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

Sasan Ghasemi and Jamal Moshtagh

Department of Electrical and Computer Engineering, University of Kurdistan, Sanandaj, PO Box 416, Kurdistan, Iran

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 re configuration, 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

Received: May 8th, 2013. Accepted: August 22nd, 2013
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:

\[
\text{Optim} \{ f \} \quad (1)
\]

Subject to:

\[
V_{\text{min}} \leq V_i \leq V_{\text{max}}, \quad I_j \leq I_j^{\text{max}} \quad (2)
\]

\[
\psi(n) = 0 \quad (3)
\]

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:

\[
\text{Min}[LC + CIC] \quad (4)
\]
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:

$$P_{loss,i} = 3R_i i^2$$  \hspace{1cm} (5)

And the energy losses is given by:

$$W_{loss,j} = P_{loss,j} T$$  \hspace{1cm} (6)

So $LC$ for line $i$ is obtained by:

$$LC_i = c_{pl} P_{loss,j} + c_{wl} W_{loss,j}$$  \hspace{1cm} (7)

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

$$LC = \sum_i LC_i$$  \hspace{1cm} (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.](image)
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):

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

![Figure 2. Equivalent reliability parameters for a branch.](image)

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]:

\[
\hat{\lambda}_l = \lambda_{SEi} + \lambda_{SEj} + \lambda_{L_l} + \lambda_{SE}
\]

\[
U_l = \lambda_{SEi}r_{SEi} + \lambda_{SEj}r_{SEj} + \lambda_{L_l}r_{L_l}
\]

\[
r_i = \frac{U_l}{\hat{\lambda}_l}
\]

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:

$$U_v = \bigcup_i U_{v_i}$$

(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:

$$U^f_{v} = \bigcup_{i=1}^{n'} U^f_{i}$$

(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:

$$U^s_{v} = \bigcup_{i=1}^{k} U^s_{i}$$

(14)

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

$$U^s_{v} = U^s_{11} \cap U^s_{12}$$

(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:

$$
\lambda_{ei,rep} = \sum_{j \in Rep} \lambda_{ej} \quad \lambda_{ei,isol} = \sum_{j \in Isol} \lambda_{ej} = \lambda_{ei,rep} + \lambda_{ei,isol}
$$

(16)

$$
U_{ei,rep} = \sum_{j \in Rep} \lambda_{j,rep} r_{ji} \quad U_{ei,isol} = \sum_{j \in Isol} \lambda_{j,isol} r_{ji} \quad U_{ei} = U_{ei,rep} + U_{ei,isol}
$$

(17)

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

(18)

So consumer interruption cost is:

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

(19)

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

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

(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:

$$
EENS = \frac{\sum_{i} P_{l,j} U_{ei}}{\sum_{i} N_i} \left[ \frac{\text{KWh}}{\text{consumer.year}} \right]
$$

(21)

$$
SAIDI = \frac{\sum_{i} N_i \lambda_{ei} r_{ei}}{\sum_{i} N_i} \left[ \frac{\text{hours}}{\text{consumer.year}} \right]
$$

(22)

4. Proposed Codification

The radial configuration, in which the distribution network operates, should not possess 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 $a_{ij}$ 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.
  - \( b_{ij} = 0 \) Otherwise.

\[ \text{(23)} \]

• 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.

\[ \text{(24)} \]

• D is matrix of order \( n \times n \) where

\[ D(i,j) = C(i,j) * B^n(i,j) \]

\[ \text{(25)} \]

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:

\[ A = \begin{bmatrix} 3 & 2 & 2 & 1 & 2 & 1 \end{bmatrix}^{T} \]

\[ B = \begin{bmatrix}
 1 & 1 & 1 & 0 & 1 & 0 & 0 & 0 \\
 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\
 1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\
 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\
 1 & 0 & 0 & 0 & 1 & 0 & 1 & 0 \\
 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\
 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 \\
 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1
\end{bmatrix} \]

\[ C = \begin{bmatrix}
 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \]

\[ a_1=14; \]
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:

\[
\begin{bmatrix}
1508 & 1520 & 2696 & 1473 & 3336 & 2677 \\
0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

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:

\[
np(i) = \sum_{k \in L_i} R_k (P_k^2 + Q_k^2) \quad (26)
\]

\[
wl(i) = \sum_{r \in \text{rep}} P_{r,i} \quad (27)
\]

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 \(D_T = \emptyset_{N_{tie},nl}\) 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 \(\Delta np\): 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 \(D_T\) are ignored.

Step 6: Switching operation: such open tie line which has the maximum node-power difference in vector \(\Delta np_{tie}\) 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-new), all members of \( DTV \) vector are cleared (\( DTV = \emptyset_{N_{\text{tie}}-1} \)), \( k = 0 \), \( f_1 = f_2 \) 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 \( \Delta np \) are replaced with \( nl \) and \( \Delta nl \) (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](image-url)
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 \text{$/kw}$, \( C_{m}=0.2 \text{$/kwh}$, \( C_{p}=5 \text{$/kw}$, \( C_{w}=1 \text{$/kwh}$.

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>
<thead>
<tr>
<th>Parameter Component</th>
<th>Failure rate (\lambda) (f/year)</th>
<th>Repair time (r_{mp}) (h)</th>
<th>Isolation time (r_{iso}) (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line (1 km)</td>
<td>0.128</td>
<td>45</td>
<td>2</td>
</tr>
<tr>
<td>Circuit breaker</td>
<td>0.036</td>
<td>16</td>
<td>2</td>
</tr>
<tr>
<td>Sectionalisair</td>
<td>0.003</td>
<td>17</td>
<td>2</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Item</th>
<th>Initial condition</th>
<th>(T=\text{Min}[LC])</th>
<th>(T=\text{Min}[CIC])</th>
<th>(T=\text{Min}[LC+CIC])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line (1 km)</td>
<td>33,37</td>
<td>7.14, 9, 32, 37</td>
<td>7.13, 13, 13, 24</td>
<td>7.14, 9, 31, 28</td>
</tr>
<tr>
<td>LC (5)</td>
<td>25689</td>
<td>11498</td>
<td>11498</td>
<td>11498</td>
</tr>
<tr>
<td>CIC (5)</td>
<td>143859</td>
<td>118957</td>
<td>83959</td>
<td>91172</td>
</tr>
<tr>
<td>LC+CIC (5)</td>
<td>501320</td>
<td>365924</td>
<td>403331</td>
<td>345884</td>
</tr>
<tr>
<td>EENS (kwh/consumer.y)</td>
<td>2.15</td>
<td>1.96</td>
<td>1.85</td>
<td>1.63</td>
</tr>
<tr>
<td>SAIDI (h/consumer.y)</td>
<td>59.61</td>
<td>56.16</td>
<td>42.29</td>
<td>60.94</td>
</tr>
<tr>
<td>CPU time (s)</td>
<td>-</td>
<td>0.417</td>
<td>1.943</td>
<td>3.023</td>
</tr>
</tbody>
</table>
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.
Table 3. Reconfiguration results for LC, CIC and LC+CIC minimization for modified 119-bus distribution system.

<table>
<thead>
<tr>
<th>Item</th>
<th>Initial condition</th>
<th>( f = \text{Min}[\text{LC}] )</th>
<th>( f = \text{Min}[\text{CIC}] )</th>
<th>( f = \text{Min}[\text{LC+CIC}] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC ($)</td>
<td>2287233</td>
<td>1563790</td>
<td>1997510</td>
<td>1697800</td>
</tr>
<tr>
<td>CIC ($)</td>
<td>1534249</td>
<td>1450480</td>
<td>1056270</td>
<td>1106060</td>
</tr>
<tr>
<td>LC+CIC ($)</td>
<td>3821482</td>
<td>3014270</td>
<td>3053780</td>
<td>2803860</td>
</tr>
<tr>
<td>EENS (kwh/consumer.y)</td>
<td>11.13</td>
<td>10.94</td>
<td>9.13</td>
<td>9.42</td>
</tr>
<tr>
<td>SAIDI (h/consumer.y)</td>
<td>622.43</td>
<td>695.27</td>
<td>505.25</td>
<td>561.74</td>
</tr>
<tr>
<td>CPU time (s)</td>
<td>-</td>
<td>3.121</td>
<td>37.502</td>
<td>63.252</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIC</td>
<td>the consumers interruption cost ($)</td>
</tr>
<tr>
<td>c_{pl}</td>
<td>power losses cost ($/kw)</td>
</tr>
<tr>
<td>c_{el}</td>
<td>energy losses cost ($/kw.h)</td>
</tr>
<tr>
<td>C_{p}</td>
<td>cost of the interrupted power ($)</td>
</tr>
<tr>
<td>C_{w}</td>
<td>cost of the energy not supplied ($)</td>
</tr>
<tr>
<td>DTV</td>
<td>vector of discarded tie lines</td>
</tr>
<tr>
<td>EENS</td>
<td>the expected energy not supplied (kwh/consumer.year)</td>
</tr>
<tr>
<td>I_{j}</td>
<td>current in the jth branch (pu)</td>
</tr>
<tr>
<td>I_{max}</td>
<td>maximum current limit of the jth branch (pu)</td>
</tr>
<tr>
<td>IC_{i}</td>
<td>interruption cost of ith consumer ($)</td>
</tr>
<tr>
<td>LC</td>
<td>losses cost ($)</td>
</tr>
<tr>
<td>N_{tie}</td>
<td>number of tie lines</td>
</tr>
<tr>
<td>N_{i}</td>
<td>the number of consumers connected to node i</td>
</tr>
<tr>
<td>N^1</td>
<td>the total number of first-order cut sets</td>
</tr>
<tr>
<td>N^2</td>
<td>the total number of second-order cut sets</td>
</tr>
<tr>
<td>nl</td>
<td>node-lp (kw.failure/year)</td>
</tr>
<tr>
<td>np</td>
<td>node-power (pu)</td>
</tr>
<tr>
<td>P_{i}</td>
<td>the loads which connected to node i (kw)</td>
</tr>
<tr>
<td>P_{i}</td>
<td>active power at sending end of branch i (pu)</td>
</tr>
<tr>
<td>P_{con,i}</td>
<td>active power losses for electrical line i (pu)</td>
</tr>
<tr>
<td>Q_{i}</td>
<td>reactive power at sending end of branch i (pu)</td>
</tr>
<tr>
<td>R_{i}</td>
<td>resistance of the ith branch (pu)</td>
</tr>
<tr>
<td>r_{i}</td>
<td>interruption duration of supply at consumption node i (h)</td>
</tr>
<tr>
<td>r_{0i}</td>
<td>restore times of supplying for a fault on the line of the branch l (h)</td>
</tr>
<tr>
<td>r_{j}</td>
<td>restore times of supplying of the branch l (h)</td>
</tr>
<tr>
<td>r_{SE}</td>
<td>restore times of supplying for a fault at the switching equipment from the nodes i (h)</td>
</tr>
<tr>
<td>r_{ij}</td>
<td>failure duration for a line between node i and j (h)</td>
</tr>
<tr>
<td>SAIDI</td>
<td>system average interruption duration (h/consumer.year)</td>
</tr>
<tr>
<td>T</td>
<td>time interval (h)</td>
</tr>
<tr>
<td>tie-loop</td>
<td>set of lines which forms a loop</td>
</tr>
<tr>
<td>U_{i}</td>
<td>unavailability at the consumption node (failure.h/year)</td>
</tr>
<tr>
<td>U_{i,iol}</td>
<td>unavailability at the consumption node i resulted from branch set Isol (failure.h/year)</td>
</tr>
<tr>
<td>U_{i,rep}</td>
<td>unavailability at the consumption node i resulted from branch set Rep (failure.h/year)</td>
</tr>
<tr>
<td>U_{i}</td>
<td>unavailability at the consumption node due to outage of elements belonging to one or more first-order cut sets</td>
</tr>
<tr>
<td>U_{ii}</td>
<td>unavailability at the consumption node due to outage of elements belonging to one or more second-order cut sets</td>
</tr>
<tr>
<td>U_{i}</td>
<td>the unavailability of the ith first-order cut set (failure.h/year)</td>
</tr>
<tr>
<td>U_{ii}</td>
<td>the unavailability of the ith second-order cut set (failure.h/year)</td>
</tr>
<tr>
<td>V_{i}</td>
<td>voltage of the sending end node of the ith branch (pu)</td>
</tr>
<tr>
<td>V_{max}</td>
<td>maximum specified system node voltage (pu)</td>
</tr>
<tr>
<td>V_{min}</td>
<td>minimum specified system node voltage (pu)</td>
</tr>
<tr>
<td>W_{lost,i}</td>
<td>energy losses for electrical line i (kw.h)</td>
</tr>
<tr>
<td>λ_{0l}</td>
<td>failure rate of electrical line l (failure/year)</td>
</tr>
<tr>
<td>λ_{ei}</td>
<td>failure rate at the consumption node i (failure/year)</td>
</tr>
<tr>
<td>λ_{ei,rep}</td>
<td>failure rate at the consumption node i resulted from branch set Rep (failure/year)</td>
</tr>
<tr>
<td>λ_{ei,isol}</td>
<td>failure rate at the consumption node i resulted from branch set Isol (failure/year)</td>
</tr>
<tr>
<td>λ_{l}</td>
<td>failure rate of the branch l (failure/year)</td>
</tr>
<tr>
<td>λ_{SEi}</td>
<td>failure rates of the switching equipment at nodes i (failure/year)</td>
</tr>
<tr>
<td>λ_{ij}</td>
<td>failure rate for a line between node i and j (failure/year)</td>
</tr>
<tr>
<td>Δnp</td>
<td>node-power difference (pu)</td>
</tr>
</tbody>
</table>

### References


Radial distribution systems reconfiguration considering power losses cost


### Appendix A.

**System data for modified 33-bus distribution network**

<table>
<thead>
<tr>
<th>Line #</th>
<th>Node i</th>
<th>Node j</th>
<th>R (Ω)</th>
<th>X(Ω)</th>
<th>Length (m)</th>
<th>Load at node i</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>P(kw)</td>
<td>Q(kw)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>0.0922</td>
<td>0.047</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>3</td>
<td>0.493</td>
<td>0.2512</td>
<td>500</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>4</td>
<td>0.3661</td>
<td>0.1864</td>
<td>350</td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>5</td>
<td>0.3811</td>
<td>0.1941</td>
<td>350</td>
<td>120</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>6</td>
<td>0.8190</td>
<td>0.7070</td>
<td>800</td>
<td>60</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>7</td>
<td>0.1872</td>
<td>0.6188</td>
<td>200</td>
<td>60</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>8</td>
<td>0.7115</td>
<td>0.2351</td>
<td>700</td>
<td>200</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td>9</td>
<td>1.0299</td>
<td>0.3400</td>
<td>1000</td>
<td>200</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>10</td>
<td>1.044</td>
<td>0.7400</td>
<td>1000</td>
<td>60</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>11</td>
<td>0.1967</td>
<td>0.0651</td>
<td>200</td>
<td>60</td>
</tr>
<tr>
<td>11</td>
<td>11</td>
<td>12</td>
<td>0.3744</td>
<td>0.1298</td>
<td>350</td>
<td>45</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>13</td>
<td>1.4680</td>
<td>1.1549</td>
<td>1500</td>
<td>60</td>
</tr>
<tr>
<td>13</td>
<td>13</td>
<td>14</td>
<td>0.5416</td>
<td>0.7129</td>
<td>550</td>
<td>60</td>
</tr>
<tr>
<td>14</td>
<td>14</td>
<td>15</td>
<td>0.5909</td>
<td>0.5260</td>
<td>600</td>
<td>120</td>
</tr>
<tr>
<td>15</td>
<td>15</td>
<td>16</td>
<td>0.7462</td>
<td>0.5449</td>
<td>750</td>
<td>60</td>
</tr>
<tr>
<td>16</td>
<td>16</td>
<td>17</td>
<td>1.2889</td>
<td>1.7210</td>
<td>1300</td>
<td>60</td>
</tr>
<tr>
<td>17</td>
<td>17</td>
<td>18</td>
<td>0.7320</td>
<td>0.5739</td>
<td>700</td>
<td>60</td>
</tr>
<tr>
<td>18</td>
<td>18</td>
<td>19</td>
<td>0.1640</td>
<td>0.1565</td>
<td>150</td>
<td>90</td>
</tr>
<tr>
<td>19</td>
<td>19</td>
<td>20</td>
<td>1.5042</td>
<td>1.3555</td>
<td>1500</td>
<td>90</td>
</tr>
</tbody>
</table>
### System data for modified 119-bus distribution network

<table>
<thead>
<tr>
<th>Line #</th>
<th>Node i</th>
<th>Node j</th>
<th>R (Ω)</th>
<th>X(Ω)</th>
<th>Load at node i</th>
<th>Length (km)</th>
<th>Node i</th>
<th>Node j</th>
<th>R (Ω)</th>
<th>X(Ω)</th>
<th>Load at node i</th>
<th>Length (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0.036</td>
<td>0.01296</td>
<td>133.84</td>
<td>0.01</td>
<td>68</td>
<td>70</td>
<td>0.504</td>
<td>0.3303</td>
<td>52.814</td>
<td>25.257</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>0.045</td>
<td>0.0162</td>
<td>34.315</td>
<td>0.15</td>
<td>71</td>
<td>73</td>
<td>0.165</td>
<td>0.06</td>
<td>594.85</td>
<td>239.74</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0.015</td>
<td>0.054</td>
<td>73.016</td>
<td>0.05</td>
<td>72</td>
<td>74</td>
<td>0.303</td>
<td>0.1092</td>
<td>132.5</td>
<td>84.363</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>4</td>
<td>0.15</td>
<td>0.042</td>
<td>144.2</td>
<td>0.05</td>
<td>73</td>
<td>75</td>
<td>0.303</td>
<td>0.1092</td>
<td>52.814</td>
<td>22.482</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>5</td>
<td>0.021</td>
<td>0.063</td>
<td>87.56</td>
<td>0.07</td>
<td>76</td>
<td>78</td>
<td>0.591</td>
<td>0.1773</td>
<td>192.39</td>
<td>122.43</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>6</td>
<td>0.116</td>
<td>0.0341</td>
<td>198.2</td>
<td>0.55</td>
<td>77</td>
<td>79</td>
<td>0.126</td>
<td>0.0453</td>
<td>65.75</td>
<td>45.37</td>
</tr>
<tr>
<td>7</td>
<td>6</td>
<td>7</td>
<td>0.112</td>
<td>0.0789</td>
<td>146.8</td>
<td>0.373</td>
<td>78</td>
<td>81</td>
<td>0.559</td>
<td>0.3687</td>
<td>238.15</td>
<td>223.22</td>
</tr>
<tr>
<td>8</td>
<td>7</td>
<td>8</td>
<td>0.187</td>
<td>0.313</td>
<td>26.04</td>
<td>0.623</td>
<td>79</td>
<td>82</td>
<td>0.186</td>
<td>0.1227</td>
<td>294.55</td>
<td>162.47</td>
</tr>
<tr>
<td>9</td>
<td>8</td>
<td>9</td>
<td>0.187</td>
<td>0.313</td>
<td>26.04</td>
<td>0.623</td>
<td>79</td>
<td>82</td>
<td>0.186</td>
<td>0.1227</td>
<td>294.55</td>
<td>162.47</td>
</tr>
</tbody>
</table>

**Radial distribution systems reconfiguration considering power losses cost**
Sasan Ghasemi received a M.Sc. degree in electrical engineering from Kurdistan University, Iran, 2013. He is currently with university of Applied Science and Technology of Ilam, Iran. His areas of interests are the reliability, reconfiguration and restoration of power distribution systems.

Jamal Moshtagh received a Ph. D. degree in electrical engineering from Bath University, United Kingdom, 2006. Currently, he is an Associate Professor in the Electrical Engineering Department, University of Kurdistan, Iran. His interest areas are planning, optimization, reliability, and quality of electrical systems.