Reliability Evaluation of Distribution Expansion Planning and Reconfiguration Using Black Hole Algorithm

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***Abstract*— The aim of expansion planning of distribution system is to determine the capacity, reinforcement of distribution substation unit and addition or upgradation of distribution feeders to meet the growing load demand in future. This paper addresses the multistage radial distribution system (RDS) expansion planning problem in the presence of distributed generator (DG) in a multiobjective optimization framework. In addition, the reliability of the RDS has been enhanced by employing reconfiguration of RDS as a failure rate reduction strategy. Expected interruption cost (ECOST) corresponding to interruption duration time is calculated using a composite customer damage function (CCDF). The complex multiobjective optimization problem has been solved using black hole algorithm (BHA). In order to evaluate the proposed algorithm, standard IEEE 33 bus is used as a test system. Different case studies were carried out on the test system and in all the case studies, customer and energy based reliability indices, i.e. SAIFI, SAIDI, CAIDI, AENS and ASAI have been determined.**

Key words: Expansion planning, distributed generation, reconfiguration, reliability indices, black hole algorithm.

I. INTRODUCTION

Distribution network expansion planning problem is the essential goal of electric distribution utilities to meet both the load growth and power quality. The multistage expansion planning is to determine the reinforcement and/or installation of substation units, installing distributed generator to supply future increasing load demand. Distribution feeders and substations are required to provide additional capacity to supply the growing electrical demand of customers without compromising the reliability of the distribution networks.

In the literature, many researchers attempted to determine the optimum location of substation and feeder in the distribution network expansion planning. In [1], imperialist competitive algorithm is proposed for the optimal expansion planning in order to determine optimal sizing and location of substation and feeder routing simultaneously. Ali Reza et al [2] presented an improved teacher learning algorithm for energy expansion planning which is formulated as a multi objective optimization problem to minimize the investment and operation costs to improve the system reliability. Similarly many others researchers have solved same problem using different artificial intelligence techniques. Hybrid evolutionary programming [3], self- adaptive global-based harmony search algorithm (SGHSA) [4], modified particle swarm optimization (MPSO) [5 & 6] algorithms have been used to determine more efficient planning options which allows the system planners to find how likely the system to be expanded and the possible actions for the future distribution system structure in the presence of DG units.

Distribution network reconfiguration is a procedure that modifies the feeder topological structure by changing the switching status of sectionalizing and tie switches. The reconfiguration problem determines the optimum topology in view of minimum power loss and improved voltage profile while satisfying the customers in radial distribution system. It becomes difficult to solve this problem by conventional linear or nonlinear programming methods. In the past decades, a number of researchers solved the reconfiguration problem with different methods. In order to minimize power loss and voltage deviation, heuristic techniques [7], expert systems [8], a brute - force approach [9], harmony search algorithms [10], evolutionary programming [11] have been proposed. Reliability-oriented distribution network reconfiguration considering demand uncertainty has been studied in [12].

Adding DG sources to the expansion planning options result in challenges in the distribution network operation, structure, design and upgrade issues. Moreover, reliability is one of the important factors in the distribution system planning for future system capacity expansion. In the literature, reliability improvement and loss reduction by locating the DGs in the optimal places of the distribution network has been addressed in [13]. Ziari et al. [14] proposed an integrated methodology for distribution network planning which optimizes the operation of DGs and cross connections. In literature many researchers have considered both non renewable and renewable energy sources as DGs [15 and 16]. In recent years, the BH algorithm and its modified versions have been used to solve optimization and engineering problems [23].

Reliability assessment estimates the performance at customer load points considering the stochastic nature of failure occurrences and outage duration. The basic indices associated with load points are: failure rate, average outage duration and annual unavailability. In order to reflect severity of an outage, customer and energy based reliability indices have to be evaluated. Most frequently used indices by utilities are System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI) and Average Energy Not Supplied (AENS) [17 and 18]. Reliability indices of a radial distribution network have been enhanced using optimum DG placement [19].

In the present work, BHA (Black hole algorithm) is proposed to solve the multistage distribution expansion planning problem in the radial distribution system. This paper emphasizes the advantage of network reconfiguration in the presence of DG units in the distribution system. The objective function is formulated to minimize the power loss, ECOST (Expected interruption cost), ENS (Energy not supplied) and to improve the reliability and bus voltages. The proposed algorithm is implemented and tested on a standard IEEE 33 bus test system. The simulation results show the effectiveness of the proposed algorithm in solving distribution expansion problem. This system is further analyzed to show the increasing reliability levels as suggested by the improvements in various reliability indices such as SAIFI, SAIDI, CAIDI and AENS.

This paper is organized as follows: Section 2 describes the reliability analysis of distribution system. The impact of DG placement on distribution system reliability enhancement is explained in section 3. Section 4 discusses the customer and energy based reliability indices. Section 5 presents the problem formulation of multi objective function which is considered on the basis of power loss index, reliability index, voltage profile index and DG investment cost index. Detailed description of the proposed algorithm is given in section 6. Section 7 discusses the results of the proposed algorithm in reducing power loss, improving voltage profile and reliability enhancement of the test system. Section 8 presents the conclusions.

II. Reliability Analysis of Distribution System

Reliability analysis of electrical distribution system is considered as a tool for the planning engineer to ensure a reasonable quality of service and to choose between different system expansion plans that cost wise were comparable considering system investment and the cost of losses. The usual method of evaluating the reliability indices is an analytical approach which based on failure mode assessment and the use of equations for series and parallel networks. The analytical approach is based on assumptions concerned with statistical distributions of failure rates and repair times. The common indices used for evaluation are the expected failure rate (λ), the average outage time (r) and the expected annual outage times (U) which is adequate for the sample radial system. The basic reliability indices of the system are given by:

$$\lambda_{sys,i} = \sum_{k \in s} \lambda_k \quad (1)$$

$$U_{sys,i} = \sum_{k \in s} \lambda_k r_k \quad (2)$$

Where λ_k, and r_k are the average failure rate and average outage time of the ith component respectively.

In this paper, expected interruption cost (ECOST) is included as part of the objective function. Evaluating ECOST enables the system planners to determine the acceptable level of reliability for customers, provided economic justifications for determining network reinforcement and redundancy allocation, identify weak points in a system, determine suitable maintenance scheduling and develop appropriate operation policies. ECOST is therefore a powerful tool for system planning [10]. ECOST at bus i is calculated as follows:

$$E\cos t_i = \sum_{i=1} L_{a(i)} C_i \lambda_i \quad (3)$$

where $L_{a(i)}$ is the average load connected to load point i in kw and C_i is the cost of interruption (in \$/kw) for the i^{th} bus.

The total ECOST of the distribution feeder is calculated as follows:

$$E\cos t = \sum_{i=1}^{NB} E\cos t_i = \sum_{i=1}^{NB} L_{a(i)} C_i \lambda_i \quad (4)$$

where NB is the total number of load points in the feeder. In order to submit the importance of a system outage, energy not supplied index (ENS) is evaluated. This index reflects total energy not supplied by the system due to faults during study period and is calculated for each load bus i using the following equation:

$$ENS_i = L_{a(i)} U_i \quad (5)$$

A customer damage function (CDF) provides the interruption cost versus interruption duration for a specified group of customers. The CCDF is basically the sum of the individual customer damage functions in the customer mix. The Sector customer damage function (SCDF) of the residential, commercial and industrial sectors etc. can be combined to create a composite customer damage function (CCDF). CCDF shows the cost of interruption as a function of interruption duration. A typical CCDF [10] is illustrated in Fig 1. Since it accounts for reliability worth and the reliability level, ECOST is a comprehensive value based reliability index and was used for this study.

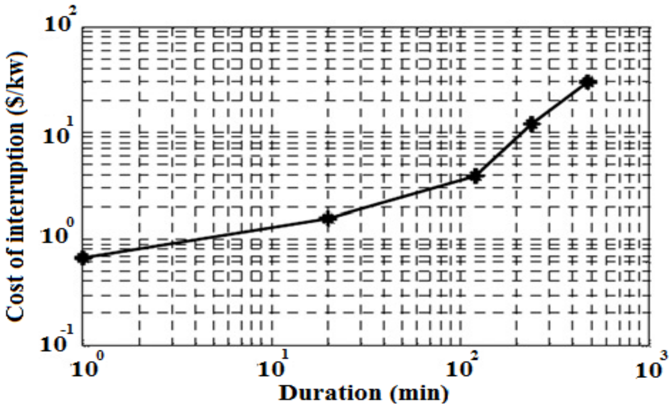

Fig. 1. Typical CCDF

III. Distribution System Reliability Enhancement using DG

The majority of the customer interruptions is caused by equipment failures in distribution systems consisting of underground cables and overhead lines. Resistive losses increase the temperature of feeders which is proportional to the square of the current magnitude flowing through the feeder. Moreover, increase in temperature causes insulation failure in underground cable and overhead lines which in turn increases the component failure rate. If DG is installed at appropriate places, they can supply part of active and reactive power demands respectively. This reduces the resistive losses due to the reduction of the magnitude of the current. These impacts on reliability are taken into consideration as a failure rate reduction of distribution feeder components.

Let us assume that any feeder i has an uncompensated failure rate of λ_i^{uncomp} before DG placement. If the reactive or active component of a feeder branch is fully compensated, its failure rate reduces to λ_i^{comp}. If the reactive and active components of current are not completely compensated, a failure rate is defined with linear relationship to the percentage of compensation. Thus, the compensation coefficient of the i^{th} branch is defined as:

$$\alpha_i = \frac{I_r^{new}}{I_r^{old}} * \frac{I_a^{new}}{I_a^{old}} \qquad (6)$$

Where I_r^{new}, I_r^{old} and I_a^{new}, I_a^{old} are the reactive and active components of the i^{th} branch current after and before compensation, respectively. The new failure rate of the i^{th} branch is computed as follows:

$$\lambda_{i-new} = \alpha_i \left(\lambda_i^{uncomp} - \lambda_i^{comp}\right) + \lambda_i^{comp} \qquad (7)$$

IV. CUSTOMER-BASED RELIABILITY INDICES

A survey by the *Electric Power Research Institute* (EPRI) has identified the most frequently used customer oriented indices are namely SAIFI, SAIDI, CAIDI, AENS and ASAI. These indices are defined as follows [21].

a. System Average Interruption Frequency Index (SAIFI):

$$SAIFI = \frac{\text{Total numbers of customer interruptions}}{\text{Total number of customers served}} = \frac{\sum \lambda_{sys,i} N_i}{\sum N_i} \qquad (8)$$

b. System average interruption duration index (SAIDI):

$$SAIDI = \frac{\text{Sum of all customer interruptions durations}}{\text{Total number of customer served}} = \frac{\sum U_{sys,i} N_i}{\sum N_i} \qquad (9)$$

c. Customer average interruption duration index (CAIDI):

$$CAIDI = \frac{\text{Sum of all customer interruption durations}}{\text{Total number of customer interruptions}} = \frac{\sum U_{sys,i} N_i}{\sum \lambda_{sys,i} N_i} \qquad (10)$$

d. Average energy not supplied (AENS):

$$AENS = \frac{\text{Sum of system annual outage duration at load point}}{\text{Sum of average load point}} = \frac{\sum L_i U_{sys,i}}{\sum N_i} \qquad (11)$$

e. Average Service Availability Index (ASAI):

$$ASAI = \frac{\text{Customer hours service availability}}{\text{Customer hours servise demand}}$$

$$= [(8760\text{-}SAIDI)/8760]*100 \qquad (12)$$

Where L_i is average load connected at i^{th} load point, which may be obtained from the load duration curve, $\lambda_{sys,i}$ is the system failure rate at i^{th} load point, N_i is the total number of customers at load point i and $U_{sys,i}$ is system annual outage duration at i^{th} load point.

V. PROBLEM FORMULATION

The main objective of this paper is to determine the optimum location and size of DG in distribution systems in order to improve the system reliability and to reduce the power loss along with minimum installation cost of DG. Losses in the distribution feeders and voltage of all nodes are found by backward – forward sweep distribution load flow analysis. In this paper a multi objective function is considered on the basis of active power loss index, reliability index, voltage profile index and DG investment cost index which are defined as follows:

A. Multiobjective Function

The multiobjective function of the problem is described as:

$$Mininize \quad J = \sum_{m=1}^{4} K_m J_m \tag{13}$$

$$K_m \in [0,1], \quad \sum_{m=1}^{4} K_m = 1 \tag{14}$$

Where, k_m are weighting factors assigned to each objectives are K_1=0.4, K_2=0.1, K_3=0.1 and K_4=0.4 attributed to power loss, reliability, voltage deviation and DG's Investment Cost Index.

B. Real Power Loss Index (J_1)

Power losses are important factor in the design of distribution systems and are calculated by backward – forward sweep load flow method in radial distribution system. At a given time, the power loss index is given by

$$J_1 = \frac{P_{L,DG}}{P_L} \tag{15}$$

Where $P_{L,DG\&Cap}$ is the total real power loss of the distribution system in the presence of DG and P_L is the total real power loss without DG in the distribution system.

C. Reliability Index (J_2)

Reliability index is given by

$$J_2 = \frac{ECOST_{DG}}{ECOST} \tag{16}$$

Where $ECOST_{DG}$ and ECOST is expected interruption cost of systems with and without DG installation.

D. Voltage deviation index (J_3)

Bus voltage is one of the most important characteristic of the system. One of the benefits of correct selection of location and size of DG is the improvement of voltage deviation. This index indicates higher voltage deviations from 1.0 per unit. Voltage deviation index **(**VDI) is expressed as

$$J_3 = \sum_{i=1}^{NB} |V_i - 1| \tag{17}$$

Where NB is the total number of the buses
V_i is the magnitude voltage on the i^{th} bus.

E. DG's Investment Cost Index (J_4)

DG is appropriate selections for minimizing both the line loss and improving the network reliability and voltage profile. However, the investment cost of DG is a significant problem that prevents engineers using them widely. This index is calculated with the following equation:

$$J_4 = \frac{Cost_{DG}}{Cost_{MCD}} \tag{18}$$

where $Cost_{DG}$ are costs of DG. $Cost_{MCD}$ are costs of DG in their maximum capacity.

VI. BLACK HOLE PHENOMENON

John Michell and Pierre Laplace were the first to introduce the concept of black holes in the eighteen century. They identified the absence of star by integrating Newton's law but the absence of star was not known as black hole at that time. Only in 1967, John Wheeler, an American physicist first named the phenomenon of mass collapsing or absence of star as a black hole. A black hole in space is what is left when a star or massive sized planet collapses. The gravitational power of the black hole is too high that even the light cannot escape from it. Anything that crosses the boundary of the black hole is swallowed by it and vanishes. The sphere-shaped boundary of a black hole in space is known as the event horizon. The radius of the event horizon is termed as the Schwarzschild radius. At this radius, the escape speed is equal to the speed of light, and once light passes through, even it cannot escape. The Schwarzschild radius is calculated by the following equation:

$$R = \frac{2GM}{C^2} \tag{19}$$

Where, G is the gravitational constant, M is the mass of the black hole, and c is the speed of light. If anything moves close to the event horizon it will be absorbed into the black hole and permanently disappear.

A. Black Hole Algorithm (BHA)

Similar to the other meta-heuristics algorithms, a population of randomly distributed candidate solutions for the given problem is created. All the population-based algorithms move the individuals towards the global best solution through certain techniques. For example, mutation and crossover operations are followed in GA. In PSO, the movement of the initial solution towards the global best solution is based on the individual best and global best in each iteration.

In BHA, the evolving of the population is done by moving all the candidates towards the best candidate in each iteration, namely, the black hole and replacing those candidates that enter within the range of the black hole by newly generated candidates in the search space [24 and 25]. The proposed BHA in this paper is more similar to the natural black hole phenomenon. In BHA the best candidate among all the candidates at each iteration is selected as a black hole. Then, all the candidates are moved towards the black hole based on their current location and a random number. The searching mechanism of BHA is as under:

A randomly generated population of solutions is taken as the initialization process. Then the fitness values of the population are evaluated and the best solution whose fitness value is the best one is the black hole. After initializing the black hole and stars, the black hole starts absorbing the stars around it and all the stars start moving towards the black hole. The absorption of stars by the black hole is formulated as follows:

$$x_i(t) = x_i(t-1) + rand(0,1)(x_{BH} -, x_i(t-1) \qquad (20)$$

where $x_i(t)$ and $x_i(t-1)$ are the locations of the i^{th} star at iterations t and $t-1$, respectively. x_{BH} is the location of the black hole in the search space. rand is a random number in the interval [0, 1]. N is the number of stars (candidate solutions). While moving towards the black hole, a star may reach a location with lower cost than the black hole. In such a case, the black hole moves to the location of that star and vice versa. Then the BHA will continue with the black hole in the new location and then stars start moving towards this new location. In addition, there is the probability of crossing the event horizon during moving stars towards the black hole. Every star (candidate solution) that crosses the event horizon of the black hole will be sucked by the black hole. Every time a candidate (star) dies – it is sucked in by the black hole – another candidate solution (star) is born and distributed randomly in the search space and starts a new search. This is done to keep the number of candidate solutions constant. The next iteration takes place after all the stars have been moved. The radius of the event horizon in the black hole algorithm is calculated using the following equation:

$$R = \frac{f_{BH}}{\sum_{i=1}^{N} f_i} \qquad (21)$$

where f_{BH} is the fitness value of the black hole and f_i is the fitness value of the i^{th} star. N is the number of stars (candidate solutions). When the distance between a candidate solution and the black hole (best candidate) is less than R, that candidate is collapsed and a new candidate is created and distributed randomly in the search space. Based on the above description the main steps in the BH algorithm are summarized as follows:

B. Implementation of BHA for RDS

Step 1: Initialize the algorithm parameters like population size, maximum number of generations and black hole.

Step 2: Each individual is a vector of the control variables. i.e. i.e. Xi= [VG1, VG2…VG NG, TP1, TP2…TP NT, Qc1, Qc2….QNC]. NP number of agents is generated by respecting the limits of control parameters.

Step 3: Calculate the fitness function values of all candidate solution by running the NR load flow.

Step 4: Determine the center of mass which has global best fitness using equation (21).

Step 5: Generate new candidates using the center of mass, particle best and global best by adding/subtracting a normal random number according to equation (20).

Step 6: Repeat steps step 2 to step 5 until stopping criteria has been achieved.

VII. SIMULATIONS AND RESULTS

The proposed method has been tested on IEEE 33 bus radial distribution system. This system consists of 33 buses, 32 sectionalizing switches and 5 tie lines as shown in fig. 2. All the calculations for this method are carried out in p.u, a system with 12.66 kV and 100 MVA base. The nominal active and reactive load on the system is 3.715 MW and 2.300 MVAr and the system details are found in [22]. The tie switches 33, 34, 35, 36 and 37 are normally open in the base configuration represented by dotted lines and sectionalizing switches are represented by solid lines as shown in fig. 2.

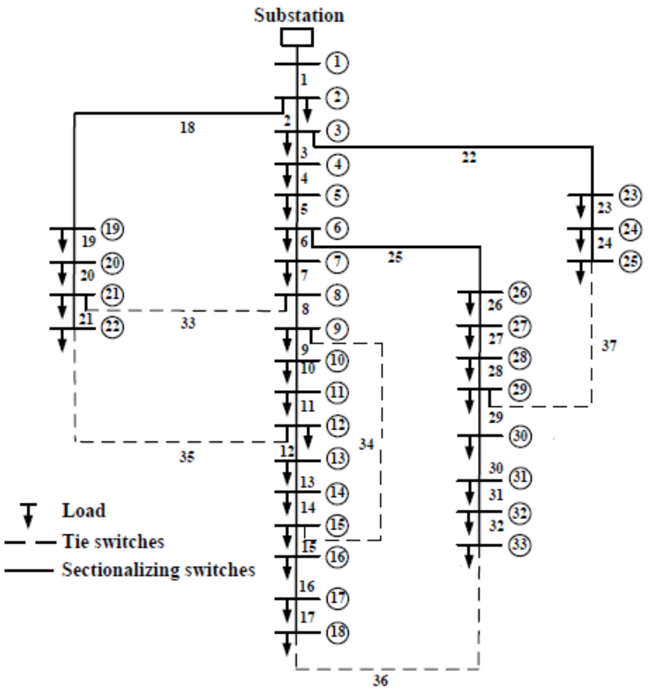

Fig.2. IEEE 33 bus distribution system

It is assumed that the section with the highest resistance has the biggest failure rate of 0.5 f/year and the section with the smallest resistance has the least failure rate of 0.1 f/year. Based on this assumption, failure rates of other sections are calculated linearly proportional to these two values according to their resistances. Furthermore, it is assumed that if the reactive or active component of a distributor section current is fully compensated, its failure rate reduces to 85% of its uncompensated failure rate [20] and for partial compensation, the failure rate is calculated using (7). In this paper, certain assumptions are made to evaluate the reliability indices. It is assumed that there is a circuit breaker (CB) at the substation with a sectionalized switch at the beginning of each section. Since the reconfiguration strategy only affects the reliability of the feeders, the other network components, such as the transformers, busbars and sectionalized switches, are assumed to be fully reliable. Besides, for each line, the repair time and failure rate are considered as 8 hours and 0.5 hours respectively.

The following Black hole algorithm is considered for the simulation. Component failure rate is optimized using the compensation coefficient (7) which is in turn used to calculate the customer reliability indices, i.e. SAIFI, SAIDI, CAIDI, AENS and ASAI before and after reconfiguration. The available DG sizes and their associated costs are given in table 1. Simulations were carried out on a 1.86 GHz system in MATLAB 7.5 version environment.

TABLE.1. DG size and costs

Size KW)	Cost ($)
250	2121
500	1500
750	1225
1000	1061
1250	949
1500	866
1750	802
2000	750

Distribution system expansion planning is carried out on the test system by introducing new load points to meet the future load growth and corresponding single line diagram is shown in fig. 3. The details of upgradable feeder section as well as new feeder section are obtained from [6] and new load point data are given in table 2.

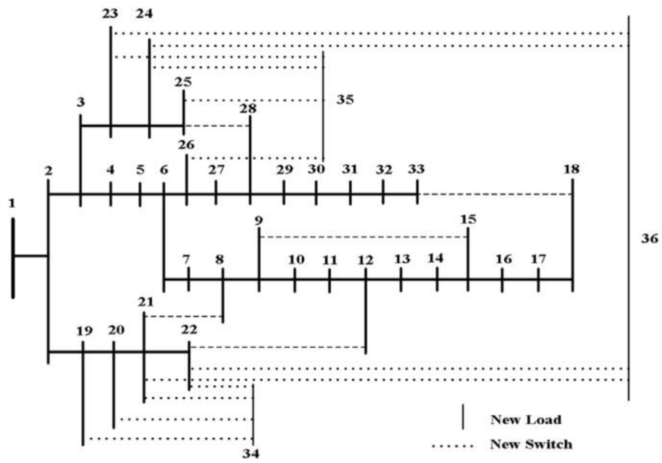

Fig.3. IEEE 33 bus distribution system with new load points

TABLE.2. Data for new load points

New buses	Real power (KW)	Reactive power (KVAr)
34	300	250
35	100	30
36	200	80

The following case studies are carried out on the test system, while solving the distribution system expansion planning problem.

1. Base case (fig. 2.)
2. 33 bus radial distribution system with additional load points (fig. 3.).
3. Reconfiguration with new load points.
4. Reconfiguration with DG in optimal locations.

In case 1, the radial distribution system is considered as such in the one line diagram and the position of tie switches (33, 34, 35, 36 and 37) and sectionalizing switches are as shown in the fig 2. In second case study, expansion planning is carried out on the test system by considering three additional load points (34, 35 and 36) to meet the load growth in future. In case 3, new reconfiguration topology with additional load points is found out in view of minimum power loss and ECOST. The obtained new position of tie switches in the reconfiguration topologies are 22, 6, 31, 12 and 16. In case 4, reconfiguration with DG placement in optimal location is considered. According to the proposed algorithm optimal size of DG is found to be 1000 KW and its location is bus number 29. In all the case studies, the proposed BFA algorithm is used to solve the radial distribution system. The results of all the case studies and % improvement are given in table 3. From the results, it is evident that the proposed reconfiguration topology and optimal placement of DG yields better performance.

TABLE.3. Results are obtained in different cases of distribution system

Case study	ECOST ($)	ENS (KWh/Yr)	P_{LOSS} (KW)	Q_{LOSS} (KVAr)	VDI (p.u)	V_{min} (p.u)
1	236809.65	13564.00	202.83	135.25	0.7013	0.9131
2	245267.11	18563.00	288.12	197.95	0.8945	0.8895
3	123768.98	10123.00	175.23	110.28	0.4678	0.9484
4	29345.78	7688.55	89.56	69.34	0.3257	0.9666
% improvement	88.03	58.58	68.91	64.97	63.58	7.97

It also shows the % improvement of case 4 when compared with case 2. Fig 4 shows the voltage profile of all the buses in case 1 to case 4. Similarly line losses in each branch in all the case studies are shown in fig 5. From these figures, it is observed that the voltage profile has been improved and line loss is reduced by the proposed method.

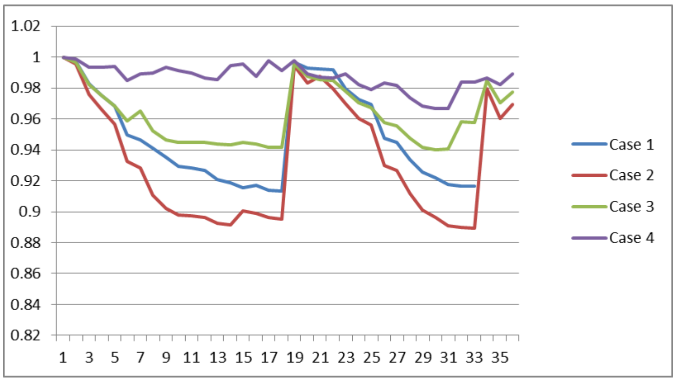

Fig.4. Voltage profile in all cases

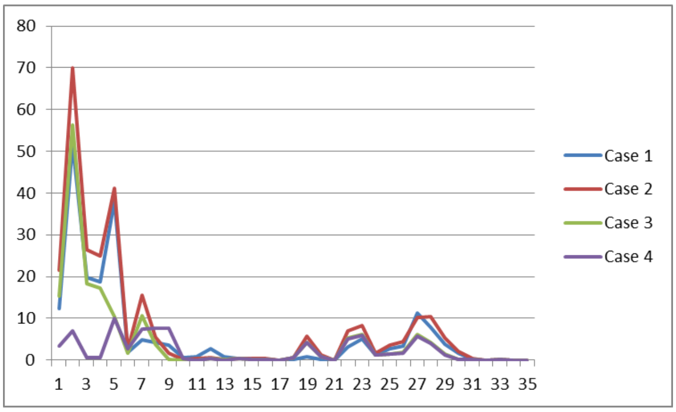

Fig.5. Line loss in all cases

Further, the customer and energy based load point reliability indices are also calculated for all the four cases and are shown in table 4. It is clear that the reliability enhancement of RDS is achieved by the new reconfiguration topology and DG placement.

TABLE.4. Customer and energy based reliability indices for 33 bus test system.

Reliability indices	Case 1	Case 2	Case 3	Case 4
SAIFI	2.1403	2.1470	0.9671	0.0982
SAIDI	1.3739	1.5529	0.7912	0.0789
CAIDI	0.6419	0.6997	0.7197	0.8323
AENS	0.2692	0.3994	0.35694	0.1283
ASAI	99.9843	99.9804	99.9982	99.9990

VIII. CONCLUSION

In this paper, multistage distribution system expansion planning problem to meet load growth has been studied and solved using black hole algorithm. The proposed algorithm has also been used to determine better reconfiguration topology in the presence of DG to enhance the reliability of the RDS. For the purpose of illustration IEEE 33 bus system is considered as test system. The energy and customer based reliability indices were evaluated using the optimized failure rates and repair times of the distributor segments. It is seen that reliability indices are also improved and voltage profile of all the buses remained stable within the limits. Power losses are also reduced and hence reliability is improved.

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