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Reliability Driven Network Reconfiguration of Power Distribution System

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Abstract
In this paper, the multi-objective goal is converted into a single objective minimization function having weighted sum of power loss and average unreliability of the load points. Based on the relative importance that will be given to each goal considered in this paper different values of weights are considered. The minimization objective function is solved by the help of Particle Swarm Optimization (PSO) algorithm using script environment of MATLAB software and an optimal position of the switches to be opened are obtained. Load flow of distribution system is done by using Backward Forward Sweep method considering power as flow variable and reliability of the distribution network is obtained by minimal cut set method. In order to reduce the search space of the reconfiguration algorithm and to check the feasibility of the generated switch during reconfiguration process, graph theory approach is implemented in which loop, common branch and prohibited group vectors are generated. The customer-oriented reliability index, SAIFI is also considered in this paper. In order to check the economic viability of the proposed technique, the payback period of the capital invested is calculated. The proposed technique of distribution system reconfiguration is first implemented in standard IEEE-33 bus radial distribution network and then its suitability is checked in real 11 kV, 56 bus distribution feeder of Anarmani Distribution Center, Nepal Electricity Authority (NEA). The results obtained provides the clear picture of the efficacy of the proposed algorithm in the distribution system.

Keywords
Radial Distribution system, Network reconfiguration, Distribution power loss, Unreliability, SAIFI, PSO

1. Introduction

Distribution system planning is an essential part of a power system in order to provide electricity to its consumers in a reliable and cost-effective way. Due to the excessively changing nature of the electrical consumers, distribution system may deliver power under heavily loaded conditions. Also, since the distribution system operates at low voltages compared with transmission systems, a significant amount of power loss occurs. Thus, distribution systems are characterized by high technical and commercial losses in comparison to transmission system. Estimating the amount of total power losses in distribution system is considered as a main tool for evaluating the system performance [1]. Electrical utilities are trying to reduce the technical loss by minimizing the real power loss occurring in distribution lines and improve overall voltage profile of the system by the help of different techniques.

Deregulation of electrical system leads to competitive market in the distribution system which enforces the electrical utilities to improve the reliability of power supply to their consumers. But, because of simple protection and coordination schemes and reduced short circuit current, distribution systems generally operate in radial topology [2]. In a radial system, each consumer is fed from a single source. Due to this, there is high probability of power outages which reduces the reliability of power supply to the consumer and effect both electrical consumers and utilities. Thus, in this paper reconfiguration of the distribution network is considered for minimizing the power loss along with improvement in reliability of electrical power supply.

There are many ways to improve the system performance. Distributed generator placement, Capacitor placement, Network reconfiguration and introducing high voltage levels are the few techniques that helps in improving the system performance [3]. Among different techniques available in the literature, Network reconfiguration improves the system reliability and minimizes losses without incurring huge cost [4] and hence it is considered to be one of the best solutions for minimizing the power loss of the distribution network. A radial distribution system is a combination of normally closed sectionalizing switches and normally opened tie switches. To achieve the best possible configuration of the network, it can be changed by performing switching behaviour. Distribution network reconfiguration is a technique in which topological structure of the network is altered by changing the open/close status of sectionalizing and tie line switches in such a way that radial topology of the network is preserved and all the loads are given[5].

Extensive studies have been carried out in the past years in the field of network reconfiguration of distribution systems. Normally distribution networks are meshed but are radially operated. With manual or automatic switching operations, the configuration of these networks may be changed to move loads from one feeder to the other. There are generally two approaches for performing Network reconfiguration. In the year 1975, Merlin and Back, took up the problem of network reconfiguration to minimize the total active power loss. In their approach, all network switches which are open initially, are closed at first. This forms a looped network. Then, in order to achieve a new radial structure, network switches are opened one at a time. The switch chosen to open at each time to form a radial network minimized the losses of the overall system.

Similar to Merlin and Back, approach by Shirmohammadi, 1989 [6] also starts by closing all network switches to obtain mesh configuration. Radiality is maintained by opening of the switch carrying the lowest current as determined by the optimum power flow. Another approach as proposed by[7, 8, 9] are based on branch exchange where the closure of any tie line switch is followed by the opening of a sectionalizing switch established from the loop, i.e. the switches are chosen in such a way as to satisfy the objectives.

Reconfiguring a distribution network can be single or multi objective. Minimization of power losses, reliability indices, voltage improvements, total network cost are some of the single objectives considered in a reconfiguration problem. On the other hand, combination of any of these objectives forms a multi-objective problem where by applying different techniques like the weighted sum approach the multi-objective problem is being converted into single objective network reconfiguration problem as in [10].

The main objective of this paper is a multi-objective formulation of a network reconfiguration problem considering reliability improvement and loss minimization.

2. Overview of the Models and Methods

This section provides the brief discussion of the methods used and models developed in this paper. The reconfiguration methodology followed in this paper aims at maximizing the reliability to the customers connected to the distribution system and minimizing the total system power losses. At first for the distribution system power loss evaluation of the primary network, distribution system load flow is performed. Similarly, the unreliability at load points is evaluated using the minimal cut set method. Also, the SAIFI index is considered for reliability assessment. The Network reconfiguration of the primary network is performed for minimizing loss and unreliability and the best possible outcome of the switches are determined using the particle swarm optimisation algorithm.

2.1 Network Reconfiguration

Because of huge number of switching combinations, even for a moderate sized distribution system, there are large number of switching options and it is computationally impractical and inefficient to perform load flow studies with all possible options. As a result, in past decades, numerous approaches have been proposed to solve the reconfiguration problem. Network reconfiguration can basically be categorized into two approaches:

Branch Exchange Method In this method, closing of any tie line switch is accompanied by opening of a sectionalizing switch formed from the loop i.e The switches are selected in such a way so as to meet the objectives of the distribution system.

Sequential Switch opening method Also called Loop cutting method. In this method, first of all, any combination of the tie switches is closed to form a weakly meshed system and then the sectionalizing switches are opened successively to retain the radial configuration.

The Network reconfiguration concept used in this paper is the branch exchange method. However, as the main operating constraint is to maintain the radial nature serving all the loads, the radial topologies that is obtained at each stage may not be feasible due to the islanding of interior and exterior nodes. So, in order to check the feasibility of the obtained switching combination, the loop vectors, common branch vectors and the prohibited group vectors [11] are introduced before solving the network reconfiguration problem as discussed below:

1. Obtain all the loop formed in a meshed network. The *Loop vector, L* is the set of elements contained in the loop.
2. Determine *Common branch vectors* having set of elements common between two loops.
3. Determine *Prohibited group vectors*, the set of common branch vectors incident at the principal nodes of the distribution network.

Each tie switch combination consists of number of switches equal to the number of loops in the system. In order to reduce the search space of the reconfiguration technique, the following rules must be satisfied: Rule 1: Each element of the switching combination must belong to its corresponding loop vector. Rule 2: Only one member from a common branch vector can be selected to form a tie switching combination. Rule 3: All the common branch vectors of any prohibited group vector cannot participate simultaneously to form a tie switching combination.

Rule-1 prevents any islanding of the nodes situated at the perimeter of the network, whereas Rule-2 and Rule-3 prevents the islanding of the nodes situated at the interior of the network. The tie switching combination generated using the above rules helps to reduce the search space for reconfiguration problem during optimisation.

Illustrative Example

To understand the application of above rules, let us take an example of an IEEE-33 bus system as shown in fig 5. For this system after closing five tie switches, the network topology identifies five *Loop vectors* and seven *Common branch vectors* as shown in the table 1.

Table 1: Loop Vectors and the Common Branch Vectors

Loop vectors	Common Branch Vectors
$L_1 = [2\ 3\ 4\ 5\ 6\ 7\ 33\ 20\ 19\ 18]$	$C_{13} = [33]$
$L_2 = [9\ 10\ 11\ 12\ 13\ 14\ 34]$	$C_{14} = [6\ 7]$
$L_3 = [8\ 9\ 10\ 11\ 35\ 21\ 23]$	$C_{15} = [3\ 4\ 5]$
$L_4 = [25\ 26\ 27\ 28\ 29\ 30\ 31\ 32\ 36\ 17\ 16\ 15\ 34\ 8\ 7\ 6]$	$C_{23} = [9\ 10\ 11]$
$L_5 = [22\ 23\ 24\ 37\ 28\ 27\ 26\ 25\ 5\ 4\ 3]$	$C_{24} = [34]$
	$C_{34} = [8]$
	$C_{45} = [25\ 26\ 27\ 28]$

Table 2: Prohibited Group Vectors and the Principal Islanded Nodes

Prohibited Group Vector	Islanded Node
$R_8 = [C_{13}\ C_{34}\ C_{14}]$	8
$R_9 = [C_{24}\ C_{34}\ C_{23}]$	9
$R_6 = [C_{14}\ C_{15}\ C_{45}]$	6
$R_{89} = [C_{13}\ C_{14}\ C_{24}\ C_{23}]$	8, 9
$R_{86} = [C_{13}\ C_{34}\ C_{15}\ C_{45}]$	8, 6
$R_{896} = [C_{13}\ C_{24}\ C_{15}\ C_{45}\ C_{45}]$	8, 9, 6

The Prohibited group vectors and the corresponding islanded nodes for the system are shown in Table 2.

2.2 Distribution System Power Loss Assessment

In order to meet the objectives of the Network reconfiguration to minimize the power loss, the total power loss for each configuration is evaluated using a backward forward sweep method considering power as a flow variable. The feeder power loss and the node voltages are two parameters that are calculated during load flow. In order to illustrate the calculation of node voltages and total power loss, lets consider a simple two bus system as shown in figure 1.

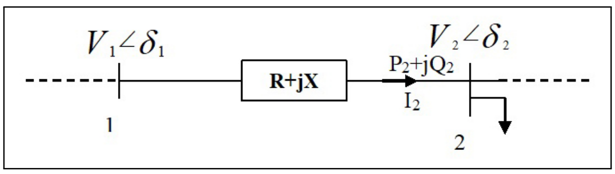

Figure 1: Simple Radial Distribution System

The Voltage magnitude $|V(m_2)|$ at the receiving end can be evaluated as,

$$|V(m_2)| = |B(j) - A(j)|^{1/2}$$

where,
$A(j) = P(m_2) \times R(j) + Q(m_2) \times X(j) - 0.5|V(m_1)|^2$
$B(j) =$
$\left\{A(j) - [R^2(j) + X^2(j)] \times [P^2(m_2) + Q^2(m_2)]\right\}^{1/2}$

j is the branch number,
m_1 and m_2 are sending end and receiving end node respectively.

Similarly, the real and reactive power losses of a respective branch are calculated as,
$LP[j] = \frac{R(j)[P^2(m_2)+Q^2(m_2)]}{|V(m_2)|^2}$
$LQ[j] = \frac{X(j)[P^2(m_2)+Q^2(m_2)]}{|V(m_2)|^2}$

The system total power loss is the sum of branch power losses. The voltage and the power loss formulae as mentioned above is subject to the contraints
Bus voltage constraints

$$V_{min} \leq V_i \leq V_{max}$$

Feeder current limitations

$$I_j \leq I_{max}$$

2.3 Reliability Assessment

Distribution system reliability assessment methods can be roughly categorized into Simulation and Analytical methods. In simulation method, Monte carlo method is used to obtain the probability distribution of load point and system indices for sample distribution systems. On the other hand, Analytical methods evaluates reliability based on system outage records. This paper focuses on the evaluation of load point indices using two different approaches, the minimal cut set analysis method and the customer oriented indices (SAIFI).

2.3.1 Reliability evaluation based on Minimal cut set method

This method is used to find the minimum number of components between the source and load such that outage of any will hinder the flow of power to the load points. *A minimal cut set is a set of system components which, when failed, causes failure of the system but when anyone component of the set has not failed, does not cause system failure.*[12] In order to evaluate the reliability at various nodes, the reliability models of the components involved in the minimal path is developed and the corresponding unavailability is evaluated.

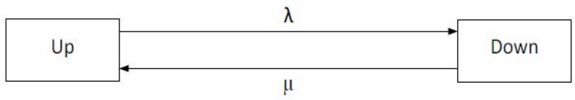

Figure 2: Two State Model representation

Table 3: Failure and repair rate [14]

Component	λ_{f1}	λ_{f1}	r_{f1}	r_{f2}	λ_m	r_M	λ_{eol}
Circuit breaker	0.1	0.142857	20	20	0.4	12	0.001
Transformer	0.05882	0.05555	144	144	1	168	0.001
Line	0.13	0.13	5	5	0.2	2	-
Bus-bar	0.0045	-	24	-	0.5	4	-
Switch	0.2	0.2	5	5	0.25	4	-

Finding the minimal cutsets The procedures followed for determining the minimal cutset has been taken from [13]. It takes the system data as input; it then prepares the network topology for each load point. Minimal paths, accompanied by the calculation of the associated minimum cut sets for the load points, are then deduced.

Modeling of components Once the minimal cut sets are found, based on their history of outage and commissioning data, the probabilistic reliability model of the different components appearing in the minimum cut sets is established. The availability of any component i in the system can be represented as

$$P_i = \frac{\sum_i 1/\lambda_i}{\sum_i 1/\lambda_i + \sum_i 1/\mu_i} = \frac{MTTF}{MTTF + MTTR}$$

where λ_i and μ_i are the failure rate and repair rate of the component i respectively. In this paper, it is assumed that each component in the system can only reside in an up-state (available) or downstate (unavailable). Therefore, the two-state Markovian model shown below in Fig 2 is used to model various system components.

In this paper, the component reliability data for each components used in the IEEE-33 bus system (Generators, Transformers, CB, Line) are assumed to be as given in Table 3

Evaluating the Reliability at Load points The minimal cut sets between the feeder and the load points are evaluated using the algorithm described previously. As per the definition of the minimal cut set it is evident that all components of a minimal cut set must be in failure state to cause system failure. Consequently, the components of the cut set are effectively connected in parallel and the failure probabilities of the components in a cut set may be

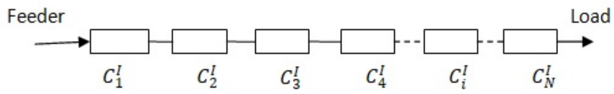

Figure 3: First order cut sets between the source and the load

combined using the principle of parallel systems. In addition, the system fails if any one of the cut sets occur and consequently each cut is effectively in series with all the other cuts. The use of this principle gives the reliability diagram of figure 3.

The unreliability at the nodes is given by

$$Q = P\left(\bigcup_i C_i\right)$$

The corresponding reliability at the load point is given by

$$R = 1 - Q$$

The average unreliability is given by

$$Q_{avg} = \frac{1}{N}\sum_{i=1}^{N} Q_{node}$$

2.3.2 Reliability Evaluation based on Customer Oriented Indices

For a distribution system, the availability and quality of power supply at each customer's service entrance is a major concern. So, for the reliability assessment of a distribution system, it is necessary to examine the interruption profiles of each customer. If the expected interruption frequencies and durations are known for each customer, basic reliability indices can be computed. Three basic load point indices are

1. average failure rate, λ
2. average outage duration, r
3. annual outage duration, U

Based on these three basic load point indices, the system reliability indexes (such as SAIFI, SAIDI, CAIDI) as well as the reliability cost/worth indexes, energy not supply (ENS), expected interruption cost (ECOST) can be calculated. In this paper the calculation of SAIFI and ENS will be addressed.

$$SAIFI = \frac{total\ customer\ hours\ of\ interruptions}{total\ customers\ served}$$

$$ENS = Total\ energy\ not\ supplied\ by\ the\ system$$

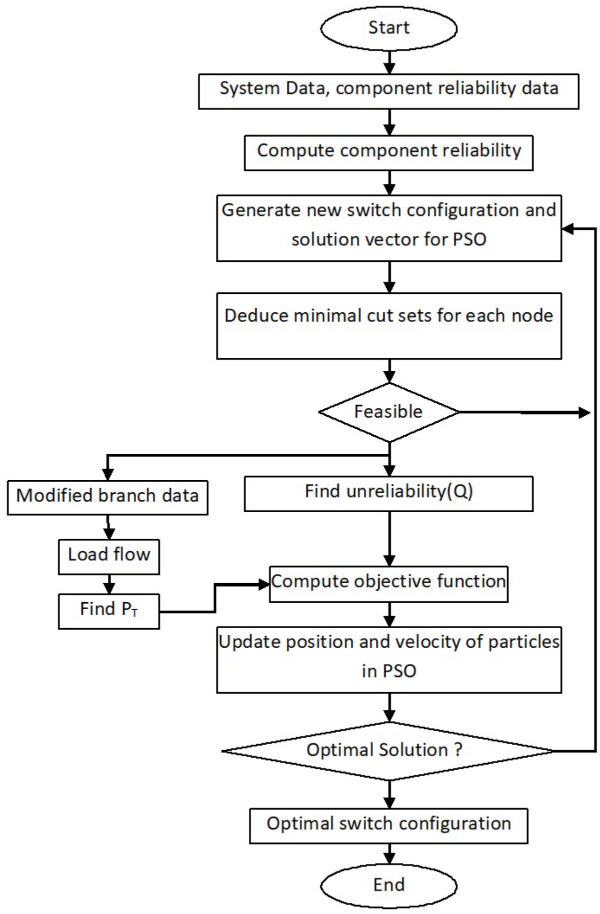

Figure 4: Flowchart showing Overall Procedure for Network Reconfiguration

2.4 Reconfiguration problem formulation

The main objective of the distribution system reconfiguration method is reduction in system unreliability and total power loss. To obtain this objective, the PSO algorithm searches for the optimum switch status. In the PSO, the particles position vectors represent the switch state for the problem of reconfiguring the distribution system. For the feasibility of the switch configuration generated, the constraint imposed on each position vector is that the electrical connection from source to the load should be retained. The overall procedure is shown in the flowchart 4. An objective function needs to be defined at each stage of the iteration to determine the suitability of the solution sought by the particles. It checks for the feasibility of the switch configuration, at first for each particle and if feasible, it evaluates the system unreliability, SAIFI, power loss, voltage at nodes, energy not supplied and energy loss per year.

The objective function that is formulated for minimization with the proposed technique is

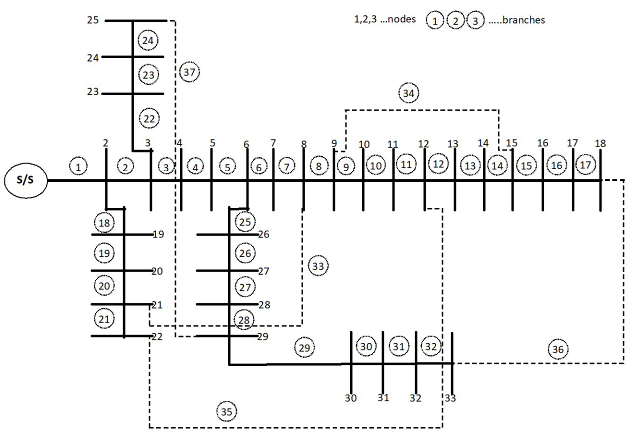

Figure 5: IEEE-33 Bus Radial Distribution System

Figure 6: Node Voltage for different values of w_1 and w_2

formulated as:

$$Minimize\ w_1 P_T + w_2 Q_{avg}$$

where,
P_T is the total real power loss in the distribution system. Q_{avg} is the average system unreliability. w_1 and w_2 are the weights assigned to the parts of the objective function. A large value K is assigned to the value of the objective function if the configuration is not feasible.

3. Test Results and Discussions

The Matlab based programming is developed in script environment that uses the described algorithm to generate the optimal switching configuration that minimizes the objective function. A standard IEEE-33 Bus radial distribution system and NEA-56 Bus Feeder of Anarmani distribution Center is used as a test system to implement the described methodology.

3.1 Case Study 1

The methodology is at first implemented to an IEEE-33 bus system as shown in figure 5. It is a 12.66kV 33 Bus system having one feeder and four different laterals, 32 line branches and 5 tie lines. It has a total peak load of 3715 kW and 2300 kVAr. For the base configuration the open switches(tie lines) are $S_{33}, S_{34}, S_{35}, S_{36}, S_{37}$ which are represented by dotted lines. The reliability data that are used for this system as in Table 3 are acquired from [14].

Table 4 shows the switches opened and other system parameters after reconfiguration considering loss, reliability and loss+reliability as the objective function for different values of w_1 and w_2. The weights w_1 and w_2 shows the relative importance of system average unreliability and power loss. The reduction in power loss considering loss, reliability and loss+reliability as objective function is 33.86%, 28.74% and 33.66% respectively while reduction in unreliability is 17.04%, 22.86% and 21.37% respectively in comparison to base case. Since, the objective is minimization and results show reduction in the considered parameters of the system hence, the selected technique for reconfiguration is justified. Also, assuming load factor as 0.5, the energy not supplied $(average\ load \times system\ downtime)$ is calculated to further justify this work. From figure 6 it can be observed that after reconfiguration at few buses there will be degradation in voltage but overall, there is improvement in voltage profile of the system.

3.2 Case Study 2

In order to check the suitability of the proposed technique in the real scenario, the reconfiguration algorithm has also been applied to NEA-56 bus feeder of Anarmani distribution centre. It consists of a 56-Bus 11 kV feeder, with five laterals, 55 branches and 56 nodes. The Total peak load is of 2038.5 kW and 906 kVAr. Five tie lines has been assumed between nodes 22-39, 4-44, 5-46, 49-53, 22-56 for the reconfiguration purpose as shown in figure 7.

The actual line data, bus data, number of customers connected at each nodes are taken from respective distribution center and the monthly tripping time and shutdown time of the feeder is collected from respective grid to calculate the annual total outage, and frequency of failure per year. From this, the

Table 4: Optimal Solution for IEEE-33 Bus System

Description	Base case	Loss as objective function		Reliability as objective function		Loss and Reliability as objective function					
		Value	% reduction	Value	% reduction	Value	% reduction	Value	% reduction	Value	% reduction
		w1=1, w2=0		w1=0, w2=1		w1=0.5, w2=0.5		w1=0.1, w2=0.9		w1=0.9, w2=0.1	
Switch opened	33 34 35 36 37	7 14 9 32 37		7 14 10 17 27		7 14 9 32 28		7 14 10 36 28		7 14 9 32 28	
Loss	210.998	139.551	33.86%	150.354	28.74%	139.978	33.66%	142.429	32.50%	139.978	33.66%
Unreliability	0.001392	0.001155	17.04%	0.001074	22.86%	0.001095	21.37%	0.001079	22.46%	0.001095	21.37%
SAIFI	2.091816	1.866629	10.77%	1.727434	17.42%	1.755938	16.06%	1.738862	16.87%	1.755938	16.06%
Min. Voltage in p.u.	0.90377	0.93782	3.77%	0.93122	3.04%	0.94129	4.15%	0.93779	3.76%	0.94129	4.15%
Down time (hours/year)	12.20	10.12		9.41		9.59		9.46		9.59	
Energy not supplied (kWhr)	22654.18	18794.42	17.04%	17475.43	22.86%	17812.15	21.37%	17565.02	22.46%	17812.15	21.37%
Energy loss per year (kWhr)	693129.48	458426.02	33.86%	493912.93	28.74%	459828.21	33.66%	467880.28	32.50%	459828.21	33.66%

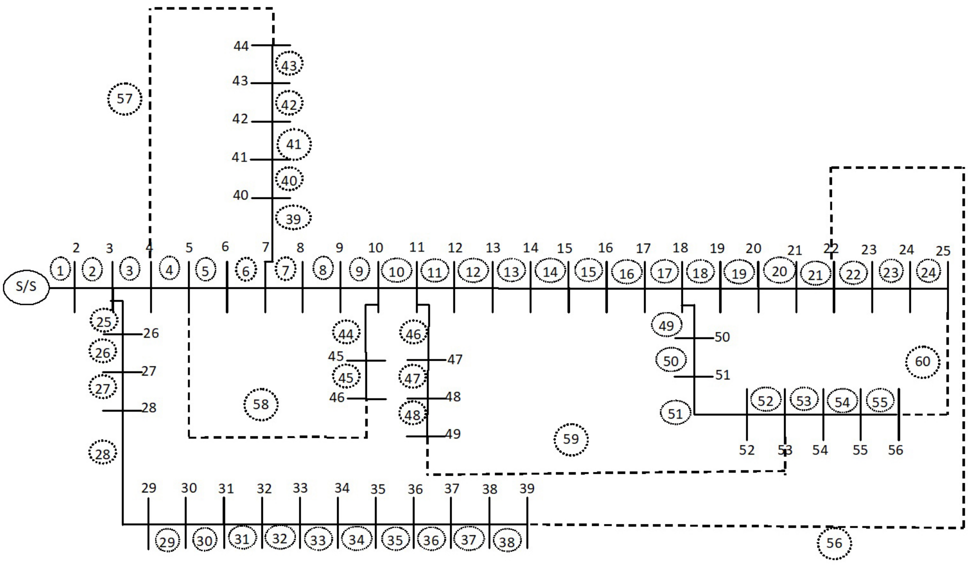

Figure 7: NEA-56 Bus Radial Distribution System

Table 5: Optimal Solution for NEA-56 Bus System

Description	Base Case	Loss as objective function		Reliability as objective function		Loss and Reliability as objective function	
		Value	% reduction	Value	% reduction	Value	% reduction
		w1=1, w2=0		w1=0, w2=1		w1=0.5, w2=0.5	
Switch opened	56, 57, 58, 59, 60	21, 39, 44, 49, 60		56, 40, 45, 17, 21		56, 40, 45, 17, 21	
Loss	52.615	36.547	30.54%	40.281	23.44%	40.281	23.44%
Unreliability	0.353117	0.300573	14.88%	0.287339	18.63%	0.287339	18.63%
SAIFI	37.046855	30.625066	17.33%	28.832459	22.17%	28.832459	22.17%
Min. Voltage in p.u.	0.93791	0.96494	2.88%	0.95808	2.15%	0.95808	2.15%
Down time (hours/year)	3093.30	2633.02		2517.09		2517.09	
Energy not supplied (kWhr)	3783418.44	3220442.92	14.88%	3078656.54	18.63%	3078656.54	18.63%
Energy loss per year (kWhr)	221235.17	153672.21	30.54%	169374.18	23.44%	169374.18	23.44%

failure rate per year and total outage duration are calculated that are used to evaluate the load point unavailability and customer indices. The failure rate of the line and annual outage duration is calculated as 3.46 $fails/Km/year$ and 86.97 $hours$ respectively for a 57Km feeder. All the other components like transformers, circuit breakers, switch and nodes are assumed to be fully reliable. Table 5 shows the optimal switch configuration before and after reconfiguration for different values of weights. The values obtained in the table clearly justifies the efficacy of the proposed methodology in the real system.

Further, assuming the initial investment required for setting up infrastructure for network reconfiguration is Rs.10 lakhs with an annual operation and maintenance cost of 5% and total energy loss savings @Rs.10/kWhr, the discounted payback period obtained in case of the considered NEA system is only 2.7 years which is very less than normal life expectancy of the equipment used in distribution system reconfiguration, thus justifying the economic feasibility of the considered methodology.

4. Conclusion

In this work, a technique for carrying out reconfiguration of distribution network in an efficient way by using graph theory is proposed considering combination of total power loss and average unreliability as an objective function. The average unreliability of the load point is obtained by using minimal cut set method. The minimization of objective function problem is solved by using PSO algorithm in script environment of MATLAB software. Different weights are assigned to parts of the objective function in order to show their relative importance. The effectiveness of proposed technique is first tested in IEEE-33 bus network and then its suitability is checked in context of Nepalese 11 kV Anarmani distribution network. The test results shows that after reconfiguration there is improvement in total power loss, reliability and voltage profile of the system. The SAIFI index of the system is also reduced indicating less customer interruptions. The obtained values of system downtime, energy not supplied and energy loss per year further justifies the work. The payback period obtained is in considerable range and hence reconfiguration of the network is found to be economically feasible. Hence, from overall scenario it is concluded that network reconfiguration can be implemented in typical Nepalese distribution system for power loss reduction, voltage profile improvement and reliability enhancement.

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