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Reconfiguration and Capacitor Placement of Radial Distribution Systems by Modified Flower Pollination Algorithm

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CONTENTS

1. Introduction
 2. Problem Description
 3. Pollination in Flowering Plants
 4. Flower Pollination Algorithm (FPA)
 5. Proposed Methodology
 6. Test Results
 7. Conclusion
- References

Abstract—This article proposes a combined methodology for network reconfiguration and optimal placement of shunt capacitors in radial distribution systems to reduce real power loss and enhance bus voltages. The power loss is reduced by network reconfiguration and capacitor placement, which in turn reduces a utility's loss of revenue. To ensure radial structure and avoid islanding of nodes, feasible tie-switch combinations are formed prior to the optimization process using a graph theory based method. The modified flower pollination algorithm uses a flower pollination process, an improved local neighborhood search method, and a dynamic switching probability approach to enhance the global search for optimization. The performance of this approach is tested on standard 33-bus, 69-bus, and 118-bus radial distribution test feeders. Results have been compared with previous methods reported in the literature, indicating the effectiveness of the combinatorial approach in terms of loss reduction, voltage enhancement, and cost saving.

1. INTRODUCTION

The common methods of reducing power loss and improving voltage profile in distribution systems are network reconfiguration, shunt capacitor placement, distributed generation, and high-voltage distribution systems [1]. Distribution system reconfiguration is a very effective means to reduce power loss, manage load congestion, improve voltage profile, and enhance system reliability. Distribution networks are generally operated in a radial configuration. The reconfiguration of a distribution system is a process that alters feeder topological structure by managing the open/closed status of sectionalizing and tie-switches in the system during contingencies or under normal operating conditions. The only requirement is the existence of sectionalizing and tie-switches in the system, allowing changes in the topology of the network.

Keywords: radial distribution system, real power loss, modified flower pollination algorithm, network reconfiguration, optimal location, sensitivity analysis, shunt capacitor, voltage deviation index, simultaneous network reconfiguration and capacitor placement, power loss minimization

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Network reconfiguration is a well-researched topic. Most of the previous works can be divided into three main categories [2]: evolutionary and knowledge-based methods, heuristics, and mixed techniques. Heuristic algorithms offer excellent results with shorter run times. Even though evolutionary and knowledge-based techniques can handle broader objectives, they suffer from very long computational run times and are therefore less suitable for on-line applications. Hybrid reconfiguration approaches are mixed solutions that combine evolutionary and heuristic techniques to reduce the computational run time without compromising solution quality. Civanlar *et al.* [3] presented a heuristic-based branch exchange method and derived a simple formula to estimate the loss reduction. Baran and Wu [4] proposed a different method for branch exchange using a heuristic approach. The authors of [5] used a population-based ant colony search algorithm to solve the optimal network reconfiguration problem. Das [6] developed a mixed technique using heuristic rules and fuzzy multi-objective approach for network reconfiguration. A modified simulated annealing (SA) technique is applied by authors of [7] for loss reduction in distribution systems. Hong and Ho [8] presented a method based on genetic algorithms (GAs) to determine the network configuration. Wang and Cheng [9] suggested a method for network reconfiguration to large-scale distribution systems based on a plant growth simulation algorithm. The authors proposed a bacterial foraging optimization method for network reconfiguration in [10]. Imran and Kowsalya [11] presented a meta-heuristics fireworks algorithm (FWA) to optimize the radial distribution network.

Power loss in the distribution feeder can be divided into two components: loss due to the active component of current and loss due to the reactive component of current. Capacitors have been very commonly used in distribution systems to provide reactive power compensation. The losses due to the reactive part of branch currents can be reduced by the installation of shunt capacitors. The problem of placing capacitors in distribution systems involves the determination of the number, type, and size of capacitors to be placed on the distribution feeders such that the total cost, due to energy loss and capacitor placement, is minimized. A capacitor bank reduces real power loss and maintains the node voltage profile within acceptable limits.

Different approaches have been developed for solving optimal capacitor placement problems. They are mainly classified into four categories [12]: analytical, numerical, heuristics, and artificial intelligence (AI) based techniques. All the early works on optimal capacitor placement used analytical methods that involved the use of calculus. These algorithms require no powerful computing resources. Chang [13] and Bae [14] used

analytical methods to maximize capacitor cost savings. Duran [15] and Fawzi *et al.* [16] solved the problem of determining the optimum number, location, and size of shunt capacitors using a numerical programming approach. Heuristics rules use fast and practical strategies that reduce the exhaustive search space. Abdel-Salam *et al.* [17] and Chis *et al.* [18] used heuristics methods to allocate capacitors to sensitive nodes to achieve loss reduction. Due to growing popularity, researchers have recently used AI techniques to solve capacitor placement problems. SA is used to minimize the capacitor installation costs [19]. Santoso and Tan [20] used an artificial neural network (ANN) for the optimal control of switched capacitors. Chin [21] used fuzzy set theory (FST) to determine nodes for capacitor placement. Sundhararajan and Pahwa [22] used a GA for the optimal selection of capacitors in distribution systems.

Most of the previous studies handled capacitor placement problems without consideration of network reconfiguration or handled network reconfiguration problems without consideration of capacitor placement. Capacitor placement and network reconfiguration were addressed in a disjointed manner, which cannot yield the minimum loss configuration. There are only a few examples in the literature for operating cost minimization of a radial distribution system (RDS) that applies network reconfiguration and capacitor placement simultaneously.

Chang [23] solved the feeder reconfiguration and capacitor placement problem using a population-based ant colony search algorithm. In [24], a combined optimization method was proposed for optimizing the sequence of loops selection and capacitor placement using a discrete GA. In [25], a hybrid approach using harmony search algorithm (HSA) based on power loss minimization and voltage profile improvement without considering the cost of capacitors was proposed. Also, in [26], an improved binary particle swarm optimization (IBPSO) method was adopted for optimal network reconfiguration and capacitor placement to reduce power loss.

This article presents a modified flower pollination algorithm (MFPA) for cost (cost of energy losses and cost of capacitors) minimization of an RDS by simultaneous network reconfiguration and capacitor placement. Cost minimization is achieved through minimization of real power loss and, hence, the associated cost of energy and optimal placement of capacitors. To reduce the overall computational time and search space, graph theory is used to generate feasible combinations of tie-switches prior to implementation of the optimization algorithm, which effectively avoids mesh check and node isolation check for each and every solution.

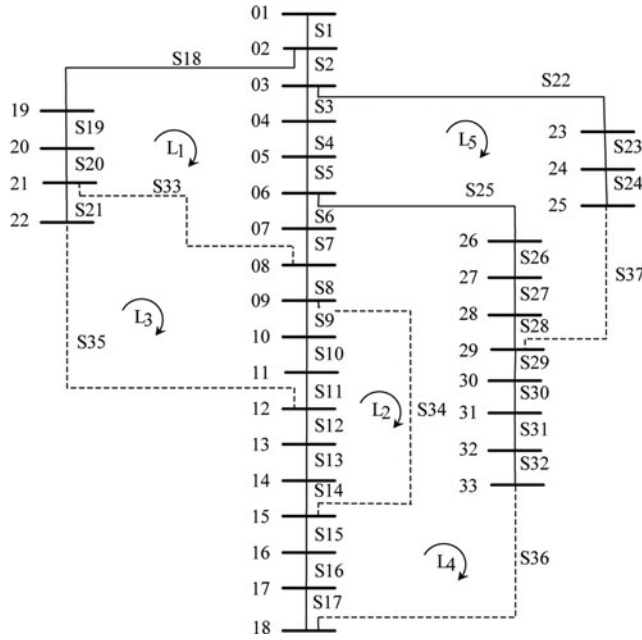


FIGURE 1. Single-line diagram of 33-bus RDS.

2. PROBLEM DESCRIPTION

The objective of the simultaneous network reconfiguration and capacitor placement problem is to minimize total cost f subject to operating constraints. The total cost includes the cost due to energy loss, the cost due to capacitor installation and maintenance, and the penalty cost due to voltage constraint. The objective function can be mathematically expressed as:

Minimize f = cost of total energy losses + cost of capacitors
+ voltage constraint penalty;

$$\begin{aligned} \text{Minimize } f = & \left\{ K_e T \sum_{b=1}^{NB} I_b^2 R_b \right\} \\ & + \left\{ df \left[(K_{ins} \times NSB) + \left(K_c \sum_{n=1}^{NSB} C_n \right) \right] \right\} \\ & + (K_{ope} \times NSB) + \{ pf \times VDI \}. \end{aligned} \quad (1)$$

The constraints are

1. radial network and
2. voltage limits must be maintained.

$$V_{\min} \leq V_i \leq V_{\max}. \quad (2)$$

To check the voltage limit violation, the voltage deviation index (VDI) [27] is used:

$$VDI = \sqrt{\frac{\sum_{i=1}^{NVB} (V_i - V_{iLim})^2}{nb}}, \quad (3)$$

where

K_e is the cost of energy losses (\$/kWh),

T is the load duration time (8760 hr),

NB is the number of branches,

I_b is the branch current,

R_b is the branch resistance,

df is the depreciation factor,

K_{ins} is the installation cost of capacitor (\$/node; location),

NSB is the number of candidate nodes for capacitor placement,

K_c is the purchase cost of capacitor (\$/kVAR),

C_n is the size of capacitor (kVAR at node n),

K_{ope} is the operating cost of capacitor (\$/year/node; location),

pf is the penalty factor (constant of multiplier for voltage deviation penalty; \$),

V_i is the voltage at the i th bus (p.u.),

V_{\min} is the minimum permitted voltage,

V_{\max} is the maximum permitted voltage,

VDI is the VDI,

NVB is the number of buses violating the voltage limit,

V_{iLim} is the lower or upper limit (whichever the i th bus is violating), and

nb is the total number of buses.

3. POLLINATION IN FLOWERING PLANTS

Flowering plants have been evolving for more than 125 million years. The ultimate objective of a flower is reproduction via pollination. Flower pollination is the transfer of pollen from one flower to another flower. Pollen is carried by wind, birds, insects, bats, and other animals. Pollination may take place in the form of biotic or abiotic; 90% of pollination is through insects and animals (biotic) with the remaining 10% by natural causes and wind (abiotic). The pollination process may be of either self-pollination or cross-pollination. Self-pollination occurs between the same flower's male and female parts or between the flowers of same plant. Cross-pollination means pollination occurring between flowers of two different plants.

4. FLOWER POLLINATION ALGORITHM (FPA)

The objective of flower pollination is the survival of the fittest and optimal reproduction of plants in terms of numbers as well as the fittest. This can be treated as an optimization process of

Common branch vectors	Prohibited group vectors	Islanded principal nodes
$CB_{13} = [s33]$	$PG_6 = [CB_{14}CB_{15}CB_{45}]$	6
$CB_{14} = [s6\ s7]$	$PG_8 = [CB_{13}CB_{14}CB_{35}]$	8
$CB_{15} = [s3\ s4\ s5]$	$PG_9 = [CB_{23}CB_{24}CB_{34}]$	9
$CB_{23} = [s9\ s10\ s11]$	$PG_{68} = [CB_{13}CB_{15}CB_{34}CB_{45}]$	6, 8
$CB_{24} = [s34]$	$PG_{89} = [CB_{13}CB_{14}CB_{23}CB_{24}]$	8, 9
$CB_{34} = [s8]$	$PG_{689} = [CB_{13}CB_{15}CB_{23}CB_{24}CB_{45}]$	6, 8, 9
$CB_{45} = [s25\ s26\ s27\ s28]$	—	—

TABLE 1. Common branch and prohibited group vectors of 33-bus system

plant species. Biotic and cross-type pollination occurs between flowers that are distant from each other. Pollinating agents, such as insects and birds, follow the Levy flight movement, with step size obeying Levy distribution, and this process can be modeled as global optimization in the optimization algorithm. Abiotic and self-pollinations can be thought of as local optimization since it occurs in the same flower/plant.

The FPA [28, 29] was developed based on the concept of pollination in the flowers of plants. The following rules are employed to mimic the pollination characteristics of flowers.

Rule 1. Biotic and cross-pollination are to be considered as global pollination processes, and pollen is carried by insects and birds obeying Levy flight movement.

Rule 2. Abiotic and self-pollination are to be treated as a local pollination process.

Rule 3. Pollinators can develop flower constancy, which is like reproduction probability, proportional to the similarity of the two flowers involved.

Rule 4. A probability factor $P \in [0, 1]$ decides the switching from local pollination to global pollination or *vice versa*. It should be slightly biased toward local pollination.

For implementation of the FPA, the above rules are converted into updating equations.

During global pollination, pollen grains are carried by pollinators over a long range; therefore, Rule 1 and flower constancy can be mathematically expressed as

$$S_i^{G+1} = S_i^G + \gamma L(\lambda) (S_i^G - S_{gbest}), \quad (4)$$

where S_i^{G+1} is the solution vector (pollen) S_i^G in generation G , S_{gbest} is the current best solution, and γ is a scaling factor to control the step size. $L(\lambda)$, which mimics the Levy flight, corresponds to the strength of the pollination, which is also the step size.

$L > 0$ is drawn from a Levy distribution:

$$L \cong \frac{\lambda \Gamma(\lambda) \sin(\frac{\pi\lambda}{2})}{\pi} \frac{1}{s^{1+\lambda}} (s \gg s_0 > 0). \quad (5)$$

Here, $\Gamma(\lambda)$ is the standard gamma distribution valid for large steps, $s > 0$, $\lambda = 1.5$.

To model local pollination, both Rules 2 and 3 are represented as

$$S_i^{G+1} = S_i^G + \varepsilon (S_j^G - S_k^G), \quad (6)$$

where S_j^G and S_k^G are pollen from different flowers of the same plant species in a limited neighborhood. Mathematically, S_j^G and S_k^G come from the same species or are selected from the same population, which is equivalent to a local random walk if ε is drawn from a uniform distribution in $[0, 1]$.

Pollination occurs in a local as well as global scale. Flowers are more likely to be pollinated by a local flower's pollen than from a distant flower. To simulate such behavior, switch probability P (Rule 4) is used to switch between local pollination and global pollination. It has been proved that for $P = 0.8$, the algorithm works better for most applications [28].

5. PROPOSED METHODOLOGY

Distribution load flow plays an important role in evaluating a solution for network reconfiguration and/or capacitor placement. Distribution networks are generally radial, and the R/X ratio is very high. Hence, conventional load flow methods are inefficient at solving such ill-conditioned distribution networks. The distribution load flow algorithm proposed in [30] is used in this article.

Using loops present in the system, feasible combinations of tie-switches are generated prior to the optimization process. To ensure radial configuration of the system and to avoid islanding of interior and exterior nodes, the strategy proposed in [31] is used to generate feasible combinations. Thus, the search space for reconfiguration of the system is reduced manifold. The feasible tie combinations are generated and arranged randomly in the “*comb*” vector and made available for the MFPA. $[NC \times T]$ is the order of the *comb* matrix, where NC is the total number of feasible combinations and T is the number of tie-switches in the network.

Item	Load levels		
	Light (0.75)	Normal (1.0)	Heavy (1.25)
33-Bus RDS			
Base case loss (kW)	109.75	202.66	329.79
Switches opened	s6-s14-s11-s36-s37	s7-s14-s9-s36-s37	s7-s14-s9-s36-s37
Nodes	30 31 17	28 29 30	28 6 29
Capacitor banks	550 150 150	200 200 550	250 150 1200
Total kVAR	850	950	1600
Total cost (\$)	36,017	60,105	97,434
P_{Loss} (kW)	56.90	101.77	163.11
V_{min} (p.u.) (node)	0.9667 (18)	0.9544 (18)	0.9425 (18)
Loss reduction (%)	48.15	51.75	50.54
Cost reduction (%)	43.15	52.04	52.87
69-Bus RDS			
Base case loss (kW)	121.02	224.98	369.02
Switches opened	s9-s12-s60-s43-s16	s10-s68-s60-s44-s15	s10-s13-s60-s41-s68
Nodes	61	64 63 62	64 63 62
Capacitor banks	650	350 600 250	550 350 500
Total kVAR	650	1200	1400
Total cost (\$)	30,353	54,131	83,885
P_{Loss} (kW)	50.39	88.03	141.72
V_{min} (p.u.) (node)	0.9666 (61)	0.9580 (61)	0.9461 (61)
Loss reduction (%)	58.36	60.87	61.59
Cost reduction (%)	60.38	62.21	67.30
118-Bus RDS			
Base case loss (kW)	697.29	1298.06	2134.40
Switches opened	s48-s26-s23-s39-s122-s59-s45-s125-s71-s73-s97-s129-s130-s109-s34	s48-s26-s23-s40-s122-s56-s45-s95-s71-s74-s97-s129-s130-s109-s34	s48-s26-s120-s39-s122-s59-s45-s125-s126-s73-s97-s129-s130-s109-s34
Capacitor banks (nodes)	500 (110) 500 (70) 300 (75) 500 (118) 450 (74) 450 (86) 150 (87) 300 (81) 200 (88)	850 (110) 200 (117) 550 (56) 650 (70) 300 (116) 150 (68) 550 (36) 1000 (75) 250 (69) 1000 (91) 450 (96) 300 (118) 1200 (38)	150 (23) 1200 (78) 1200 (110) 1200 (35) 1100 (70) 650 (117) 1200 (89) 1200 (24) 150 (116) 150 (18) 1200 (79) 150 (68) 1200 (20)
Total kVAR	3350	7450	10,750
Total cost (\$)	234,646	381,842	724,195
P_{Loss} (kW)	403.95	640.28	1240.73
V_{min} (p.u.) (node)	0.9561 (40)	0.9529 (41)	0.9080 (39)
Loss reduction (%)	42.06	50.67	41.86
Cost reduction (%)	41.65	49.43	41.49

TABLE 2. Performance analysis of 33-, 69-, and 118-bus RDSs at different load levels

The efficient methodology suggested in [32] is utilized to reduce the search space of the capacitor placement problem. Loss sensitivity factor ($\partial P_{line loss} / \partial Q_{effective}$) is derived for each bus, and buses are sorted in descending order of loss sensitivity factors to decide the sequence of buses for placing capacitor bank. Normalized voltage magnitude “norm” is calculated at the corresponding buses and buses for which norm values greater than 1.01 are considered for compensation.

5.1. MFPA

To enhance the local searching and global searching abilities, the FPA is modified as follows. Two optimization strategies have been applied to the basic FPA: the local neighborhood searching strategy (LNSS) [33] and the dynamic switching probability strategy (DSPS) [34].

The FPA uses a differential evolution (DE) algorithm to do a local search, which has limited local searching ability.

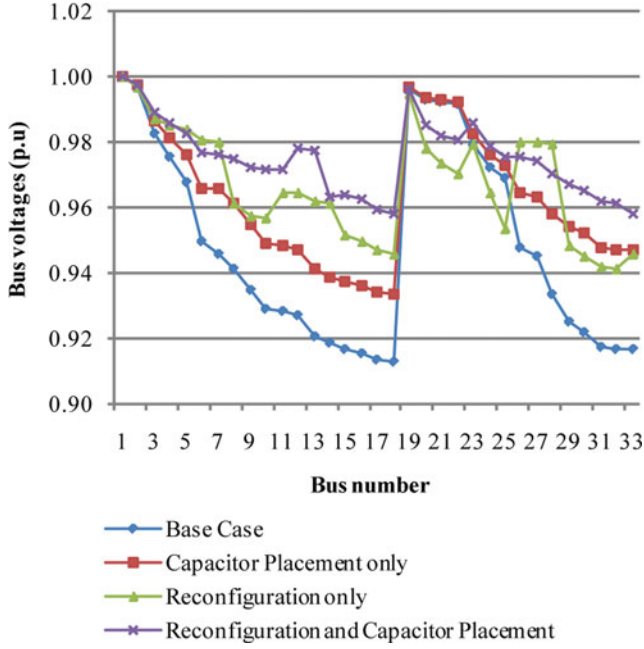


FIGURE 2. Voltage profile comparison of 33-bus system for different scenarios.

Thus, LNSS is employed for the local pollination process to enhance its exploitation ability. Each S_i^G ($i = 1, 2, 3, \dots, NP$) is a parameter vector with dimension D . Each vector subscript index is randomly divided to ensure the diversity of each neighborhood. For each vector S_i^G , a neighborhood of radius k (subject to $2k + 1 < NP$) is defined. The neighborhood vector of $S_i^G = [S_{i-k}^G, \dots, S_i^G, \dots, S_{i+k}^G]$.

Local pollination is given by

$$S_i^{G+1} = S_i^G + \alpha (S_{n_{best,i}}^G - S_i^G) + \beta (S_p^G - S_q^G), \quad (7)$$

where

$i \in (1, NP)$,

NP is the number of flowers in the population,

G is the current generation/iteration number,

$S_{n_{best,i}}^G$ is the best solution vector in the neighborhood vector of S_i^G , and

$p, q \in (i - k, i + k); p \neq q$.

A better optimization algorithm is supposed to do more global searches during the initial generations and more local searches as it proceeds toward the end. Hence, instead of having constant switching probability P , DSPS is employed to adjust the proportion of both searches. Dynamic switching probability (DSP) for the current generation G is given by

$$P^G = P - 0.1 \times \frac{(N_{iter} - G)}{N_{iter}}, \quad (8)$$

where N_{iter} is the total number of iterations.

The proposed solution methodology based on the MFPA for simultaneous network reconfiguration and capacitor placement is now given.

Step 1: Read the system configuration (line data, load data, tie-switches, and combination vector (*comb*)) of the RDS.

Step 2: Perform base case load flow to calculate power loss and node voltages.

Step 3: Get MFPA parameters N_{iter} (number of iterations), P (self-pollination probability), NP (number of flowers in a population), K (radius of the local neighborhood), and NSB (number of candidate buses for capacitor placement).

Step 4: Generate initial population of flowers S ; the structure of S is

$$S_i^G = comb_i \text{ kVAR}_1, \text{ kVAR}_2, \dots, [\text{ kVAR}_{NSB},] \quad (9)$$

where $comb_i$ is the integer representing an element in the *comb* vector, and kVAR_{sb} is the kVAR value of capacitor placed at sensitive bus *sb*.

Step 5: Evaluate solution S^G in the current population for fitness value f .

Step 6: Find the best fitness value $f_{g_{best}}$ and the corresponding solution $S_{g_{best}}$.

Step 7: Get the probability value for current generation P^G using Eq. (8).

Step 8: Pick up solution S_i^G and generate random number P_1 in the uniform interval (0, 1).

Step 9: If $P_1 > P^G$, go to Step 12.

Step 10: Else, form a local neighborhood with radius K for the current solution from the population in generation G .

Step 11: Do self-pollination using Eq. (7), find next generation solution S_i^{G+1} , and go to Step 14.

Step 12: Draw one-dimensional step vector L , which obeys the Levy distribution; the order of L is $((NSB + 1) \times 1)$.

Step 13: Do global pollination using Eq. (4) and find next generation solution S_i^{G+1} .

Step 14: Round off $comb_i$ in solution S_i^{G+1} , evaluate the solution to get fitness value fit , and store corresponding solution sol .

Step 15: Apply greedy selection between S_i^G and S_i^{G+1} and update S_i^{G+1} .

Step 16: Update $f_{g_{best}}$ and $S_{g_{best}}$ if current fitness fit is better than $f_{g_{best}}$.

Step 17: Repeat Steps 8 to 16 for all solutions in current generation G .

Step 18: Repeat Steps 7 to 17 N_{iter} times.

Step 19: Print the global fitness value and global best solution $f_{g_{best}}$ and $S_{g_{best}}$, respectively.

Parameters	SA [25]	HSA [25]	IBPSO [26]	MFPA
Scenario 1				
Switches opened	s7-s14-s9-s32-s37	s33-s14-s8-s32-28	s7-s14-s9-s32-s37	s7-s14-s9-s32-37
P_{Loss} (kW)	142.60	137.78	139.55	139.54
V_{min} (p.u.) (node)	0.9294 (32)	0.9301 (32)	0.9378 (32)	0.9378 (32)
Loss reduction (%)	29.63	32.02	31.14	31.14
Cost reduction (%)	31.83	32.07	33.06	33.06
Scenario 2				
Capacitor banks (nodes)	1050 (6) 450 (28) 300 (29) 300 (30)	900 (6) 300 (28) 600 (29) 300 (30)	900 (2) 300 (4) 300 (15) 300 (23) 300 (25) 600 (31) 600 (32)	750 (6) 150 (28) 850 (29)
Total kVAR	2100	2100	3300	1750
P_{Loss} (kW)	136.11	135.16	140.40	139.57
V_{min} (p.u.) (node)	0.9301	0.9379	0.9402	0.9302
Loss reduction (%)	32.84	33.33	30.72	31.13
Cost reduction (%)	18.46	18.85	16.82	14.94
Scenario 3				
Switches opened	s7-s14-s9- s32-37	s33-s14-s8-s32-s28	s7-s9-s14- s32-37	s7-s14-s9-s36-s37
Capacitor bank (node)	1050 (6) 450 (28) 300 (29) 300 (30) 150 (9)	900 (6) 300 (28) 600 (29) 300 (30) 300 (9)	600 (7) 300 (12) 300 (25) 600 (30) 300 (33)	200 (28) 200 (29) 550 (30)
Total kVAR	2050	2400	2100	950
P_{Loss} (kW)	124.29	119.72	93.06	101.77
V_{min} (p.u.) (node)	0.9399	0.9411	0.9585	0.9544
Loss reduction (%)	38.67	40.92	54.08	51.75
Total cost (\$)	78,678	78,325	62,092	60,105
Cost reduction (%)	37.22	37.50	50.45	52.04

TABLE 3. Comparison of results of 33-bus RDS

6. TEST RESULTS

To demonstrate the applicability and efficiency of the proposed methodology in solving the network reconfiguration and capacitor placement simultaneously using the MFPA, it has been applied to three test systems available in the literature. The following three scenarios are investigated at three different load levels.

1. Only network reconfiguration;
2. Only capacitor placement; and
3. Simultaneous network reconfiguration and capacitor placement.

The loads are treated as constant power loads, and a design period of 1 year is taken for the purpose of analysis. A depreciation factor of 20% is applied to the installation and purchase cost of capacitor banks. The following parameters are used in the objective function [1]: energy cost of losses, $K_e = \$0.06/\text{kWh}$; purchase cost of capacitor, $K_c = \$25/\text{kVAR}$; installation cost, $K_{ins} = \$1600/\text{location}$; operating cost, $K_{ope} = \$300/\text{year/location}$. The lower and upper voltage limits are assumed to be 0.95 and 1.05 p.u., respectively. A significant

value is given to penalty factor pf , which will make the optimization algorithm move away from the undesirable solution. The proposed algorithm has been run on MATLAB platform (The MathWorks, Natick, Massachusetts, USA) installed in a Pentium dual core, 2.7-GHz personal computer (Dell, India).

6.1. Numerical Results of 33-bus RDS

The test system has 32 sectionalizing switches and 5 tie-switches. The single-line diagram is shown in Figure 1. The data of the system are obtained from [4]. Total real and reactive power loads on the system are 3715 kW and 2300 kVAR, respectively. The system operating voltage is 12.66 kV. The loop vectors are $L_1 = [s2\ s3\ s4\ s5\ s6\ s7\ s33\ s20\ s19\ s18]$, $L_2 = [s9\ s10\ s11\ s12\ s13\ s14\ s34]$, $L_3 = [s8\ s9\ s10\ s11\ s35\ s21\ s33]$, $L_4 = [s25\ s26\ s27\ s28\ s29\ s30\ s31\ s32\ s36\ s17\ s16\ s15\ s34\ s8\ s7\ s6]$, and $L_5 = [s22\ s23\ s24\ s37\ s28\ s27\ s26\ s25\ s5\ s4\ s3]$. Common branch vectors, prohibited group vectors, and islanded principal nodes of the 33-bus system are formed using the graph theory and are tabulated in Table 1. The *comb* vector formed is of the order $(50,751 \times 5)$. Iteration parameters used are $N_{iter} = 50$, $NP = 25$, and $P = 0.8$. Total number of evaluations is $25 \times 50 = 1250$. The system is analyzed at

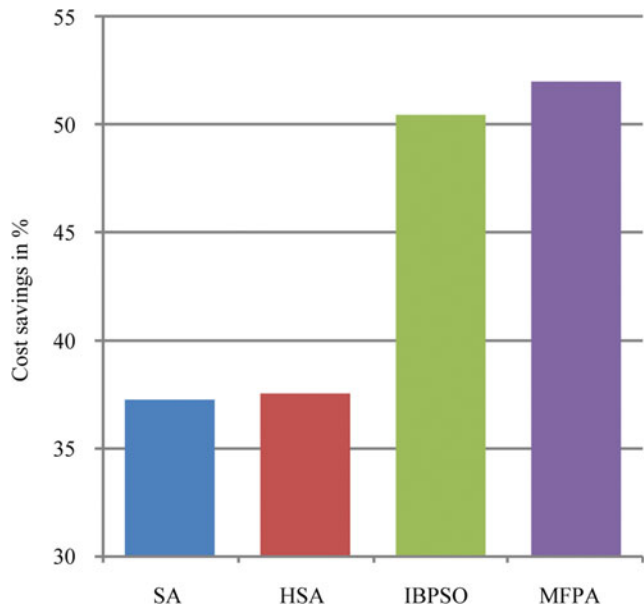


FIGURE 3. Cost saving comparison of 33-bus RDS.

different load levels. The detailed results of the 33-bus system for various load levels are given in Table 2. The results during nominal load condition are discussed in what follows. The base case loss is 202.66 kW. After reconfiguration and capacitor placement, power loss is 101.77 kW. The loss reduction by proposed method is 51.75%. From the comparison of results it can be found that the MFPA gives the highest cost

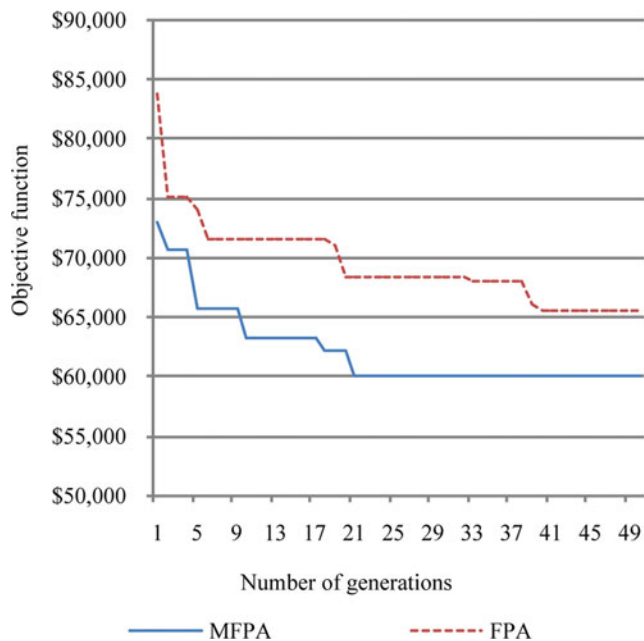


FIGURE 4. Convergence characteristics of FPA and MFPA for 33-bus system.

Best cost (\$)	60,105
Worst cost (\$)	63,778
Average cost (\$)	61,630
Standard deviation	1,329
Average cost reduction (%)	50.83
Number of generations	50
Average time elapsed (sec)	13.07

TABLE 4. Statistical results of 33-bus RDS with 100% loading condition (for100 runs)

saving of 52.04%. The number of capacitor banks is three, with net reactive power injection of 950 kVAR. Hence, cost saving per kVAR injected is high in the proposed method. Operating cost of base case system is \$125,324, whereas it is \$60,105 in the optimal system. The overall cost saving is \$65,219/year. It is found that the minimum voltage has been improved from 0.9131 to 0.9544 p.u. Figure 2 shows the voltage profile comparison of the system in different scenarios. The results of the proposed methodology are compared with the HSA [25], SA [25], and IBPSO [26] in Table 3. The proposed approach gives a maximum cost saving of 52.04% when compared to other methods, as shown in Figure 3. A comparison of convergence characteristics of the objective function using the MFPA with FPA for the 33-bus system is shown in Figure 4. It is found that the MFPA gives better convergence than the FPA. Statistical results of 33-bus RDS with 100% loading condition (for 100 runs) has been presented in Table 4.

6.2. Numerical Results of 69-bus Radial Distribution Test System

The line and load data for the 69-bus system is obtained from [27]. The test system has 68 sectionalizing switches and 5 tie-switches. The system voltage rating is 12.66 kV. The comb vector formed has the order of (272,616 × 5). Iteration parameters used are $N_{iter} = 50$, $NP = 25$, and $P = 0.8$. Total number of evaluations is $25 \times 50 = 1250$. The proposed methodology is applied to the system at various load levels, and the results are tabulated in Table 2. The results during nominal load condition are discussed in what follows. The base case loss is 224.98 kW. After reconfiguration and capacitor placement, power loss is 88.03 kW. The loss reduction by the proposed method is 60.87%, and the saving in cost is \$89,135/year, which accounts to a cost saving of 62.21%.

6.3. Numerical Results of 118-bus Radial Distribution Test System

This is a large-scale distribution system. The line and load data for the 118-bus system are obtained from [35]. The single-line diagram of the system is shown in Figure 5. The system has

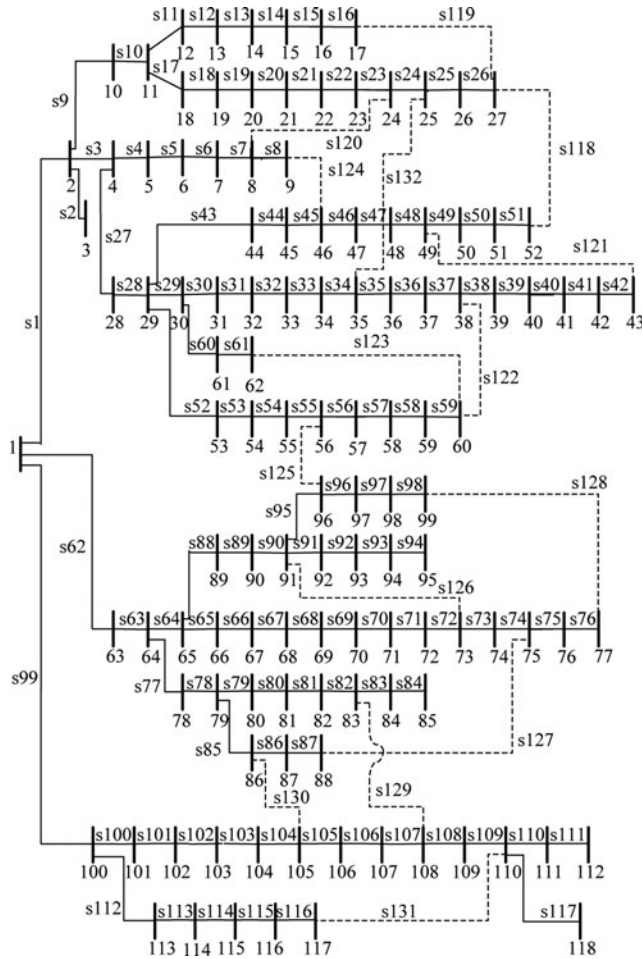


FIGURE 5. Single-line diagram of 118-bus RDS (bus and line numbers reordered).

118 buses, 117 sectionalizing switches, and 15 tie-switches. For proper analysis of the system, the bus and line numbers are reordered. Iteration parameters used are $N_{iter} = 50$, $NP = 50$, and $P = 0.8$. Total number of evaluations is $50 \times 50 = 2500$. The proposed methodology is applied to the system at various load levels, and the results are tabulated in Table 2. The base case loss of the system is 1298.06 kW with a total cost of \$755,110/year. After reconfiguration and capacitor placement, power loss and total cost are 640.28 kW and \$381,842, respectively. The loss reduction by the proposed method is 50.67%, and cost saving is 49.43%.

7. CONCLUSION

This work presents a combined network reconfiguration and capacitor placement algorithm for minimizing the total cost of energy losses and capacitor installation using the MFPA. The

convergence characteristics of the MFPA indicate its searching ability. The proposed approach is studied under three different scenarios for the 33-bus system, and it is found that the combined reconfiguration and capacitor placement (scenario 3) gives better cost and loss reduction. Voltage profile of the system is also better than the other scenarios. The combined optimization through the proposed algorithm is also tested on 69-bus and 118-bus systems, and results are provided. The results indicate considerable reduction in cost of operating the systems.

REFERENCES

- [1] El-Fergany, A. A., and Abdelaziz, A.Y., "Artificial bee colony algorithm to allocate fixed and switched static shunt capacitors in radial distribution networks," *Electr. Power Compon. Syst.*, Vol. 42, No. 5, pp. 427–438, 2014.
- [2] Ababei, C., and Kavasseri, R., "Efficient network reconfiguration using minimum cost maximum flow-based branch exchanges and random walks-based loss estimations," *IEEE Trans. Power Syst.*, Vol. 26, No. 1, pp. 30–37, February 2011.
- [3] Civanlar, S., Grainger, J. J., Yin, H., and Lee, S. S. H., "Distribution feeder reconfiguration for loss reduction," *IEEE Trans. Power Del.*, Vol. 3, No. 3, pp. 1217–1223, July 1988.
- [4] Baran, M. E., and Wu, F. F., "Network reconfiguration in distribution systems for loss reduction and load balancing," *IEEE Trans. Power Del.*, Vol. 4, No. 2, pp. 1401–1407, April 1989.
- [5] Su, C.-T., Chang, C.-F., and Chiou, J.-P., "Distribution network reconfiguration for loss reduction by ant colony search algorithm," *Electr. Power Syst. Res.*, Vol. 75, No. 1, pp. 190–199, August 2005.
- [6] Das, D., "A fuzzy multiobjective approach for network reconfiguration of distribution systems," *IEEE Trans. Power Del.*, Vol. 21, No. 1, pp. 202–209, January 2006.
- [7] Cheng, H.-C., and Kou, C.-C., "Network reconfiguration in distribution systems using simulated annealing," *Electr. Power Syst. Res.*, Vol. 29, pp. 227–238, May 1994.
- [8] Hong, Y.-Y., and Ho, S.-Y., "Determination of network configuration considering multiobjective in distribution systems using genetic algorithms," *IEEE Trans. Power Syst.*, Vol. 20, No. 2, pp. 1062–1069, May 2005.
- [9] Wang, C., and Cheng, H. Z., "Optimization of network configuration in large distribution systems using plant growth simulation algorithm," *IEEE Trans. Power Syst.*, Vol. 23, No. 1, pp. 119–126, February 2008.
- [10] Kumar, K. S., and Jayabharathi, T., "Power system reconfiguration and loss minimization for distribution systems using bacterial foraging optimization algorithm," *Int. J. Electr. Power Energy Syst.*, Vol. 36, No. 1, pp. 13–17, March 2012.
- [11] Imran, A. M., and Kowsalya, M., "A new power system reconfiguration scheme for power loss minimization and voltage profile enhancement using fireworks algorithm," *Int. J. Electr. Power Energy Syst.*, Vol. 62, No. 1, pp. 312–322, November 2014.

- [12] Ng, H. N., Salama, M. M. A., and Chikhani, A. Y., "Classification of capacitor allocation techniques," *IEEE Trans. Power Del.*, Vol. 15, No. 1, pp. 387–392, January 2000.
- [13] Chang, N. E., "Locating shunt capacitors on primary feeder for voltage control and loss reduction," *IEEE Trans. Power Apparatus Syst.*, Vol. 88, No. 10, pp. 1574–1577, October 1969.
- [14] Bae, Y. G., "Analytical method of capacitor allocation on distribution primary feeders," *IEEE Trans. Power Apparatus Syst.*, Vol. 97, No. 4, pp. 1232–1238, July/August 1978.
- [15] Duran, H., "Optimum number, location, and size of shunt capacitors in radial distribution feeders, a dynamic programming approach," *IEEE Trans. Power Apparatus Syst.*, Vol. 87, No. 9, pp. 1769–1774, September 1968.
- [16] Fawzi, T. H., El-Sobki, S. M., and Abdel-Halim, M. A., "New approach for the application of shunt capacitors to the primary distribution feeders," *IEEE Trans. Power Apparatus Syst.*, Vol. 102, No. 1, pp. 10–13, January 1983.
- [17] Abdel-Salam, T. S., Chikhani, A. Y., and Hackam, R., "A new technique for loss reduction using compensating capacitors applied to distribution systems with varying load condition," *IEEE Trans. Power Del.*, Vol. 9, No. 2, pp. 819–827, April 1994.
- [18] Chis, M., Salama, M. M. A., and Jayaram, S., "Capacitor placement in distribution systems using heuristic search strategies," *IEEE Proc. Gener. Transm. Distrib.*, Vol. 144, No. 3, pp. 225–230, May 1997.
- [19] Anandhapadmanabha, T., Kulkarni, A. D., Rao, A. S. G., Rao, K. R., and Parthasarathy, K., "Knowledge-based expert system for optimal reactive power control in distribution system," *Electr. Power Energy Syst.*, Vol. 18, No. 1, pp. 27–31, 1996.
- [20] Santoso, N. I., and Tan, O. T., "Neural-net based real-time control of capacitors installed on distribution systems," *IEEE Trans. Power Del.*, Vol. 5, No. 1, pp. 266–272, January 1990.
- [21] Chin, H. C., "Optimal shunt capacitor allocation by fuzzy dynamic programming," *Electr. Power Syst. Res.*, Vol. 35, No. 1, pp. 133–139, 1995.
- [22] Sundhararajan, S., and Pahwa, A., "Optimal selection of capacitors for radial distribution systems using a genetic algorithm," *IEEE Trans. Power Syst.*, Vol. 9, No. 3, pp. 1499–1507, August 1994.
- [23] Chang, C.-F., "Reconfiguration and capacitor placement for loss reduction of distribution systems by ant colony search algorithm," *IEEE Trans. Power Syst.*, Vol. 23, No. 4, pp. 1747–1755, November 2008.
- [24] Farahani, V., Vahidi, B., and Abyaneh, H. A., "Reconfiguration and capacitor placement simultaneously for energy loss reduction based on an improved reconfiguration method," *IEEE Trans. Power Syst.*, Vol. 27, No. 2, pp. 587–595, May 2012.
- [25] Rao, R. S., "An hybrid approach for loss reduction in distribution systems using harmony search algorithm," *Int. J. Electr. Electron. Eng.*, Vol. 4, No. 7, pp. 461–467, 2010.
- [26] Sedighzadeh, M., Dakhem, M., Sarvi, M., and Kordkheili, H. H., "Optimal reconfiguration and capacitor placement for power loss reduction of distribution system using improved binary particle swarm optimization," *Int. J. Energy Environ. Eng.*, Vol. 5, No. 3, pp. 1–11, 2014.
- [27] Chandramohan, S., Atturulu, N., Devi, R. P. K., and Venkatesh, B., "Operating cost minimization of a radial distribution system in a deregulated electricity market through reconfiguration using NSGA method," *Int. J. Electr. Power Energy Syst.*, Vol. 32, No. 1, pp. 126–132, February 2010.
- [28] Yang, X.-S., "Flower pollination algorithm for global optimization," *Unconvent. Computat. Natural Computat. LNCS*, Vol. 7445, No. 1, pp. 240–249, 2012.
- [29] Yang, X.-S., Karamanoglu, M., and He, X., "Multi-objective flower algorithm for optimization," *Proc. Int. Comput. Sci. (ICCS 2013)*, Vol. 18, No. 1, pp. 861–868, 2013.
- [30] Teng, J.-H., "A direct approach for distribution system load flow solutions," *IEEE Trans. Power Del.*, Vol. 18, No. 3, pp. 882–887, July 2003.
- [31] Swarnkar, A., Gupta, N., and Niazi, K. R., "Minimal loss configuration for large-scale radial distribution systems using adaptive genetic algorithms," *16th National Power Systems Conference*, pp. 647–652, Hyderabad, India, 15–17 December 2010.
- [32] Prakash, K., and Sydulu, M., "Particle swarm optimization based capacitor placement on radial distribution systems," *IEEE Power Engineering Society General Meeting*, pp. 1–5, Tampa, FL, 24–28 June 2007.
- [33] Das, S., Abraham, A., Chakraborty, U. K., and Konar, A., "Differential evolution using a neighborhood-based mutation operator," *IEEE Trans. Evolut. Computat.*, Vol. 13, No. 3, pp. 526–553, 2009.
- [34] Wang, R., and Zhou, Y., "Flower pollination algorithm with dimension by dimension improvement," *Math. Prob. Eng.*, Vol. 2014, No. 1, pp. 1–9, 2014.
- [35] Zhang, D., Fu, Z., and Zhang, L., "An improved tabu search algorithm for loss minimum reconfiguration in large-scale distribution systems," *Electr. Power Syst. Res.*, Vol. 77, No. 6–7, pp. 685–694, 2007.

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