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Balanced and unbalanced distribution networks reconfiguration considering reliability indices

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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, those are consumers and distribution system companies, need to be met. One of the most significant parameters in this regard is to increase the reliability of the 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 modified heuristic approach for distribution system has been presented. Also, in order to consider reliability indexes, a number of new formulas have been presented. The effectiveness of the proposed method is demonstrated on balanced and unbalanced test distribution systems.

1. Introduction

Distribution network reconfiguration is accomplished by changing the topological state of open/closed of some electric lines. The states of these lines, with respect to maintaining the radial configuration, can be changed. These changes must be resulted in objective function improvement which, in this regard, network constraints should be taken into account.

In order to solve reconfiguration problem, Civanlar et al. [1] employed load transfer from a feeder to neighbor feeder. Cherkaoui et al. [2] presented "branch exchange" strategy. Modified Tabu Search utilized for distribution system reconfiguration by Garcia-Martinez [3] and Abdelaziz [4] respectively.

Recently, some other approaches like hybrid evolutionary algorithm (EA) [5], non-dominated sorting genetic algorithm-II (NSGA-II) [6], plant growth simulation algorithm (PGSA) [7], ant colony algorithm [8], multi objective honey bee mating optimization (MHBMO) [9], harmony search algorithm (HSA) [10], heuristic approach [11–13] also employed to find optimal solution for reconfiguration problem of distribution networks.

A comprehensive survey on electric distribution network reconfiguration techniques considering loss minimization, load balancing, voltage profile improvement and service restoration is presented by Tang et al. [14]. Kavousi-Fard et al. [15] proposed a bat algorithm considering DG and a probabilistic load flow and, the same authors in [16] proposed a clonal selection algorithm with a probabilistic load flow and a sensitivity analysis to optimize the configuration of the distribution networks. Asrari [17] used Shuffled frog leaping algorithm (SFLA) to find optimal configuration of distribution networks. Voltage sag and voltage drop are the main objective functions which are considered. A systematic approach to determine an optimal long-term reconfiguration schedule is proposed by Asrari et al. [18]. To solve the optimization problem, a novel adaptive fuzzy-based parallel genetic algorithm (GA) is proposed that employs the concept of parallel computing in identifying the optimal configuration of the network. Haghighat et al. [19] presented a method of determining the minimum loss network configuration of a distribution system with uncertain load and renewable generation. In this regards a mixed-integer two-stage robust optimization formulation and a decomposition algorithm in a master-slave structure are proposed to solve the problem. Huang et al. presented an optimal reconfiguration based dynamic tariff (DT) method for congestion management and line loss reduction in distribution networks with high penetration of electric vehicles.

In the recent years, many researchers have been interested in considering reliability related issues in the distribution network reconfiguration process. Tristiu [20] proposed a reconfiguration approach to reduce the interruption numbers of a distribution network. Amanulla [21], solved the network reconfiguration problem

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considering network reliability and power losses. Some reconfiguration methods are developed to minimize a weighted sum of reliability indexes (SAIDI, SAIFI and MAIFI) [22], the expected interruption cost (ECOST) [23] and energy not supplied (ENS) [24]. In order to evaluate basic reliability indices, Arya et al. [25] presented a new methodology based on smooth boot strapping technique. For reliability enhancement of distribution networks, a new approach based on determining optimal values of repair times and failure rates of each elements of the network introduced by Arya et al. [26]. Kavousi-Fard and Akbari-Zadeh presented [27] improved shuffled frog leaping algorithm (ISFLA) to solve the distribution network reconfiguration problem from the reliability enhancement point of view. Binary particle swarm optimization-based search algorithm to maximize the reliability and minimize the real power losses of network through distribution network reconfiguration is utilized by Amanulla et al. [28].

Alonso et al. [29] presented an artificial immune system algorithm. The reliability is calculated with a specialised index called: power interruption equivalent frequency index, that uses a binary matrix to represent the out-of-service nodes in case of a given fault. Gupta et al. [30] proposed a genetic algorithm with weighing factors in the objective function to determine the dominance between the active power losses and the reliability indices. Narimani et al. [31] proposed an enhanced gravitational search algorithm in order to minimize the active power losses, the operational costs and to improve the system's AENS. The methodology used to calculate each node's reliability is based on the difference between the duration of the interruptions in the nodes upstream the fault and the rest of the nodes, Duan et al. [32] considered three ways that faults affect each node's reliability: first, if the fault is in another feeder; second, if the fault is in the upstream path of the node; and third, if the fault is not in the upstream path of the node.

Bilibin and Capitanescu [33] proposed centralised thermal overload management in active distribution networks considering the capability of network reconfiguration. A reconfiguration strategy for active distribution network considering maximum power supply capability (PSC) was proposed by Liang et al. [34].

Ahmadi et al. [35] utilized a mixed-integer programming formulation of network reconfiguration based on graph theory to identify the configuration with minimum power losses. Jazebi [36] presented shuffled frog leaping algorithm (SFLA) and imperialist competitive algorithm to simulate the network reconfiguration problem closer to reality by considering the impact of harmonic loads. The objective functions of the defined problem are power loss, deviation of voltage nodes, and the violations of branches current.

Larimi et al. [37] developed a risk-based distribution network reconfiguration. Load, reliability parameter and generation of sources, losses and reliability as the objectives of the reconfiguration problem have been considered and also the scenario-based risk assessment is used to solve that problem. López et al. [38] presented a convex mixed-integer second-order conic programming (MISOCP) model for the robust reconfiguration of electric distribution network with reliability constraints, considering uncertainty of the reliability parameters. Asrari et al. [39] proposed a reliability-based frog coding to solve the reconfiguration problem of distribution networks which a switch reliability index (SRI) is defined for each switch. SRI is a fuzzy value between zero and one. A switch with a higher value of SRI has a higher chance to be selected for generating the initial population (i.e., the initial configuration) of the optimization process.

The main contribution of this paper is to find the optimal configuration of unbalanced distribution networks which improve the reconfiguration objective functions (losses, voltage profile and load balancing index) and the reliability indexes. Also the heuristic approach which presented in [40] is improved so that it can be used in reconfiguration of unbalanced distribution networks. Further, the proposed improved approach finds optimal solution in much less CPU time as compared with other methods.

This paper is organized as follows: Section 2 presents the mathematical model of the reconfiguration optimization problem. The objective function evaluation will be discussed in Section 3. Then, in Section 4 the proposed heuristic algorithm for distribution network reconfiguration is presented. Case studies are shown in Section 5. Conclusions are drawn in Section 6. Nomenclature is provided in Appendix A.

2. Problem formulation

The problem of distribution networks reconfiguration can be mathematically modeled as follows:

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

Subject to:

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

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

Eq. (1) shows the objective function which should be optimized. Eq. (2) indicates voltage and current limits of network and finally, Eq. (3) shows the radiality constraint of the network ($\psi = 0$ for radial topologies, otherwise $\psi = 1$).

3. Objective function evaluation

In this paper, the objective function that should be minimized is a combination of losses cost (*LC*) and consumer interruption cost (*CIC*). Therefore, the objective function *f* is:

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

The evaluation details of both abovementioned terms are explained in the next sections.

3.1. Evaluation of losses cost (LC)

According to [41], the power losses and energy losses are the most important components of losses. The power losses and energy losses for a three-phase electrical line *i*, are:

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

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

So *LC* for line *i* is given by:

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

Therefore, the total losses cost (*LC*) is:

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

One of the most importance results of distribution network reconfiguration is the load balancing improvement. the load balancing index of branch *i* is $\frac{S_i}{S_i^{\max}}$, if *i*th branch of the network is lightly loaded, the value of $\frac{S_i}{S_i^{\max}}$ is low (less than 1), in critical condition its equal to 1 and in bad condition, when the branch rated capacity is exceeded, its value will be greater than 1. If the loads are unbalanced, the load balancing indices of individual branches will differ widely, whereas, the balanced load will make the load balancing indices of all the branches nearly equal. An effective strategy to

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reduce the load balancing index of the network is to transfer part of loads of heavily loaded feeders to lightly loaded feeders. So, the load balancing index of the network can be defined as [42,43]:

$$LBI = \text{Variance}\left(\frac{S_1}{S_1^{\max}}, \frac{S_2}{S_2^{\max}}, \frac{S_3}{S_3^{\max}}, \ldots, \frac{S_{N_l}}{S_{N_l}^{\max}}\right) \tag{9}$$

3.2. Evaluation of interruption cost (CIC)

First of all, in order to understand the behavior of the network after a fault occurred in the network, we need to be aware of switching equipment. In this regards, the sectionaliser and Circuit breaker switching equipment are defined as follow:

- Sectionaliser: is a switching equipment which has been designed to act in normal condition in order to change on/off state of a line or to separate two circuits.
- Circuit breaker: is a switching equipment that has been designed to act in both normal and emergency conditions (interrupting the fault current).

The radial topology of the distribution network causes any consumer has been connected to the supplied source through a specified and unique of branches.

Additionally, the radial constraint eliminates supplying power from more than one source. Thus, a consumer is supplied successfully when all the line sections located in the path between the consumer and the substation are closed. Also, all branches which connected to this path directly without any switching equipments must be in service.

Unsuccessful supply and fault path definitions are so complex. Based on existing switching equipment in the network, there are different states related to time duration of fault and interrupted areas.

Fig. 1 shows an occurred short circuit fault in the network which cause to power supply interruption in downstream area. Supply restoration can be accomplished using different ways. One of them is repairing the fault element of the network and resupplying through the first path. This goal may be obtained by isolating the fault and connect one of the downstream nodes to the same source of power or connecting to another source of power. For the upstream consumers the subsequences of the fault and the power interruption time are related to *SE*.

If *SE* is a sectionaliser, the first equipment which operates after fault is *CB*. This switching operation caused to power interruption of all consumers.

If *SE* is a circuit breaker, it itself will disconnect the line and isolate the faulted area. Thus, the upstream area remains energized.

A branch of the network include a line or a transformer and two switching equipment. As it illustrated in Fig. 2, a branch l between the nodes i and j can be described by two reliability indices:

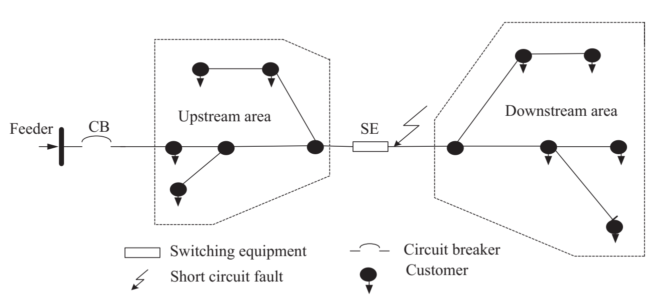

Figure 1. A radial distribution network.

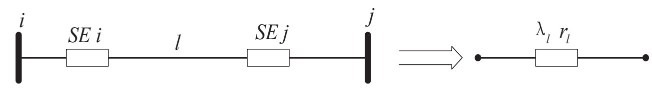

Figure 2. Reliability characteristic of a branch.

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

The process of fault clearance can be summarized as four main steps which are explained as follow [44]:

1. Locating and isolating the fault
2. Resupplying the consumers which are not located in the fault area
3. Load transfer to other feeders
4. Repairing faulted elements and energizing the interrupted consumers through pre-fault paths.

After any fault, steps 1, 2 and 4 are done; however, doing step 3 depends on some other factors, like lines capacity and network structure.

So, the reliability parameters related to branch l can be described as follow [45]:

$$\lambda_l = \lambda_{SEi} + \lambda_{0l}L_l + \lambda_{SEj} \tag{10}$$

$$U_l = \lambda_{SEi}r_{SEi} + \lambda_{0l}r_{0l} + \lambda_{SEj}r_{SEj} \tag{11}$$

$$r_l = \frac{U_l}{\lambda_l} \tag{12}$$

The power of a consumption node, which connected to the feeder through first-order cut sets, will be interrupted if one of the elements of this cut sets fail.

As a result, for minimizing probability of power interruption of consumption nodes, we need to use second or higher order cut sets. The elements of a second or higher order cut set connected in parallel, therefore, it fails if any of the elements of the cut set fail. This feature of second or higher order cut sets, helps network to be more reliable.

In the following the reliability at the consumption node for different types of cut sets is evaluated. The unavailability at the consumption node can be evaluated by:

$$U_e = \bigcup_l U_l \tag{13}$$

3.2.1. First-order cut sets

Fig. 3 depicts a group of first-order cut sets which connected the feeder to the consumption node. The unavailability at the consumption node can be evaluated by:

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

3.2.2. Second-order cut sets

A group of second-order cut sets is depicted in Fig. 4 which connected a consumption node to the feeder. The power of the

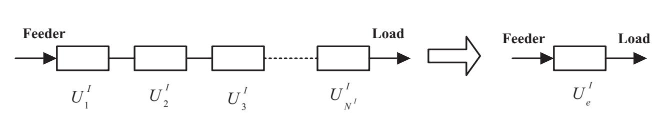

Figure 3. Single-line diagram of first-order cut sets.

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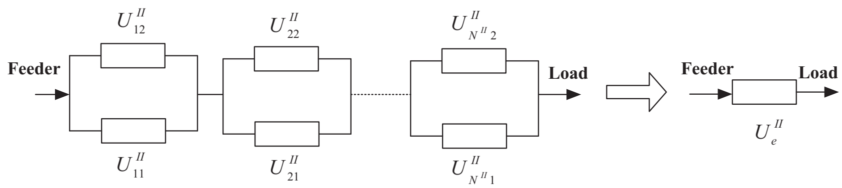

Figure 4. Single-line diagram of second-order cut sets.

consumption node will be interrupted if both elements in the second-order cut set fail. So, the unavailability at the consumption node affected by fail of components related to second-order cut sets is obtained by:

$$U_e^{II} = \bigcup_{l=1}^{N^{II}} U_l^{II} \tag{15}$$

When both elements of a second-order cut set fail, its can cause a power interruption. So:

$$U_l^{II} = U_{l1}^{II} \cap U_{l2}^{II} \tag{16}$$

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

Power supply restoration of consumption node *i*, through feeder, for each fault at any of branches between feeder and node *i* is done after repairing the fault. These set of branches are called *Rep-set* for node *i*. After a fault occurrence at one of the branches between node *i* and M, the power supply restoration of node *i* is accomplished after isolation of the fault. These set of branches is known as *Isol-set* for node *i*. It should be noted that the radial constraint of distribution network eliminates transferring load *i* to other feeders.

So, the reliability parameters related to the consumption node *i*, are evaluated by:

$$\lambda_{ei,rep} = \sum_{j \in Rep-set} \lambda_j, \quad \lambda_{ei,isol} = \sum_{j \in Isol-set} \lambda_j, \quad \lambda_{ei} = \lambda_{ei,rep} + \lambda_{ei,isol} \tag{17}$$

$$U_{ei,rep} = \sum_{j \in Rep-set} \lambda_j r_{j,rep}, \quad U_{ei,isol} = \sum_{j \in Isol-set} \lambda_j r_{j,isol}, \quad U_{ei} = U_{ei,rep} + U_{ei,isol} \tag{18}$$

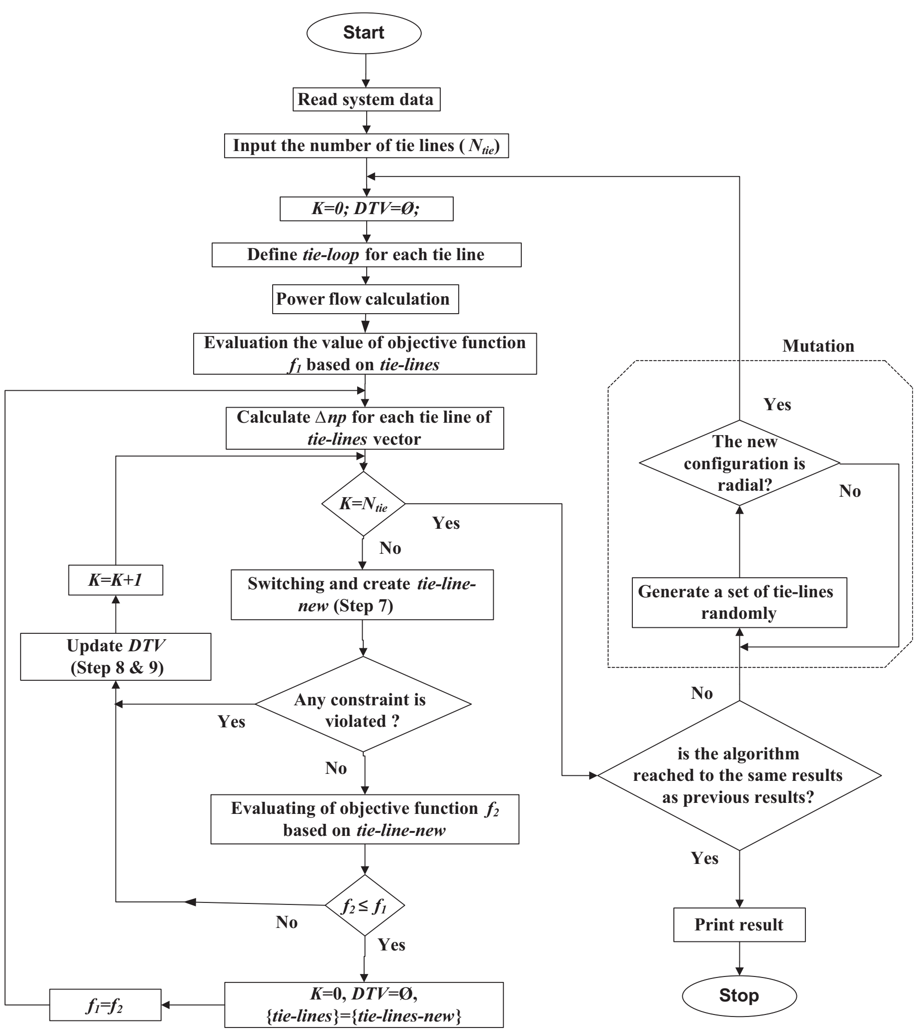

Figure 5. Flow chart of the proposed algorithm.

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$$r_{ei} = \frac{U_{ei,rep}}{\lambda_{ei,rep}} + \frac{U_{ei,isol}}{\lambda_{ei,isol}} \quad (19)$$

Thus, interruption cost of a consumer is:

$$IC_i = \lambda_{ei}\left[c_p(r_{ei}) + c_w(r_{ei})r_{ei}\right]P_{l,i} \quad (20)$$

As a result, the interruption cost of all consumers (*CIC*) is given by:

$$CIC = \sum_{i=1}^{n} IC_i \quad (21)$$

It can be seen from recent published papers that the expected energy not supplied (*EENS*) and system average interruption duration index (*SAIDI*) are two widely used reliability indices to show reliability issues in process of reconfiguration. These two reliability indices can be obtained by:

$$EENS = \frac{\sum_i P_{l,i} U_{ei}}{\sum_i N_i} \quad \left[\frac{\text{kW h}}{\text{consumer} \cdot \text{year}}\right] \quad (22)$$

$$SAIDI = \frac{\sum_i N_i \lambda_{ei} r_{ei}}{\sum_i N_i} \quad \left[\frac{\text{hours}}{\text{consumer} \cdot \text{year}}\right] \quad (23)$$

4. Proposed modified heuristic algorithm

Before explaining proposed approach for reconfiguration, the terms *node-power* (*np*), *node-lp* (*nl*) and *tie-line 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:

$$np(i) = \sum_{k \in L_i} R_k \left(P_k^2 + Q_k^2\right) \quad (24)$$

$$nl(i) = \lambda_{ei,rep} \cdot p_{l,i} \quad (25)$$

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

4.1. Reconfiguration to find configuration with minimum LC

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: Read the system data (lines and loads data, the tie-lines vector (*tie-lines*), *tie-loop* for each tie-line, number of tie-lines (N_{tie})).
Step 2: Put the value of k into 0 and $DTV = \emptyset_{N_{tie}\times 1}$ (discarded tie-lines vector).
Step 3: Evaluate the value of the objective function f_1 using results of the power flow based on the existing tie-lines (*tie-lines*).
Step 4: Compute node-power difference across all of the open tie-lines ($[\Delta np_{tie}]$, for $tie = 1, 2, \ldots, N_{tie}$).
Step 5: If $k = N_{tie}$, then save the results and go to step 11, otherwise go to step 6.
Step 6: Ignore the node-power difference ($[\Delta np_{tie}]$) across such open tie-lines which belong to *DTV*.
Step 7: Find such open tie-line which has the maximum node-power difference in vector Δnp_{tie} and detect one ends of this tie-line that has the highest *np*. Change the status of switches of both sides of this node so that the detected tie-line is changed into closed and also its neighbor line in corresponding *tie-loop*

Table 1
Initial conditions of test distribution systems.

Test system	Tie-lines	System voltage (kV)	LBI	Nominal real load (MW)	Nominal reactive load (MVAr)	Real power losses (MW)	Minimum node voltage (pu)
69-Bus	69–73	12.66	0.1546	3.8019	2.6941	0.22493	0.909
119-Bus	118–132	11	1.5388	22.7097	17.0411	1.3019	0.8688
33-Bus (unbalanced)	33–37	12.66	0.0112	3.715	2.300	0.20782	V_a = 0.9225
			0.0152				V_b = 0.9099
			0.0128				V_c = 0.9003

Table 2
Comparison results for test distribution systems.

Test system	Method	Losses (kW)	Losses reduction (%)	LBI	LBI improvement (%)	CPU time (s)	Tie-lines	Minimum node voltage (pu)
69-Bus	Ref. [43]	98.59	56.2	0.0907	41.33	NA	69, 70, 14, 58, 61	0.9495
	Ref. [6]	98.90	56.03	0.1025	33.70	27.3	69, 61, 58, 13, 12	0.9495
	Ref. [51]	99.62	55.73	–	–	NA	69, 70, 13, 58, 62	0.9483
	Ref. [52]	98.61	56.13	–	–	NA	69, 70, 14, 44, 50	0.9495
	Ref. [53]	98.59	56.2	0.0907	41.33	NA	14, 58, 61, 69, 70	0.9495
	Proposed	98.59	56.2	0.0907	41.33	~0.7	69, 70, 14, 58, 61	0.9495
119-Bus	Ref. [54]	883.13	32.2	1.3029	15.33	17.51	43, 27, 23, 52, 49, 62, 40, 126, 74, 73, 77, 83, 131, 110, 33	0.9321
	Ref. [50]	865.86	33.5	1.3167	14.43	600	24, 27, 35, 40, 43, 52, 59, 72, 75, 96, 98, 110, 123, 130, 131	0.9323
	Proposed	865.86	33.5	1.3167	14.43	7.64	43, 27, 24, 52, 123, 59, 40, 96, 75, 72, 98, 130, 131, 110, 35	0.9323
33-Bus (unbalanced)	Ref. [50]	143.87	29.67	0.0085	24.11	4.59	7, 9,14, 28, 32	0.9533
				0.0120	26.67			0.9300
				0.0086	32.81			0.9323
	Proposed	142.71	31.33	0.0077	31.25	~1	7, 9,14, 37, 32	0.9448
				0.0108	28.95			0.9312
				0.0079	38.28			0.9363

is changed to open and create the new arrangement of tie-lines (*tie-lines-new*).

Step 8: Check the constraints. If any constraint is violated, then $k = k + 1$ and such tie-line which is selected to switching operation (in step 7), add to *DTV* vector and return to step 5, otherwise go to step 9.

Step 9: Evaluate the value of the objective function f_2 using results of the power flow based on the new arrangement of tie-lines (*tie-lines-new*). If $f_2 \leqslant f_1$, then go to step 10, otherwise $k = k + 1$ and such tie-line which is selected to switching operation (in step 7), add to *DTV* vector and return to step 5.

Step 10: Accept the switching operation (*tie-lines* = *tie-lines-new*), clear all members of *DTV* vector ($DTV = \varnothing_{N_{tie}\times 1}$), $k = 0$, $f_1 = f_2$ and go to step 4.

Step 11: Mutation: In this step, the algorithm generates the tie-lines randomly and accomplish steps 1–10. If the obtained results from this step are the same as previous results (obtained from step 5), finish the algorithm and print the results, otherwise do this step again.

In this paper, mutation is used to allow proposed algorithm to avoid local optima and to explore new search areas. After

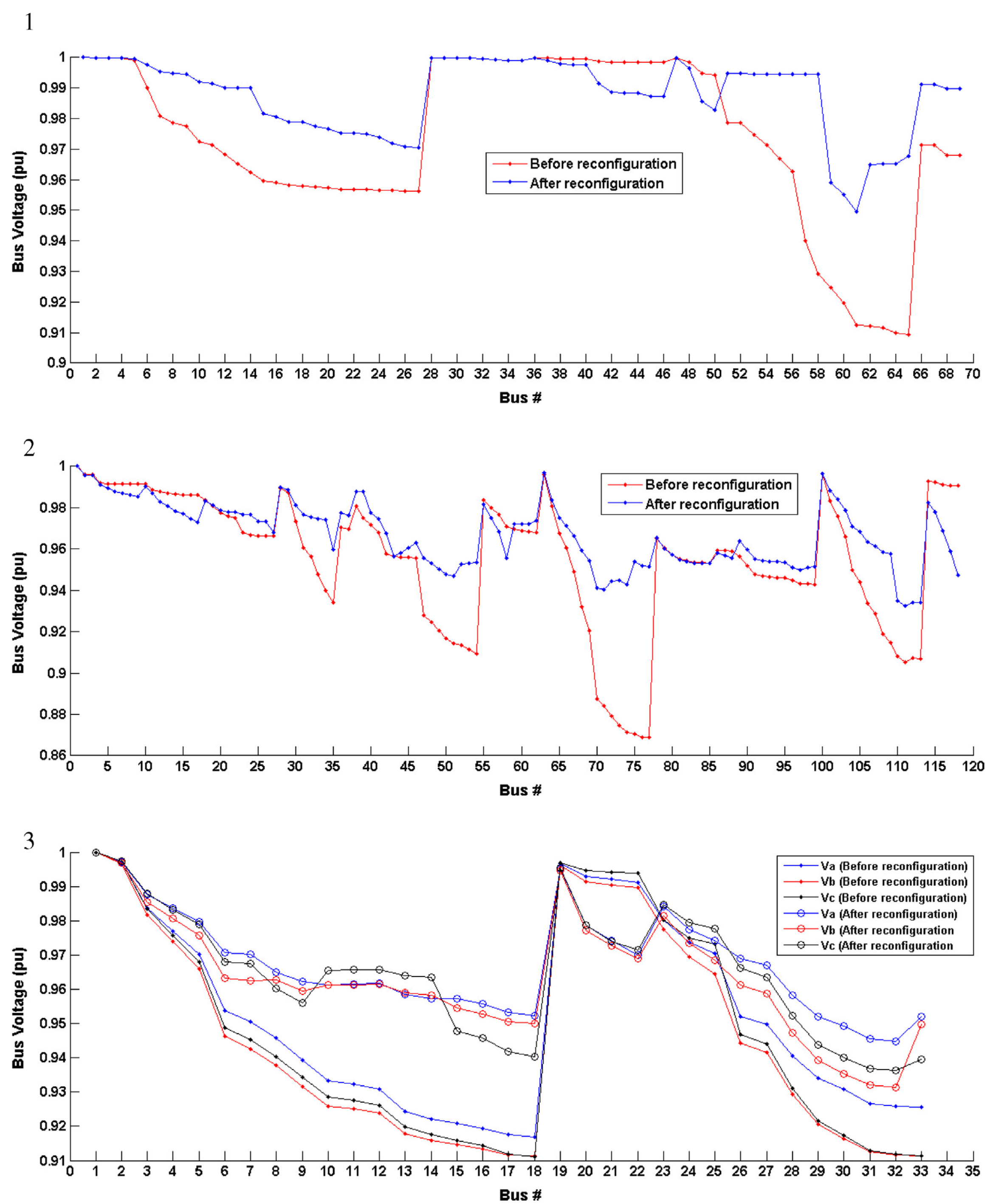

Figure 6. Voltage profile before and after reconfiguration of test distribution systems. (1) 69-bus distribution system. (2) 119-bus distribution system. (3) 33-bus unbalanced distribution system.

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stopping the improvement of objective function, in order to ensure that the algorithm is not reached to a local optimum solution, the tie-lines of the network are randomly selected. Then the fitness of the mutated tie-lines is evaluated by the new above-mentioned codification. If the randomly selected tie-lines are qualified, the algorithm calculates optimum solution based on these tie-lines. If the algorithm reach to the same tie-lines obtained in the previous steps, it is reached to global optimum; otherwise, the mutation is done again until the algorithm reach to global optimum.

The proposed algorithm use mutation to ensure that the final solution is the optimal. So, it reaches to optimal solution in first time which is performed.

In step 8, the state electrical quantities assigned to the nodes (voltages) and branches (currents) are obtained through a load flow calculation, by applying the improved BW/FW sweep method [46] which formulated for single phase balanced and three-phase unbalanced radially operated networks and the Kirchhoff algebraic method [47] is employed to check the radiality constraint.

4.2. Reconfiguration to find configuration with minimum CIC

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*.

4.3. Reconfiguration to find configuration with minimum {LC + CIC}

Here, the algorithm employs a combination of both above mentioned processes. 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 and another which has caused minimum damage cost due to power fault at consumption nodes, which will lead to minimum total amount of losses cost, damage cost due to power supply interruption.

The flow chart of the proposed reconfiguration algorithm is presented in Fig. 5.

5. Test results

First of all, in order to illustrate the validity and effectiveness of proposed method based on losses reduction, it is tested on a 69-bus distribution system [48], a 119-bus distribution system [49] and a 33-bus unbalanced distribution system [50].

The initial condition of these test distribution systems are given in Table 1. 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.

Table 2 shows the optimal result obtained by the proposed method and other methods available in the literature. From Table 2, it can be found that the power losses and minimum node voltage for the optimal solution which obtained by proposed method are either same or better than those optimal solutions obtained by other methods.

The Table also shows that the computation time using the proposed method is much less as compared to the computation times mentioned in the literature. From Table 2, it can be seen that the proposed method provides significant improvement in load balancing index (*LBI*) for these test distribution networks.

Fig. 6 shows the voltage profile improvement achieved by the proposed method. As shown, most of the node voltages have been improved after reconfiguration.

Efficiency of proposed method in this paper for multi criteria reconfiguration is first applied on a modified 33-bus distribution system which shown in Fig. 7. The detailed data for this system is given in Appendix B. This system work at the nominal voltage of 12.66 kV and the base apparent power is 10 MVA.

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 3. Coefficients value of losses and interruption cost are as follows [23]:

$$C_{pl} = 10\$/\text{kW},\ C_{wl} = 0.2\$/\text{kW h},\ C_p = 5\$/\text{kW},\ C_w = 1\$/\text{kW h}.$$

Table 3
Reliability data of elements.

Component	Parameter		
	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

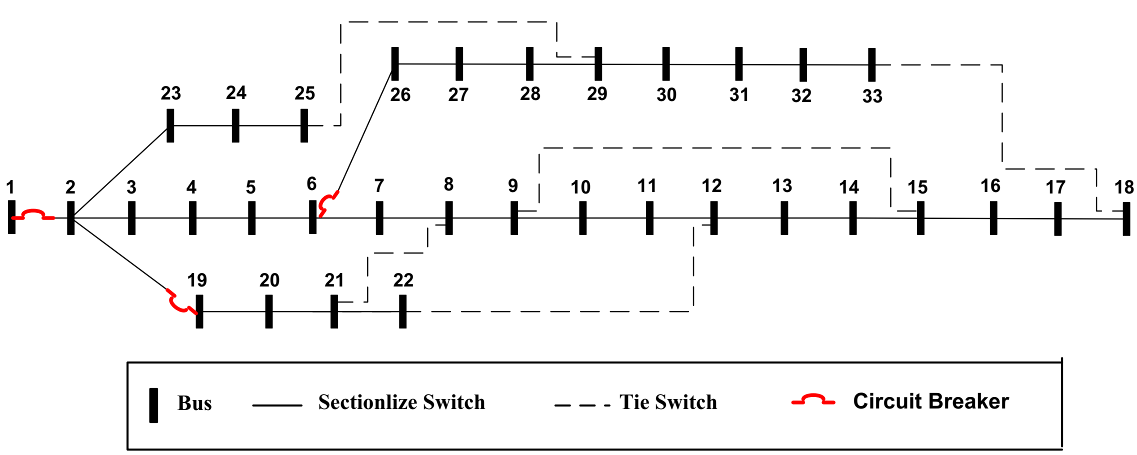

Figure 7. The IEEE 33-bus test distribution system.

The study period (T) is considered a year. The maximum capability of lines and the time of load transferring from one feeder to another are 650 kW and 5 h respectively.

The reconfiguration results, considering LC criterion, CIC criterion and both LC and CIC criteria at the same time have been presented in Table 4.

Table 4
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 ($)	358,481	**246,987**	319,372	254,712
CIC ($)	142,839	118,937	**83,959**	91,172
LC + *CIC* ($)	501,320	365,924	403,331	**345,884**
EENS (kW h/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

The bolad values are the minimum ones in each rows.

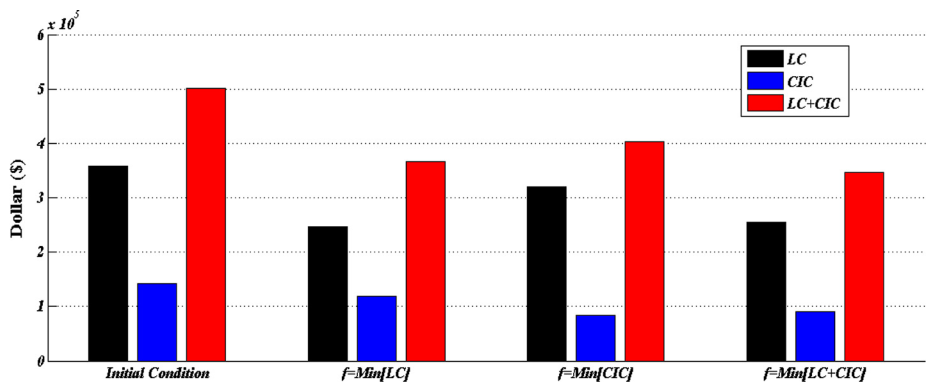

Figure 8. Comparison of obtained results for modified 33-bus distribution system.

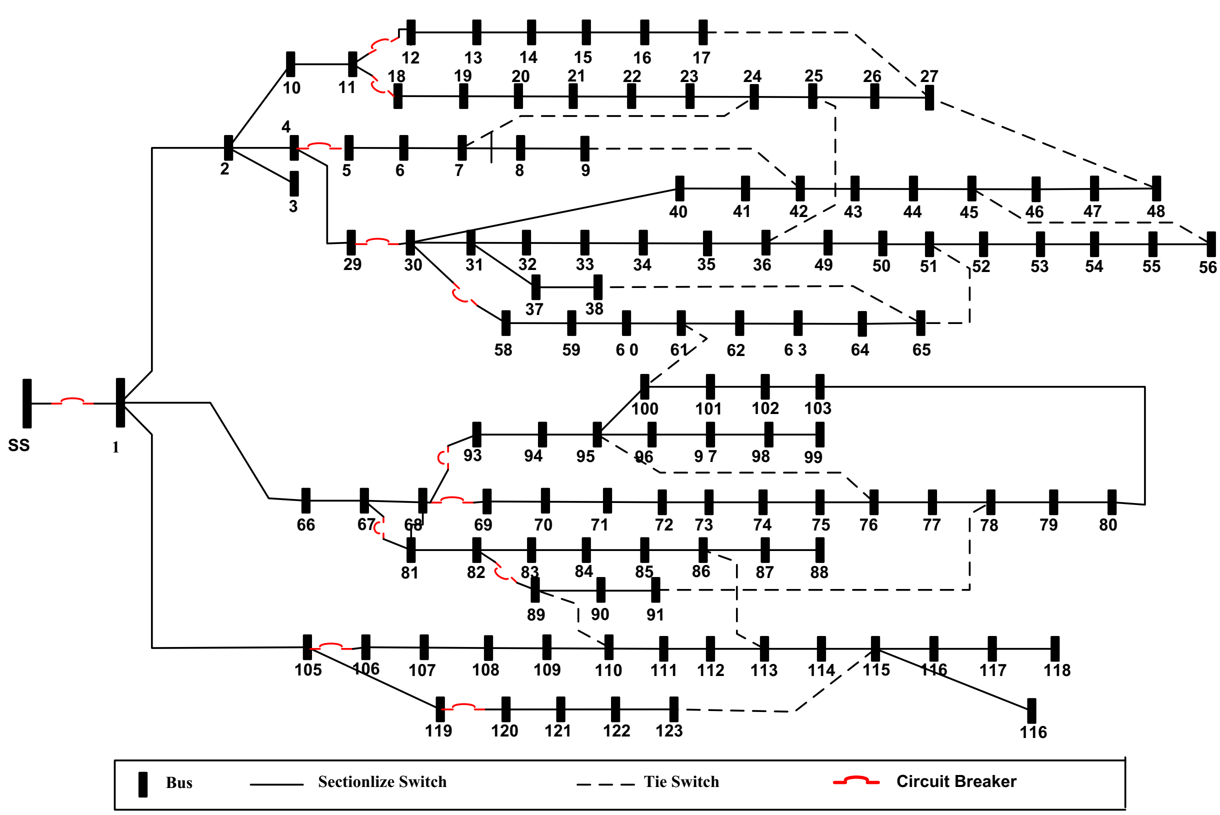

Figure 9. The 119-bus test system.

Table 5
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 ($)	2,287,233	**1,563,790**	1,997,510	1,697,800
CIC ($)	1,534,249	1,450,480	**1,056,270**	1,106,060
LC + *CIC* ($)	3,821,482	3,014,270	3,053,780	**2,803,860**
EENS (kW h/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

The bolad values are the minimum ones in each rows.

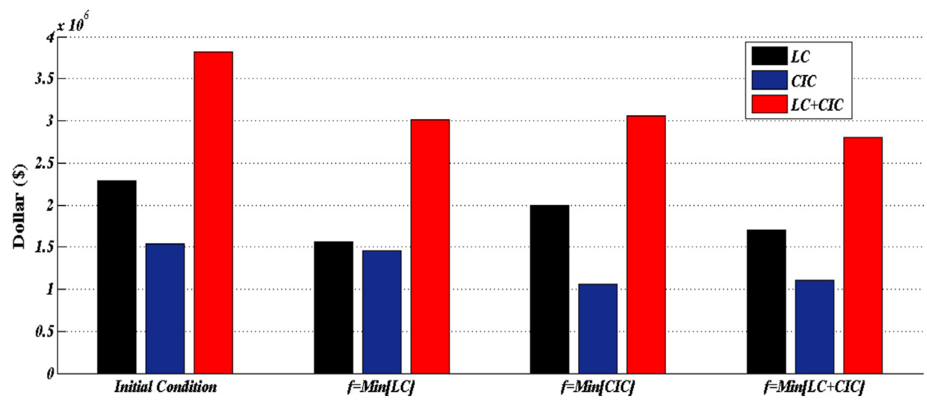

Figure 10. Comparison of obtained results for modified 119-bus distribution system.

In order to better understand of the results, Fig. 8 depicts the optimal values of cost losses and damages cost due to power interruption of consumers for *LC*, *CIC* and *LC* + *CIC* criteria.

The proposed method is also applied on the modified IEEE 119-bus test distribution network. This test network is a 11 kV distribution network with 118 sectionalizing switches and 15 tie switches as shown in Fig. 9. The detailed data for this modified test network is given in Appendix B. The reconfiguration results for the modified IEEE 119-bus test distribution network are shown in Table 5.

As shown in Fig. 9, it has been assumed that there are twelve circuit breakers and the other existing switching equipment are sectionaliser. The optimal values of *LC*, *CIC* and *LC* + *CIC* of reconfiguration for minimum losses cost, minimum damages cost due to power interruption of consumers and minimum losses cost and damages cost of power interruption of consumers are illustrated in Fig. 10.

6. 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.

The proposed method is successfully applied on balanced and unbalanced test distribution networks.

Appendix A. Nomenclature

CIC	The consumers interruption cost ($)	SAIDI	System average interruption duration (h/consumer·year)
c_{pl}	Power losses cost ($/kW)	S_i	The apparent power in the sending bus of the *i*th branch (KVA)
c_{wl}	Energy losses cost ($/kW h)	S_i^{max}	Maximum capacity of the *i*th branch (KVA)
C_p	Cost of the interrupted power ($/kW)	*T*	Time interval (h)
C_w	Cost of the energy not supplied ($/kW h)	*tie-loop*	Set of lines which forms a loop
DTV	Vector of discarded tie-lines	U_e	Unavailability at the consumption node (failure·h/year)
EENS	The expected energy not supplied (kW h/consumer·year)	U_{ei}	Unavailability at the consumption node *i* (failure·h/year)
I_j	Current in the *j*th branch (pu)	$U_{ei,Isol}$	Unavailability at the consumption node *i* resulted from branch set *Isol-set* (failure·h/year)
I_j^{max}	Maximum current limit of the *j*th branch (pu)	$U_{ei,rep}$	Unavailability at the consumption node *i* resulted from branch set *Rep-set* (failure·h/year)
IC_i	Interruption cost of *i*th consumer ($)	U_e^I	Unavailability at the consumption node due to outage of elements belonging to one or more first-order cut sets

(*continued on next page*)

LC	Losses cost ($)
LBI	Load balancing index
N_{tie}	Number of tie-lines
N_i	The number of consumers connected to node i
N^{I}	The total number of first-order cut sets
N^{II}	The total number of second-order cut sets
Nl	Node-lp (kW·failure/year)
Np	Node-power (pu)
$P_{l,i}$	The loads which connected to node i (kW)
P_i	Active power at sending end of branch i (pu)
$P_{loss,i}$	Active power losses for electrical line i (pu)
Q_i	Reactive power at sending end of branch i (pu)
R_i	Resistance of the ith branch (pu)
r_{ei}	Interruption duration of supply at consumption node i (h)
r_{0l}	Restore times of supplying for a fault on the line of the branch l (h)
r_l	Restore times of supplying of the branch l (h)
r_{SEi}	Restore times of supplying for a fault at the switching equipment from the nodes i (h)
r_{ij}	Failure duration for a line between node i and j (h)
U_e^{II}	Unavailability at the consumption node due to outage of elements belonging to one or more second-order cut sets
U_l	Unavailability of the branch l (failure·h/year)
U_l^{I}	The unavailability of the lth first-order cut set (failure·h/year)
U_l^{II}	Unavailability of the lth second-order cut set (failure·h/year)
V_i	Voltage of the sending end node of the ith branch (pu)
V_{max}	Maximum specified system node voltage (pu)
V_{min}	Minimum specified system node voltage (pu)
$W_{loss,i}$	Energy losses for electrical line i (kW h)
λ_{0l}	Failure rate of electrical line l (failure/year)
λ_{ei}	Failure rate at the consumption node i (failure/year)
$\lambda_{ei,rep}$	Failure rate at the consumption node i resulted from branch set *Rep-set* (failure/year)
$\lambda_{ei,isol}$	Failure rate at the consumption node i resulted from branch set *Isol-set* (failure/year)
λ_l	Failure rate of the branch l (failure/year)
λ_{SEi}	Failure rates of the switching equipment at nodes i (failure/year)
λ_{ij}	Failure rate for a line between node i and j (failure/year)
$\psi(n)$	Radial constraint for the nth topology
Δnp	Node-power difference (pu)

Appendix B.

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	–	–	–	–	–	–	–	–

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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

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Appendix B. (*continued*)

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)	
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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