123	0.489	0.438	33.9	18.98	1.63
52	53	54	0.12	0.0789	66.68	56.608	0.4	119	48	27	0.5258	0.2925	0	0	1.753
53	54	55	0.405	0.1458	42.207	40.184	1.35	120	17	27	0.5258	0.2916	0	0	1.753
54	55	56	0.405	0.1458	433.74	283.41	1.35	121	8	24	0.4272	0.1539	0	0	1.424
55	30	58	0.391	0.141	62.1	26.86	1.303	122	56	45	0.48	0.1728	0	0	1.6
56	58	59	0.406	0.1461	92.46	88.38	1.353	123	65	51	0.36	0.1296	0	0	1.2
57	59	60	0.406	0.1461	85.188	55.436	1.353	124	38	65	0.57	0.572	0	0	1.9
58	60	61	0.706	0.5461	345.3	332.4	2.353	125	9	42	0.53	0.3348	0	0	1.767
59	61	62	0.338	0.1218	22.5	16.83	1.127	126	61	100	0.3957	0.1425	0	0	1.319
60	62	63	0.338	0.1218	80.551	49.156	1.127	127	76	95	0.68	0.648	0	0	2.267
61	63	64	0.207	0.0747	95.86	90.758	0.69	128	91	78	0.4062	0.1464	0	0	1.354
62	64	65	0.247	0.8922	62.92	47.7	0.823	129	103	80	0.4626	0.1674	0	0	1.542
63	1	66	0.028	0.0418	478.8	463.74	0.093	130	113	86	0.651	0.234	0	0	2.17
64	66	67	0.117	0.2016	120.94	52.006	0.39	131	110	89	0.8125	0.2925	0	0	2.708
65	67	68	0.255	0.0918	139.11	100.34	0.85	132	115	123	0.7089	0.2553	0	0	2.363
66	68	69	0.21	0.0759	391.78	193.5	0.7	133	25	36	0.5	0.5	0	0	1.667
67	69	70	0.383	0.138	27.741	26.713	1.277	-	-	-	-	-	-	-	-

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