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ENERGY LOSS MINIMIZATION AND RELIABILITY ENHANCEMENT IN RADIAL DISTRIBUTION SYSTEMS DURING LINE OUTAGES

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ABSTRACT

This paper proposes a methodology for energy loss minimization and reliability enhancement in radial distribution systems during line outages. Energy loss is reduced by simultaneous network reconfiguration and capacitor placement. In addition, network reconfiguration also helps in service restoration. The solution methodology have two parts: In part one, sensitivity analysis is done for all the possible line outage conditions considering single line outage at a time, from which the common set of nodes for capacitor placement is identified and fixed for capacitor placement. In the second part, Global best guided Artificial Bee Colony algorithm is used for reconfiguration and capacitor placement. The proposed approach has been tested on two test feeders.

Keywords: distribution system, energy loss minimization, service restoration, global best guided artificial bee colony algorithm.

INTRODUCTION

Distribution system provides final link between the high voltage transmission system and the low voltage consumers. The power and hence energy loss in a distribution system is significantly high because of its low voltage and high current. High resistance of the feeders causes significant voltage drop. The I^2R loss can be separated into two parts based on the active and reactive components of branch currents [1]. The losses produced by both active and reactive components of branch currents are reduced by reconfiguration of existing system by changing the status of tie and sectionalising switches. The main benefits of network reconfiguration are service restoration, energy loss reduction, voltage stability enhancement, improved reliability and protection from overloading. The loss produced by reactive components of branch currents can be reduced by the installation of shunt capacitors. Shunt capacitors installed in the system have major impact on energy loss minimization, voltage profile management, power factor improvement, stability enhancement and capacity release of source generators and transformers enabling additional loading.

During line outages, due to fault, supply of power to the loads could be partially or completely isolated. To restore the power supply to the isolated loads, proper reconfiguration of the Radial Distribution System (RDS) is required.

Distribution systems have two types of switches: tie-switches (normally open) and sectionalizing switches (normally closed). Feeder reconfiguration is the process of closing and opening of the switches to alter the network topology. Baran and Wu [2] formulated a general feeder reconfiguration problem for loss reduction and load balancing and employed a branch exchange method to search over different radial configurations. They also developed an approximate load flow to calculate loss reduction. Authors of [3] introduced an ant colony search algorithm inspired from the natural behaviour of the ant colonies to solve the optimal network reconfiguration problem for power loss reduction. Das [4] developed a heuristic based fuzzy multi-objective approach for optimizing network configuration. The four different objectives considered were minimization of power loss, branch current constraint violation, node voltage deviation and load balancing of various feeders. Sachin Singh *et al.* [5] presented a bacterial foraging technique to solve the feeder routing problem of radial distribution system. They used the bacterial foraging technique in a different way so that it does not require tuning of all parameters. Sedighizadeh *et al.* [6] proposed a fuzzy framework based modified big bang-big crunch algorithm for reconfiguration of RDS.

The problem of capacitor placement mainly involves the determination of the number, location and size of capacitors to be placed in the distribution system such that power and energy losses are reduced. Sundhararajan and Pahwa [7] proposed genetic algorithm to select the optimum values of shunt capacitors required to be placed on radial distribution systems and used a sensitivity analysis to find the candidate nodes. A fuzzy expert system containing a set of heuristic rules is used in [8] to determine the capacitor placement suitability at each node in the distribution system. In [9] two new heuristic techniques for solving the capacitor allocation problem in radial distribution system have been presented; one is based on maximum cost reduction and the other is based on maximum loss reduction. The authors of [10] developed loss sensitivity factors to determine the sequence of nodes to be compensated and employed particle swarm optimization algorithm to find the ratings

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of capacitor banks. They treated the capacitor sizes as continuous variables. Srinivasa Rao *et al*. [11] presented a methodology using plant growth simulation algorithm to estimate optimal size of capacitors. Authors of [12] proposed an Artificial Bee Colony algorithm based methodology for solving the capacitor allocation problem.

Most of the researchers formulated capacitor placement algorithms without considering network reconfiguration and network reconfiguration algorithms without capacitor placement. The authors of [13] proposed a single comprehensive algorithm for reconfiguration and capacitor control, where simulated annealing and a discrete optimization algorithm were used to optimize switch configuration and capacitor control respectively. Authors in [14-15] presented a method using Ant Colony search Algorithm (ACA) to solve the combined reconfiguration and capacitor placement problem. Srinivasa Rao [16] proposed a hybrid approach that combines network reconfiguration and capacitor placement using Harmony Search Algorithm (HSA) to minimize power loss and improve voltage profile. In [17], a joint optimization algorithm was proposed using discrete genetic algorithm considering different load patterns. Sedighizadeh *et al*. [18] presented an algorithm using Improved Binary Particle Swarm Optimization (IBPSO) and used binary strings to represent the network switches and capacitors. Esmaeili *et al*. [19] proposed a fuzzy harmony search algorithm for combined optimization with harmonic consideration.

Distribution systems are generally radial in structure. Due to its high R/X ratio, the convergence characteristics are poor with conventional load flow methods. A simple, fast and efficient load flow method suitable for radial distribution system suggested in [20] is used in this method.

In this paper, Global best guided Artificial Bee Colony algorithm (GABC), presented in [21], has been applied with domain based approach to solve combined optimization problem of network reconfiguration and capacitor placement for energy loss reduction and reliability enhancement during line outages.

PROBLEM DESCRIPTION

The objective of the proposed method is to minimize the energy loss subject to operating constraints during line outages. The objective function is mathematically expressed in equation (1).

$$Minimize\ f = T\sum_{b=1}^{NB} I_b^2 R_b \quad (1)$$

Where,

f = Total energy loss of the system

T = Load duration time (one hour)

NB = Number of branches

I_b= Branch current

R_b= *Branch resistance*

The constraints are,

a) Radiality of the system should be maintained
b) Bus Voltages must be maintained within limits

GLOBAL BEST GUIDED ARTIFICIAL BEE COLONY (GABC) ALGORITHM

Artificial Bee Colony (ABC) is a swarm based meta-heuristic algorithm that simulates the foraging behaviour of honey bees. It was proposed by Karaboga *et al.* [22-23]. The ABC consists of three groups of bees namely employed, onlooker and scout. Employed bees exploit food source and share the information about the food source with onlookers. Onlooker bees wait in the hive for information of food sources from employed bees. Employed bees share information about food sources by dancing in the dance area and the nature of dance is proportional to the nectar content of food source just exploited. Onlooker bees observe dance and choose a food source according to the probability which is proportional to the quality of that food source. Therefore, good food sources attract more onlooker bees. Whenever a bee, whether it is scout or onlooker, finds a food source it becomes employed. Whenever a food source is exploited fully, all the employed bees associated with it abandon it and become scouts. Scout bees search for new food sources.

The ABC algorithm has good global search capability but poor local search capability, while the Particle Swarm Optimization (PSO) algorithm has good local search ability but poor global search ability. In order to enhance the exploitation capability of ABC algorithm by applying the knowledge of the previous good solutions and hence to find even better candidate solutions, Global best guided Artificial Bee Colony (GABC) algorithm [21] is developed by combining ABC and PSO.

In GABC algorithm, each food source position represents a possible solution for the optimization problem. It could be comfortably represented as a vector. The nectar amount of a food source corresponds to the value (quality) of the associated solution. The number of employed or the onlooker bees is equal to the number of the food sources in the population. In other words, for every food source, there is only one employed bee. Each cycle of algorithm constitutes three bee phases; employed phase, onlooker phase and scout phase.

The equations of GABC are modified to suit our problem which has an integer solution set where the solution variables must be an integer. Domain based approach is applied to GABC, where solution may consist of different regions or domains, similar variables are grouped together to form a domain. Thus each domain consists of similar set of variables. The number and size of each domain is dependent on the optimization problem. The domain variables share a common search space.

Fitness function for minimizing objective function 'f' is defined as below:

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$$Fitness = \frac{1}{(1+f)} \tag{2}$$

The various phases of GABC are described below.

Initialization: During initialization, solutions are randomly initialized using scout bees. The number of initialized solutions will be equal to number of employed bees. Initialized solution 'X_i' with 'd' domains and 'n' variables along each domain will be of the form given below. For explanation purpose each domain is assumed to be of equal size / equal number of variables 'n', though in actual problem it may vary. The initialized solutions are evaluated for fitness and the best solution is stored as global best, 'Gbest'.

X_i =	$X_{i11}X_{i12}...X_{i1n}$	$X_{i21}X_{i22}...X_{i2n}$	. . .	$X_{id1}...X_{idn}$

Employed Bee Phase: The initialized solutions are passed to the employed bee phase. Each employed bee picks up a solution and mutates a variable from randomly chosen domain (search for food in the neighbourhood). The domain 'y' along where neighbourhood search occurs is given by its dynamic domain choosing probability P_y.

Where, $\sum_{y=1}^{d} P_y = 1$

Foraging of employed bees in solution 'i' is explained below. A random solution 'k' is selected from the neighbourhood such that k≠i; the domain for search 'y' is chosen based on dynamic domain choosing probability and the variable within the domain is selected randomly as 'j'.

$$V_{iyj} = X_{iyj} + R(X_{iyj} - X_{iyk}) + S(X_{iyj} + Gbest_{yj}) \tag{3}$$

Where,

Gbest is the Global best solution
R is the random integer in the interval (-1 0 1)
S is the random integer in the interval (0 2)

The employed bees greedily select between the new and old solution using the fitness value of each solution. The probability value for onlooker selection for each solution is calculated using equation (4).

$$P_i = \frac{\text{fitness}_i}{\sum_{m=1}^{E} \text{fitness}_m} \tag{4}$$

Where, E is the number of employed bees

The greedily selected solutions are compared with global best 'Gbest' and if found better 'Gbest' will be updated. From equation (3), it can be seen that the Global and local information are utilized for updating.

Onlooker Bee Phase: The solutions from the employed bee phase are passed to the onlooker phase. The number of onlookers exploring a particular solution depends on the probability value of the solution (4). The onlooker bees explore the solutions according equation (3). The solutions are then evaluated and greedily selected between the new and the old solution. If any solution is found better than 'Gbest', 'Gbest' will be updated.

Scout Bee Phase: The solutions from the onlooker phase are checked for exploitation limit. At most one scout bee is allowed in a cycle. The scout bee chooses any one of the limit violated solution and replaces it with a new solution using equation (5). The solutions from the scout phase are again passed to employed phase and cycle continues till maximum cycle limit is reached or till the solution converges.

$$V_{iyj} = X_{min,y} + r(X_{max,y} - X_{min,y}) \tag{5}$$

Where,

y is the domain selected based on domain choosing probability
r is the random integer in the interval (-1 1)
$X_{max,y}$ is the maximum value of X in the domain 'y'
$X_{min,y}$ is the minimum value of X in the domain 'y'
j is the randomly chosen variable from the domain 'y'

Dynamic domain choosing probability

The domain where the bees forage is decided by the dynamic domain choosing probability. In some problems the search space of each domain varies considerably and the overall fitness of solution is largely affected by interdependency of domains. For example in our context the first domain is reconfiguration of the switches and second domain is capacitor placement along the candidate buses. The search space of reconfiguration is quite large in contrast to the search space of discrete capacitor placement along candidate buses. The overall fitness of the solution likely depends more on reconfiguration than capacitor placement. Based on heuristic, during the initial stages of optimization it is better to have huge search along reconfiguration domain and during the later stages of the optimization it is better to have huge search along the capacitor placement domain to get a more fit solution. Hence a dynamically varying domain choosing probability value is assigned to each domain such that, probability for neighbourhood search in reconfiguration domain is high during initial cycles while probability for capacitor placement is high during later stages of algorithm.

$$P_{re}^{G} = P_{re} + \frac{0.1 * (maxcycle - G)}{maxcycle} \tag{6}$$

$$P_{cp}^{G} = 1 - P_{re}^{G} \tag{7}$$

Where,
G is the current cycle of algorithm

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P_{re} is the probability for foraging in reconfiguration domain
P_{cp} is the Probability for foraging in capacitor placement domain

PROPOSED METHODOLOGY

The main goal of this work is to provide a combined optimisation process that obtains the best combinations of open /closed switches of the given system and to place optimal size of capacitors at candidate buses to give minimum energy loss and also to enhance the reliability of supply to consumers.

The loss sensitivity method suggested in [10] is used to find out the sensitive nodes. Loss Sensitivity Factor ($\partial \mathrm{P_{lineloss}} / \partial \mathrm{Q_{effective}}$) is derived for each node and the nodes are sorted in descending order of loss sensitivity factor to decide the sequence of nodes for placing capacitor banks. Normalised voltage magnitude, 'norm' is calculated at corresponding nodes and nodes whose 'norm' value is greater than 1.01 are considered for compensation and are called as candidate nodes. This helps to reduce the search space of capacitor placement problem.

It is well known that for each line outage condition candidate nodes will be different. It may not be cost effective if we place capacitors at different nodes during different line outage conditions. So a common set of nodes for capacitor placement is identified, as common candidate nodes, based on the frequency of its selection during various line outages. A consolidated solution with capacitors needed for different outage scenario of the system is found.

The number of open switches in distribution system is held constant during reconfiguration, so as to maintain radiality and to prevent islanding of nodes. Hence number of open switches in any configuration is equal to initial number of tie switches. The open switches are represented as a tie set vector [s1 s2 s3 s4 ... sN], where N= number of tie switches. During optimization only feasible switching combinations (tie set vector) are to be used. Infeasible switching combinations are combinations which results in either meshed system or islanding the nodes (loads). In the proposed approach, prior to the optimization procedure, feasible switching combinations is generated using graph theory [24] and are arranged randomly in a vector named 'comb'. The 'comb' vector will be made available for the GABC algorithm. This will eliminate the computational effort and time required for eliminating the infeasible solutions. The feasible switching combinations vector, 'comb' is of the order [NC × N]; where NC is the total number of feasible combinations.

Capacitor bank sizes in multiples of 150 kVAR such as 150, 300, 450, 600, 900 and 1200 kVAR are represented in the form of a column vector named 'bank' where, each element represents capacitor bank's size in kVAR. Thus the solution consists of two domains, a variable for reconfiguration and a set of variables for capacitor placement. The reconfiguration variable is a non-zero integer representing the index of 'comb' vector. Each capacitor placement variable is a non-zero integer, an index pointing the column of 'bank' vector. Thus each variable of the solution vector is a non-zero integer.

To evaluate a solution vector, which contains information about tie-switch combination and capacitor banks for service restoration and capacitor placement, it should be properly decoded into tie set combination and capacitor bank values. The base case system is reconfigured based on tie set combination. The capacitor banks specified by the solution are placed on the corresponding common candidate nodes. The new system is evaluated and the fitness value is obtained using equation (1) and (2) respectively.

One of the main applications of network reconfiguration is service restoration. Service restoration is needed when there is an outage in the network. The most common outage in distribution system is the outage of lines. The reasons are falling of a branch of a tree or any accidents or sudden rise in load. If these conditions happen then the particular line is open, so it is treated as a tie switch. With the remaining switches the network reconfiguration is done and power is restored. In the outage cases the voltage profile is affected as the network is over loaded. Therefore capacitor placement has to be done for improving the voltage and reducing the power and energy losses. In this paper outage of single line at a time is considered.

Computational procedure to find common set of nodes for capacitor placement

The computational steps of the proposed solution procedure to find common set of nodes for capacitor placement are given below.

a) Run the base case load flow.

b) Get the outage line number.

c) Find the optimal tie switch combination using GABC algorithm.

d) Find the candidate nodes using sensitivity factors for the reconfigured system.

e) Repeat the step-2 to step-4 for all the line outage conditions taking one line outage at a time.

f) Find the common set of nodes for capacitor placement based on its frequency of occurrence in various line outage scenarios.

Computational procedure for service restoration and capacitor placement

The computational steps of the proposed solution procedure based on Gbest guided Artificial Bee Colony algorithm for simultaneous network reconfiguration for

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service restoration and capacitor placement during line outages are given below.

A. Read system data such as line data, load data, tie switches, combination vector (‘comb’) of the radial distribution system and ‘bank’ vector containing capacitor bank sizes.

B. Get outage line number and common candidate nodes for capacitor placement. Restrict ‘comb’ vector such that the outage line is in open condition in all the possible combinations.

C. Get iteration parameters such as ‘maxcycle’- maximum number of cycles, ‘P_{re}’- probability for search in reconfiguration variable, number of food sources, number of employed bees/onlooker bees, and ‘ncb’- number of candidate nodes for capacitor placement if needed.

D. Initialize food sources, structure of ‘ X_i’ is

X_i =	$comb_i$	$In_{i,1}$	. . .	$In_{i,sb}$	. . .	$In_{i,ncb}$
	Reconfiguration domain	Capacitor Placement domain				

Where,

“$comb_i$” is the reconfiguration variable, index pointing a row of the ‘comb’ vector.

“$In_{i,sb}$” is the capacitor placement variable, index pointing a column of the ‘bank’ vector, which has the kVAR value of capacitor bank to be placed in the candidate node ‘sb’.

E. Evaluate the solution set ‘X’ for fitness using equation (1) and (2).

F. Find the best fitness value ‘fit_{gbest}’ and corresponding solution ‘Gbest’ in the solution set ‘X’.

G. Let each employed bee occupy a solution and search the neighbourhood using equation (3) and dynamic domain choosing probability (equations (6) and (7)), to get neighbourhood solution set ‘V’.

H. Evaluate ‘V’ for fitness and apply greedy selection between ‘X’ and ‘V’; update ‘X’.

I. Get onlooker selection probability value *P* using equation (4).

J. Allocate onlookers to solution set ‘X’ using onlooker selection probability *P* through roulette wheel selection.

K. Onlookers search for food source ‘V’ in the neighbourhood using equation (3), along domain decided by dynamic domain choosing probability (equation (6)and(7)).

L. Evaluate ‘V’ for fitness and apply greedy selection between ‘X and ‘V’; update ‘X’.

M. Find the best fitness value ‘fit_{gbest}’ and corresponding solution ‘Gbest’ in solution set ‘X’.

N. Check for exhausted solution and if found, send a scout bee to replace the solution using equation (5).

O. Increment cycle count and if it is less than ‘maxcycle’ go to step-7.

P. Evaluate ‘Gbest’ solution and display result.

TEST RESULTS AND DISCUSSION

The proposed algorithm has been programmed on MATLAB platform installed in a Pentium dual core, 2.7GHz personal computer. The performance of the proposed methodology is tested on 33-bus and 69-bus RDS.

Switched capacitor banks of sizes 150, 300, 450, 600, 900 and 1200 kVAR are considered for placement. T, the time period of analysis is taken as one hour, the lower and upper voltage limits are assumed as 0.9 p.u and 1.1 p.u respectively. GABC parameters used are: maxcycle = 50; number of employed bees or onlooker bees = 25; number of food sources = 25.

Case study-1: 33-bus test system

The proposed algorithm is tested on a 33-bus system [16]. The test system has 32 sectionalizing switches s1 to s32 and 5 tie switches s33 to s37. Line and load data of the system is obtained from the reference [2]. The system operating voltage is 12.66 kV. The total real and reactive power loads on the system are 3715 kW and 2300 kVAR. The base case energy loss of the system per hour is 202.66 kWh. The loops of the system are L_1, L_2, L_3, L_4 and L_5. Using graph theory, common branch vectors are found as CB_{13}= [s33], CB_{14}= [s6 s7], CB_{15}= [s3 s4 s5], CB_{23}= [s9 s10 s11], CB_{24}= [s34], CB_{34}= [s8] and CB_{45}= [s25 s26 s27 s28]. Prohibited group vector and corresponding islanded principal nodes of 33-bus system are found using graph theory and shown in Table-1. The ‘comb’ vector formed is of the order (50751×5).

Figure-1 shows the selection of common candidate nodes for 33-bus system. The common candidate nodes are selected as 25, 29, 30, 28 and 8. The system is examined for various line outage contingencies. Reconfiguration and capacitor bank switching schedule for service restoration is shown in Table-2. During the outage of line 1, system cannot be restored since no alternative path is available. Whereas during outage of the line 2, minimum voltage is below prescribed limit of 0.9 p.u, hence such solution is treated as infeasible and load shedding is suggested.

Table-1. Prohibited group vectors and corresponding islanded principal nodes of the 33-bus system.

Prohibited group vectors	Islanded principal nodes
PG_6=[$CB_{14}CB_{15}CB_{45}$]	6
PG_8=[$CB_{13}CB_{14}CB_{35}$]	8
PG_9=[$CB_{23}CB_{24}CB_{34}$]	9
PG_{68}=[$CB_{13}CB_{15}CB_{34}CB_{45}$]	6,8
PG_{89}=[$CB_{13}CB_{14}CB_{23}CB_{24}$]	8,9
PG_{689}=[$CB_{13}CB_{15}CB_{23}CB_{24}CB_{45}$]	6,8,9

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During normal operating state, it is preferred to operate the system considering line number 9 as open, as this condition gives minimum energy loss. The elapsed time is 7.16 seconds for this system. The energy saved per hour is 109.64kWh, whereas energy saving of 960.45MWh per year is achieved. Table-3 shows the results of the 33-bus system during normal operation. In order to establish the performance of the proposed approach, the results are compared with ACA [15], HSA [16] and IBPSO [18]. The results are presented in table 4 and compared in Figure-2.

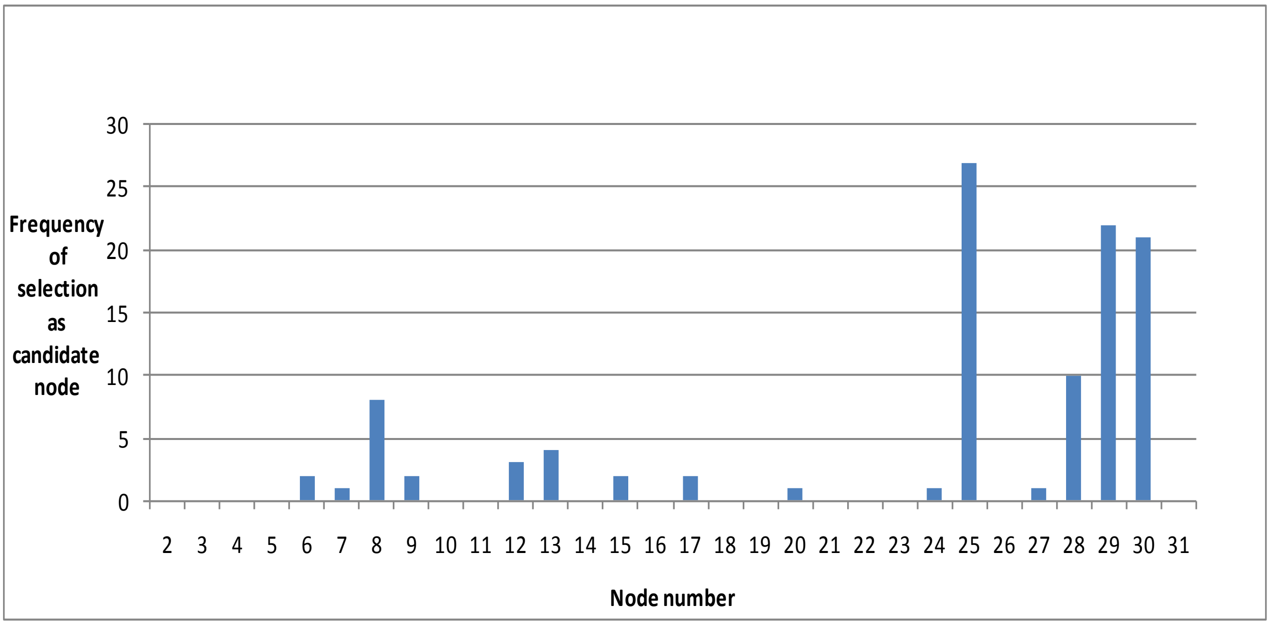

Figure-1. Selection of common candidate nodes for 33-bus system.

Table -2. Service restoration of 33-bus system with common candidate nodes fixed for capacitor placement.

Line outage	Switches opened	Node number					Energy loss/hour (kWh)	Min. voltage (p.u)	Remarks
		29	30	28	25	8			
none	s33-s34-s35-s36-s37	---	---	---	---	---	202.66	0.9131	feasible
1	---	---	---	---	---	---	---	---	infeasible
2	s2-s34-s8-s29-s24	600	900	300	150	600	395.23	0.8792	infeasible
3	s3-s34-s10-s17-s27	0	600	150	600	600	124.43	0.9515	feasible
4	s4-s14-s9-s16-s26	300	600	0	600	600	117.75	0.9527	feasible
5	s5-s14-s 9-s17-s 27	300	450	300	450	600	113.90	0.9578	feasible
6	s6-s14-s10-s32-s37	300	450	300	450	600	97.53	0.9538	feasible
7	s7-s14-s10-s36-s37	0	900	150	450	300	93.41	0.9588	feasible
8	s6-s34-s8-s17-s37	600	300	150	600	600	101.75	0.9559	feasible
9	s7-s14-s9-s34-s37	150	900	0	450	450	93.02	0.9596	feasible
10	s7-s14-s10-s36-s37	300	600	0	300	600	95.20	0.9556	feasible
11	s7-s14-s11-s34-s37	900	150	0	450	450	95.16	0.9582	feasible
12	s7-s12-s -s17-s 37	600	450	150	300	450	98.31	0.9551	feasible
13	s7-s13-s10-s34-s37	0	600	450	300	600	96.72	0.9567	feasible
14	s7-s14-s9-s32-s 37	300	450	150	450	450	93.30	0.9590	feasible
15	s6-s14-s10-s15s37	450	300	600	450	450	103.76	0.9511	feasible
16	s6-s34-s11-s16-s37	150	600	300	450	600	99.58	0.9515	feasible

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17	s7-s14-s11-s17-s37	300	600	300	450	300	96.02	0.9550	feasible
18	s18-s13-s35-s17-s28	0	600	0	900	900	141.77	0.9529	feasible
19	s19-s12-s11-s17-s28	450	900	150	0	600	133.39	0.9513	feasible
20	s20-s13-s10-s17-s28	300	600	0	600	450	127.44	0.9502	feasible
21	s7-s13-s21-s36-s37	600	300	150	450	600	105.48	0.9543	feasible
22	s7-s14-s9-s31-s22	0	300	0	1200	600	160.86	0.9408	feasible
23	s6-s14-s10-s31-s23	1200	150	0	0	600	155.20	0.9307	feasible
24	s6-s14-s10-s34-s24	0	150	300	900	450	120.68	0.9507	feasible
25	s7-s14-s9-s32-s25	600	300	150	300	450	103.79	0.9593	feasible
26	s7-s14-s10-s 36-s26	0	900	150	300	300	101.27	0.9584	feasible
27	s7-s34-s11-s17-s27	300	600	150	450	450	102.31	0.9565	feasible
28	s7-s14-s9-s32-s28	600	300	150	300	450	95.61	0.9596	feasible
29	s33-s14-s9-s29-s27	0	900	450	450	300	134.20	0.9293	feasible
30	s7-s14-s9-s30-s37	600	0	300	600	900	116.38	0.9316	feasible
31	s7-s14-s 9-s31-s28	450	600	300	150	600	102.66	0.9409	feasible
32	s7-s14-s11-s32-s 37	150	450	450	450	600	94.57	0.9605	feasible

Table-3. Test results of the 33-bus system during normal operation.

Description	Base case	Optimal case
Tie-Switches	s33-s34-s35-s36-s37	s7-s14-s9-s34-s37
Node No. kVAR	----	29 30 28 25 8 150 900 0 450 450
Energy loss per hour (kWh)	202.66	93.02
Energy saving (%)	----	54.10
Minimum voltage (p.u)	0.9131	0.9596

Table-4. Comparison of results for the 33-bus system during normal operation.

Description	HSA [16]	ACA [15]	IBPSO [18]	Proposed method
Tie switches	s33-s14-s8-s32-s28	s7-s9-s14-s32-s37	s7-s9-s14-s32-s37	s7-s14-s9-s34-s37
Node no. kVAR	6 28 29 30 9 900 300 600 300 300	29 28 20 600 450 600	7 12 25 30 33 600 300 300 600 300	29 30 28 25 8 150 900 0 450 450
Energy loss per hour (kWh)	119.72	95.79	93.06	93.02
Energy saving (%)	40.92	52.73	54.08	54.10
Min.voltage (p.u)	0.9411	0.9656	0.9585	0.9596

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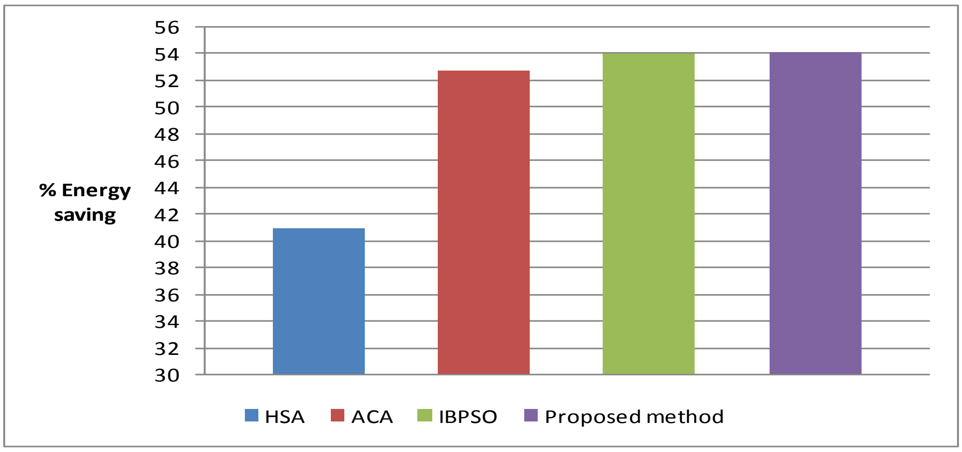

Figure-2. Energy loss saving comparison of proposed approach with other methods during normal operation.

Case study-2: 69-bus test system

The algorithm is also tested on a sample 69-bus radial distribution system. The single line diagram is shown in Figure-3. The line and load data for 69-bus system is obtained from [25]. It has 68 branches and 7 laterals. The system has 68 sectionalizing switches s1 to s68 and five tie switches s69 to s73. The system operating voltage is 12.66 kV. Total real and reactive power loads on the system are 3802.29 kW and 2694.10 kVAR. The base case energy loss of the system per hour is 224.98 kWh. The loops of the system L_1, L_2, L_3, L_4 and L_5 are shown in figure 3. Common branch vectors are C13= [s9]; C15= [s8 s10]; C25= [s70 s68 s67]; C35= [s52 s53 s54 s55 s56 s57 s58 s59 s60 s61 s62 s63 s64 s71] and C45= [s3]. Prohibited group vector and islanded principle node are P1= [C13 C15 C35] and node 10 respectively. The combination vector, 'comb', is formed based on the graph theory. The 'comb' vector formed is of the order (345990×5).

Figure-4 shows the selection of common candidate nodes for 69-bus system.The common candidate nodes are selected as 64, 63, 62, 61 and 60. The system is examined for various line outage contingencies. Reconfiguration and capacitor bank switching schedule for service restoration is shown in Table-5. During the outages of line 1 and 2, system cannot be restored since no alternative path is available. Whereas during outages of the lines 4, 5, 6 and 7 minimum voltage is below prescribed limit of 0.9 p.u, hence such solutions are treated as infeasible and load shedding is suggested.

During normal operating state, it is preferred to operate the system considering line number 59 as open, as this condition gives minimum energy loss. The elapsed time is 14.12 seconds for this system. Table 6 shows the results of the 69-bus system during normal operation. The energy saved per hour is 138.31 kWh, whereas energy saving of 1211.59 MWh per year is achieved.

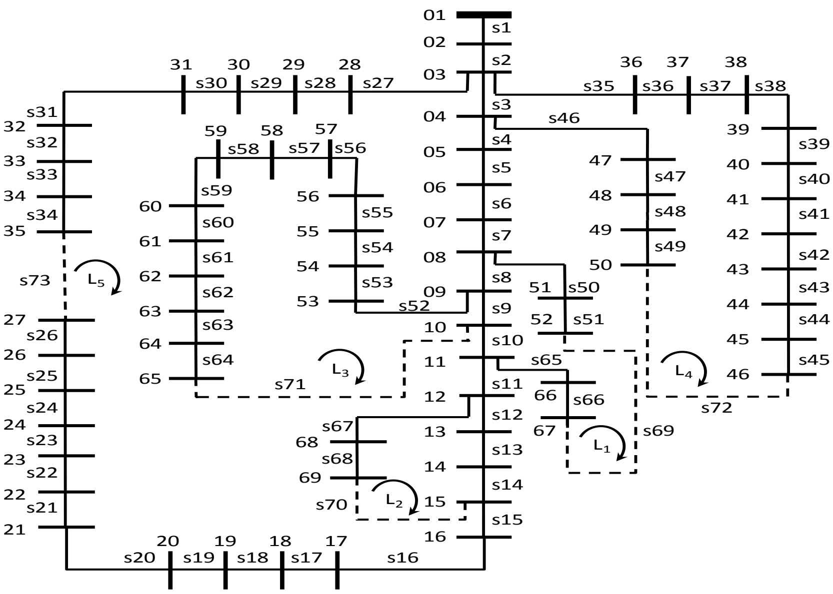

Figure-3. Single line diagram of the 69-bus radial system.

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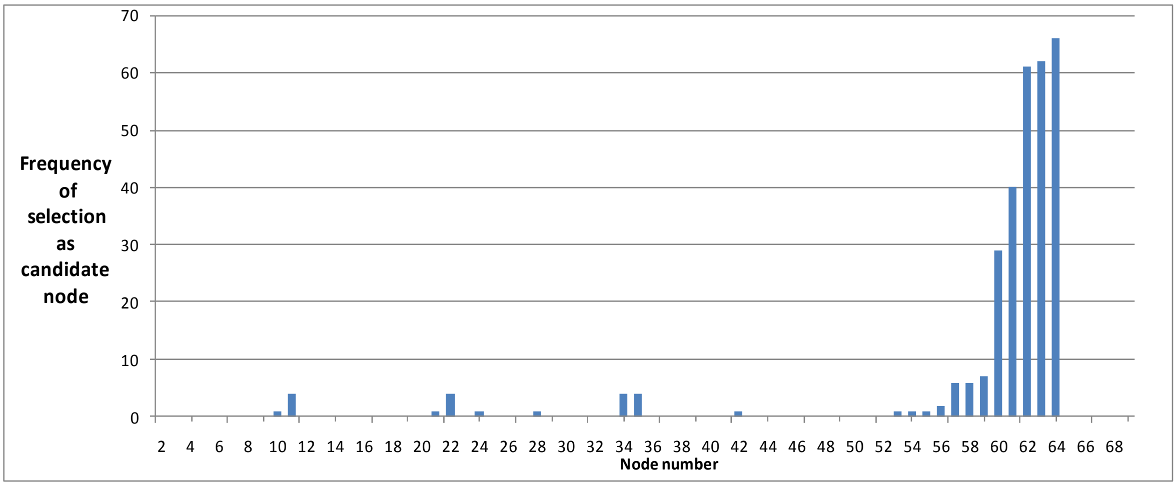

Figure-4. Selection of common candidate nodes for 69-bus system.

Table-5. Service restoration of 69-bus system with common candidate nodes fixed for capacitor placement.

Line outage	Switches opened	Node numbers					Energy loss (kWh)	Min. voltage (p.u.)	Remarks
		64	63	62	61	60			
none	s69-s70-s71-s72-s73	---	---	---	---	---	224.98	0.9092	feasible
1	---	---	---	---	---	---	---	---	infeasible
2	---	---	---	---	---	---	---	---	infeasible
3	s51-s14-s59-s3-s10	600	450	300	300	0	215.44	0.9261	feasible
4	s50-s12-s60-s36-s4	300	600	150	600	300	693.13	0.7848	infeasible
5	s9-s12-s60-s43-s5	450	600	450	300	150	690.04	0.7860	infeasible
6	s9-s13-s60-s43-s6	600	300	450	450	150	687.07	0.7860	infeasible
7	s9-s12-s60-s42-s7	900	450	450	0	150	660.83	0.7897	infeasible
8	s8-s68-s60-s45-s15	150	300	450	600	150	96.24	0.9602	feasible
9	s9-s68-s60-s43-s16	450	150	300	450	150	91.12	0.9582	feasible
10	s10-s13-s60-s42-s16	300	0	900	0	300	87.36	0.9591	feasible
11	s10-s14-s60-s39-s11	450	0	450	450	150	94.52	0.9621	feasible
12	s10-s12-s59-s41-s20	150	300	150	150	600	90.21	0.9594	feasible
13	s10-s13-s60-s42-s16	150	450	300	600	150	88.03	0.9624	feasible
14	s10-s14-s59-s49-s68	600	0	600	300	0	88.79	0.9613	feasible
15	s10-s67-s59-s40-s15	300	0	150	300	450	87.86	0.9587	feasible
16	s10-s68-s59-s38-s16	300	0	600	450	0	87.41	0.9600	feasible
17	s10-s70-s60-s72-s17	0	300	600	300	150	87.01	0.9590	feasible
18	s10-s14-s59-s45-s18	300	0	600	150	300	88.67	0.9591	feasible
19	s10-s12-s60-s44-s19	300	300	600	150	150	88.25	0.9593	feasible
20	s10-s13-s60-s37-s20	150	0	600	600	150	88.72	0.9600	feasible
21	s10-s12-s60-s44-s 21	150	300	300	600	150	92.63	0.9589	feasible
22	s10-s12-s60-s44-s22	300	150	450	450	150	92.65	0.9585	feasible
23	s10-s13-s59-s41-s23	300	600	0	150	300	94.00	0.9578	feasible

24	s10-s13-s60-s72-s24	150	300	900	0	300	95.14	0.9589	feasible
25	s10-s14-s60-s43-s25	600	0	450	300	150	95.22	0.9575	feasible
26	s10-s14-s60-s38-s26	300	0	300	600	300	95.86	0.9571	feasible
27	s10-s14-s60-s42-s27	450	150	600	150	150	102.98	0.9568	feasible
28	s10-s12-s60-s43-s28	300	0	450	600	150	100.63	0.9576	feasible
29	s10-s70-s60-s36-s29	450	450	0	450	150	102.79	0.9571	feasible
30	s10-s12-s60-s42-s30	300	300	600	150	150	99.00	0.9576	feasible
31	s10-s12-s60-s41-s31	600	150	0	600	150	98.80	0.9569	feasible
32	s10-s13-s59-s38-s32	450	450	0	300	300	100.54	0.9584	feasible
33	s10-s12-s60-s42-s33	450	150	300	450	150	97.64	0.9574	feasible
34	s10-s13s59-s36-s34	300	0	450	450	150	97.83	0.9576	feasible
35	s10-s12-s59-s35-s68	450	600	150	150	0	89.10	0.9598	feasible
36	s10-s68-s60-s36-s18	150	600	600	0	150	90.29	0.9595	feasible
37	s10-s70-s59-s37-s15	300	600	0	450	0	87.64	0.9600	feasible
38	s10-s67-s59-s38-s17	600	0	150	300	300	88.77	0.9587	feasible
39	s10-s13-s59-s39-s68	0	150	300	900	0	88.51	0.9615	feasible
40	s10-s67-s59-s40-s19	300	150	150	600	150	89.79	0.9591	feasible
41	s10-s12-s59-s41-s16	150	300	300	600	0	87.14	0.9603	feasible
42	s10-s68-s60-s42-s15	0	450	0	900	150	87.32	0.9616	feasible
43	s10-s13-s60-s43-s16	450	600	0	300	150	86.75	0.9597	feasible
44	s10-s68-s59-s44-s16	150	300	0	300	600	88.48	0.9604	feasible
45	s10-s14-s60-s45-s17	600	150	0	450	150	87.21	0.9574	feasible
46	s69-s67-s60-s46-s16	300	0	450	600	150	104.86	0.9573	feasible
47	s10-s12-s59-s47-s16	300	600	450	0	300	99.60	0.9630	feasible
48	s10-s68-s60-s48-s18	150	600	0	600	150	96.43	0.9597	feasible
49	s10-s14-s60-s49-s67	150	450	450	300	300	89.74	0.9619	feasible
50	s50-s14-s60-s39-s67	300	450	300	450	0	96.57	0.9594	feasible
51	s51-s14-s60-s42-s15	450	0	600	300	300	95.56	0.9579	feasible
52	s66-s13-s52-s42-s67	450	0	600	300	150	103.95	0.9535	feasible
53	s10-s68-s53-s39-s15	600	150	300	150	450	97.54	0.9573	feasible
54	s10-s70-s54-s72-s16	150	600	150	450	0	93.75	0.9554	feasible
55	s10-s13-s55-s41-s17	300	600	150	300	0	93.21	0.9559	feasible
56	s10-s68-s56-s45-s16	150	900	0	150	150	92.96	0.9569	feasible
57	s10-s67-s57-s40-s15	450	150	300	300	300	92.98	0.9588	feasible
58	s10-s14-s58-s37-s17	150	450	0	600	150	93.26	0.9568	feasible
59	s10-s70-s59-s45-s16	300	300	150	450	150	86.67	0.9599	feasible
60	s10-s14-s60-s72-s17	150	600	450	150	150	87.02	0.9600	feasible
61	s9-s14-s61-s 42-s16	150	0	300	600	600	104.71	0.9481	feasible
62	s9-s12-s 6-s44-s15	450	0	300	450	300	105.90	0.9455	feasible
63	s10-s14-s63-s41-s16	300	0	600	150	300	105.66	0.9446	feasible
64	s10-s13-s64-s35-s16	150	300	150	600	0	129.78	0.9359	feasible

65	s65-s67-s60-s36-s15	300	600	150	300	150	94.61	0.9578	feasible
66	s66-s14-s59-s43-s68	300	150	150	300	450	94.84	0.9580	feasible
67	s10-s13-s59-s45-s67	450	150	300	450	0	87.76	0.9603	feasible
68	s10-s13-s60-s35-s68	300	600	300	0	150	88.59	0.9590	feasible

Table-6. Test results of the 69-bus system during normal operation.

Description	Base case	Optimal case
Tie-switches	s69-s70-s71-s72-s73	s10-s70-s59-s45-s16
Node no. kVAR	---- ----	64 63 62 61 60 300 300 150 450 150
Energy loss per hour(kWh)	224.98	86.67
Energy saving (%)	----	61.47
Minimum voltage(p.u)	0.9092	0.9599

CONCLUSIONS

This paper has presented a methodology for energy loss minimization and reliability enhancement in radial distribution systems during line outages through a combined approach for reconfiguration and capacitor placement using Gbest guided Artificial Bee Colony algorithm. The proposed methodology is tested on 33-bus and 69-bus radial distribution systems. Voltage profile during various operating state is also obtained. The service restoration tables provided can be used by the system operator as a ready reckoner. Minimum energy loss configuration for normal state of operation is obtained and is compared with the available literature.

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