



Optimal Placement and Sizing of Capacitors in Radial Distribution Systems: A Two-Stage Method

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Authors' contributions

This work was carried out in collaboration among all authors. Author SAS designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors AAB, SOA and HAA made their necessary inputs, adjusted the manuscript and provided an enabling environment for the completion of this paper. All authors read and approved the final manuscript.

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ABSTRACT

Optimal allocation of shunt capacitors in the radial distribution networks results in both technical and economic benefits. This paper presents a two-stage method of Loss Sensitivity Factor (LSF) and Cuckoo Search Algorithm (CSA) to find the optimal size and location of shunt capacitors with the objective of minimizing cost due to power loss and reactive power compensation of the distribution networks.

The first stage utilizes the LSF to predict the potential candidate buses for shunt capacitor placement thereby reducing the search space of the second stage and avoiding unnecessary repetitive load flow while the second stage uses the CSA to find the size and actual placement of the shunt capacitors satisfying the operating constraints.

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The applicability of the proposed two stage method is tested on the standard IEEE 33-bus and Ayepe 34-bus Nigerian radial distribution networks of the Ibadan Electricity Distribution Company. After running the algorithm, the simulation results gave percentage real and reactive power loss reduction of 34.28% and 28.94% as compared to the base case for the IEEE 33-bus system while the percentage real and reactive power loss reduction of 22.89% and 21.40% was recorded for the Ayepe 34-bus system.

Comparison of the obtained results with other techniques in literatures for the standardized IEEE 33-bus reveals the efficiency of the proposed method as it achieved technical benefits of reduced total power loss, improved voltage profile and bus voltage stability, and the economic benefit of reduced total cost due to electrical power loss and compensation.

Keywords: Radial distribution system; power loss reduction; voltage profile; voltage stability index; loss sensitivity factors; cuckoo search algorithm.

ABBREVIATIONS

OF_{min} ; Objective Function
 w_c ; weighing coefficient for overall annual cost (f_c)
 w_v ;weighing coefficient for VSI
 w_Q ; weighing coefficient for the total reactive power loss
 f_c ; overall annual cost
 f_v ; objective function for improving VSI
 f_Q ; objective function for reactive power loss
 P_{Tloss} ; the total power losses
VSI; Voltage Stability Index
 VSI_{min} ;minimum VSI
 k_p ;the annual cost per unit of power losses (\$/kW)
 C_{inst} ;installation cost in \$
N ; total number of candidate buses for capacitor placement
 C_{cap} ;purchase cost of capacitor
 Q_{cn} ;shunt capacitor placed at bus n
 C_{ope} ;operating cost of the capacitor
 VSI_{min} ;minimum VSI
I;branch current magnitude
X–reactance of branch
 Q_{min} ;minimum compensation limit
 Q_{max} ;maximum compensation limit
 V_{min} ;minimum voltage limit in p.u.
 V_{max} ;maximum voltage limit in p.u.
 Q_{total} ;total reactive load
V;voltage in p.u.
i ; sending node
I+1;receiving node
P;real power
Q;reactive power
R;resistance
X; reactance
 Q_c ;reactive power of capacitor
LSF ;loss sensitivity factor
 P_{eff} ; total effective active power supplied beyond the bus 'i'

Q_{eff} ;total effective reactive power supplied beyond the bus 'i'
 $P_{L(loss)}$; real power loss
CSA ;Cuckoo Search Algorithm
n ;number of nest
 α ;step size
 p_a ;probability to discover foreign eggs
X ; solution vector
 P_{Tloss} ; total real power losses
 V_{bus} ;voltage at each bus
FF;fitness function

1. INTRODUCTION

Due to the high resistance to reactance of Radial Distribution Networks (RDN) [1], it is associated with numerous technical and inevitable operational problems such as high voltage drops, low voltage stability, bad quality and reliability of power delivered to the end consumers, and, as the main challenge, high power losses. Consequently, the largest power loss portion among the three power system, which are generation, transmission, and distribution section, occurs at the distribution level which constitute about 13% of the total power generation [2]. These aforementioned problems have negative impact on the economic and effectiveness of the overall power system. Hence, many efforts have been made by researchers to significantly reduce the losses in the distribution networks. The capacitor placement is among the efforts used to mitigate this problem.

The application of shunt capacitor in radial distribution network supplies a part of the reactive power demands and can invariably reduce a portion power losses of the distribution system. The benefits of capacitor placement in distribution systems are power factor correction, bus voltage regulation, improved voltage stability index, power and energy loss reduction, feeder

and system capacity release as well as power quality improvement [3]. The extent of the aforementioned advantages of capacitor placement depends on how capacitors are allocated as wrong placement and sizing may result in further power losses and other disadvantages. This means that the optimization, namely, capacitor placement problem should be formulated with the desired objective function and other technical constraints (such as the limits of voltage levels and power flow). After that, the proper optimization techniques should be applied simultaneously determine the optimal number, location, type and size of the capacitors to be installed [4].

Several optimization techniques have been employed for solving optimal capacitors allocation problem such as analytical, classical/numerical, heuristic/meta-heuristic and artificial intelligence methods. Rao *et al.* (2011) proposed a Loss Sensitivity Factors (LSFs) and Plant Growth Simulation Algorithm (PGSA) which is free from parameter tuning is proposed for optimal capacitor sizing with the objective of power loss minimization. The proposed method was tested on 10, 34 and 85 bus radial distribution systems. The results show a considerable reduction in the total power loss in the systems [5]. Analytical method based on Voltage Stability Index (VSI) and fuzzy-real coded Genetic Algorithm for optimal capacitors sizing have been performed by Abdul' Wafaet *al.* (2014) with the objective of minimizing power losses and total cost. The applicability of the method was verified using the IEEE 33-bus distribution network. It was revealed that the proposed method was is effective foe achieving maximum net money savings on power/energy loss and capacitor banks expenditure [6].

A combination of LSF, VSI and Bacterial Foraging Optimization Algorithm (BFOA) for optimal location and sizing of capacitor in radial distribution system in a load changing environment was proposed by Devabalaji *et al.* (2015) with the objective of power loss minimization. The proposed methodology was tested on IEEE 34-bus and 85-bus radial systems and test result indicated significant power loss reduction [7]. Shuaib *et al.* (2015) proposed Loss Sensitivity Factor (LSF) which reduces the search space and to attain at the accurate location for capacitor banks and Gravitational Search Algorithm (GSA) is used for the optimal capacitors size with the objective of minimization of power loss and maximization of net savings. The applicability of the proposed

method was tested on IEEE 33 and 69-bus radial systems [8]. The results revealed that the proposed method is effective in minimizing the power loss and maximizing the net savings. El-Ela *et al.* (2018) proposed a water cycle algorithm for simultaneous optimal allocation of capacitors and Distributed Generation units with the objective of minimizing the power losses, total energy cost and total emissions. The proposed method was tested on IEEE 33 and 69 radial systems [9]. Salimonet *al.* (2020) proposed Cuckoo Search Algorithm for optimal placement and sizing of capacitors on radial distribution system with the objective of minimizing the total annual cost due to network power losses and reactive power compensation. The applicability of the proposed method was verified on the IEEE 33-bus and Nigerian Ayepe 34-bus radial systems. The results demonstrated that the proposed method was capable of saving significant amount of total annual cost, reduce total power losses and attain improvement in voltage profile and stability [10].

This paper uses a two-stage method to solve the problem of capacitor bank allocation. The first stage uses the LSFs to predict the potential buses for reactive compensation and this greatly reduces the search space of the optimization algorithm while the second stage uses the Cuckoo Search Algorithm to obtain the exact bus locations and optimal sizes of the capacitor banks on IEEE 33-bus and Nigerian radial distribution systems.

2. METHODOLOGY

2.1 Problem Formulation

The recommended objective of this work is formulated using the weight method as given below:

$$OF_{min} = w_c f_c + w_v f_v + w_Q f_Q \quad (1)$$

In this study, w_c is taken as 0.6 while w_v and w_Q are both taken as 0.2.

The first objective function, f_c is the overall annual cost due to total power loss and the reactive power compensation. The cost of reactive power compensation includes purchase, installation and cost of capacitors. f_c is given as:

$$f_c = K_p \times P_{Tloss} + \alpha[(C_{inst} \times N) + C_{cap} \sum_{i=1}^N Q_{ci}] + (C_{ope} \times N) \quad (2)$$

Where P_{loss} is the total power losses, where K_p is the annual cost per unit of power losses (\$/kW), C_{inst} is installation cost, N is the total number of

candidate buses for capacitor placement, C_{cap} is the purchase cost of capacitor, Q_{cn} is the shunt capacitor size placed at bus n and C_{ope} is the operating cost of the capacitor.

The second objective function, f_v is obtained by taking the inverse of voltage stability index of the bus with the minimum value. The VSI is given by [11]:

$$VSI_{(i+1)} = |V_i|^4 - 4[P_{i+1}R_{i+1} + Q_{i+1}X_i] |V_{i+1}|^2 - 4[P_{i+1}R_{i+1} + Q_{i+1}X_{i+1}]^2 \quad (3)$$

The index is modified to become an objective function for improving VSI, as follows:

$$f_v = \frac{1}{VSI_{min}} \quad (4)$$

The third objective function, f_Q is the total reactive power loss as given below:

$$f_Q = \sum_{i=1}^n I_i^2 X_i \quad (5)$$

The objective functions are subject to the following constraints as follows:

$$Q_{min} \leq Q_c \leq Q_{max} \quad (6)$$

$$V_{min} \leq V_i \leq V_{max} \quad (7)$$

In radial distribution networks $V_{min} = 0.95$ and $V_{max} = 1.05$

$$\sum_{n=1}^N Q_{cn} < Q_{total} \quad (8)$$

2.2 Sensitivity Analysis and Loss Sensitivity Factors (LSFs)

The sensitivity analysis is widely used for the placement of DG units and capacitors through the use of Loss Sensitivity Factors (LSFs). The LSF is able to predict which bus will have the biggest loss reduction when a DG unit or capacitor is placed. Hence, these sensitive buses can serve as candidate buses for DG units and capacitors placement. The estimation of these candidate buses helps in the reduction of search space for the optimization problem [12].

Consider a distribution line 'K' with an impedance $R + jX$ connected between 'i' and 'i+1' buses and a load of $P_{eff} + jQ_{eff}$ beyond the 'i+1' bus as shown in Fig. A.

The real power loss ($P_{L(loss)}$) in the Lth distribution line in Fig. A is given by $I_k^2 R_k$ which is expressed as:

$$P_{L(loss)} = \frac{(P_{eff}^2 + Q_{eff}^2)R_k}{V_{i+1}^2} \quad (9)$$

Now, the LSFs is obtained by partially differentiating the active power line loss with respect to Q_{eff} as given in Eq. (16)

$$\frac{\partial P_{L(loss)}}{\partial Q_{eff}} = \frac{2 Q_{eff} R_k}{V_{i+1}^2} \quad (10)$$

The LSFs, $\frac{\partial P_{L(loss)}}{\partial Q_{eff}}$ as given in Eq. (16) is calculated from the base case load flows. In addition, normalized voltage magnitudes are calculated by considering the base case voltage magnitudes given by equation (11)

$$\text{Normalized [i]} = V[i]/0.95 \quad (11)$$

The buses whose normalized [i] values are less than 1.01 are considered as candidate buses requiring the capacitor placement. These candidate buses are ranked in the descending order of the LSF values. In other words, the ranking based on the descending order of the LSF values will decide the sequence in which the buses are considered for capacitor installation [13].

2.3 Cuckoo Search Algorithm

Cuckoo search is a nature-inspired metaheuristic algorithm proposed by [14]. It is inspired by the aggressive reproduction of cuckoo species combining with behaviour of Levy flight. The female cuckoo lays her fertilized eggs in nests of other host birds. In this way, the host birds unwittingly raise her brood. If a cuckoo egg in a nest of a host bird is discovered, the host bird will throw it out or abandon her nest and start her own brood elsewhere. In the CS algorithm, each egg of host birds in a nest represents a solution, and a cuckoo egg represents a new solution. If a new solution is better than the one in the nest, the worse one will be replaced. For simplicity in describing the CS, we now use the following three idealised rules [15]:

- i. Each cuckoo lays one egg at a time, and dumps it in a randomly chosen nest.
- ii. The best nests with high quality of eggs (solutions) will carry over to the next generations.
- iii. The number of available host nests is fixed, and a host can discover an alien egg with probability P_a [0,1]. In this case, the host bird either throw the egg away or abandon the nest so as to build a completely new nest in a new location.

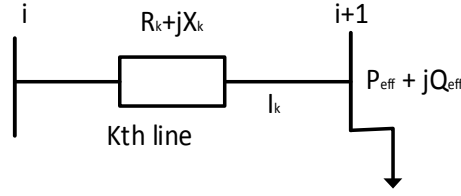


Fig. A. Radial distribution line with an impedance and load

The new solutions (new position), $x^{(t+1)}$ for say cuckoo 1, a Levy flight is described by the following equation:

$$x_i(k+1) = x_i(k) + \alpha \oplus \text{Levy}(\lambda) \quad (12)$$

Where $\alpha > 0$ is the step size, which should be related to the scale of the problem interest. The product \oplus means entry-wise multiplications [16]. The Levy flight essentially provides a random walk while the random step length is drawn from a Levy distribution

$$\text{Levy}(u) = t^{-1-\beta}, \quad 0 < \beta \leq 2 \quad (13)$$

The step size generating new nest is different from α and is defined as follows:

$$S(k) = \alpha(x_i(k) - x_j(k)) \oplus \text{Levy}(\beta) \quad (14)$$

The update of position of x_i is given by

$$x_i(k+1) = x_i(k) + r_i S_i(k) \quad (15)$$

Where r_i is a random number generated by the uniform distribution in interval [0,1]. The CS algorithm employs a discovery probability p_a to replace the nests abandoned by the hosts. Then, the update law is defined as follows:

$$x^* = \begin{cases} x_i + r^* & \text{if } P_a > p_a \\ x_i & \text{else} \end{cases} \quad (16)$$

Where p_a is the discovery probability to create a new nest, and P is a random number in interval [0,1], while r^* is the step size to generate new nest is different from that of equation (5), and it is defined by

$$r^* = \text{rand}(x_i - x_j)x_i, \quad x_j \in [1, n] \quad (17)$$

2.4 Proposed Methodology

This paper proposes a two-stage method utilizing the Loss Sensitivity Factors (LSFs) and Cuckoo Search Algorithm (CSA) to minimize the objective

functions- the overall cost, VSI and total reactive power losses. The total real power loss was not included in the objective function because the overall cost is partly a function of the total real power loss. The first stage of the algorithm is to basically reduce the search space and the repetitive load flow of the search algorithm while the second stage finds the actual bus locations and sizes of the shunt capacitor in the radial distribution network.

First Stage: Determination of Potential Buses through Calculation of LSFs.

The algorithm are the following steps performed to determine the potential or candidate buses for DG placement:

- Step 1- Run the load flow of the base case.
- Step 2- Calculate the LSFs at the buses of the distribution networks using equation (10).
- Step 3- Arrange the values of the LSFs in descending order. Also store the respective buses into bus position vector 'bpos [i]' called Ranking.
- Step 4- Calculate the normalized voltage magnitude Normalized [i] of the buses using equation (11).
- Step 5- The buses whose Normalized [i] is less than 1.01 are selected as possible potential candidate buses for Capacitor placement.

Second Stage: Determination of Actual Placement and Sizing using CSA

- Step 1- Input data: the data to be fed as input are number of buses, line and load data of distribution network, bus voltage limit and CS parameters. The potential buses for capacitor placement obtained in step 1 is also entered.
- Step 2-Generate initial population of the hoist nest (solution vector) X

An individual solution is defined as $[x_1 \ x_2 \]$ where x_1 represents the location index for capacitor banks where $1 \leq x_1 \leq L_b$, and L_b is the highest location index; that assuming that the

location considered for capacitor placement are numbered successively from 1, L_b is the index number of the last bus. The second part, x_2 carries the integer representing size of the capacitor bank to be placed.

$$X = \begin{bmatrix} x_{11} & x_{12} \\ \vdots & \vdots \\ x_{n1} & x_{n2} \end{bmatrix} \quad (18)$$

Step 3- Evaluate the solutions X using load flow and to get the following for each solution.

- (i) the total active power losses, P_{loss}
- (ii) The voltage at each bus, V_{bus}
- (iii) Distribution line flows.

Step 4- Calculate the annual cost function for each nest (solution) using the objective function in Eq. (10).

Step 5- Calculate the fitness function for each nest.

$$FF = \{F_{min} + \sum_{i=1}^{n_b} (penalty\ factor) \times (V_i - V_{max})^2 + i=1n_b penalty\ factor \times V_i - V_{min} + i=1n_b penalty\ factor \times Flow_i - Flow_{max}\} \quad (19)$$

Where the penalty factor is taken as:

$$penalty\ factor = \begin{cases} 0 & \text{if constraints are not violated} \\ 200 \times F_{min} \times iteration^2 & \text{if constraints are violated} \end{cases} \quad (20)$$

Step 6- Generation of Cuckoo: A cuckoo, $x^{i(t+1)}$ which is a new solution is generated by Levy flight as given in Eq. (12).

Step 7- Evaluate the cuckoo, new solution, using the load flow to obtain its P_{loss}, V_{bus} and line flows. Calculate the annual cost function for the cuckoo using Eq. (10) and its fitness function, FF using Eq. (14) to determine the quality of the cuckoo.

Step 8- Replacement: A nest is selected among n randomly, if the quality new solution in the selected nest is better than the old solution, it is replaced by the new solution (cuckoo).

Step 9- Generation of new nest: The worst nest are abandoned based on the probability (P_a) and new ones are built using Levy flight.

Step 10- The algorithm is terminated after a maximum generation of 50 iterations and the result displayed, else the process shifts step 6.

3. RESULTS AND DISCUSSION

The proposed two stage method using LSF and CSA have been applied on standard IEEE 33 bus and a Nigerian Ayepe 34 radial distribution systems. The Backward/Forward Sweep technique utilizing the equivalent current injection (ECI), the node injection to branch current (BIBC) and branch to node-voltage matrix (BCBV) as obtained in [17] was adopted for the load flow. The problem is solved by minimizing the objective function (OF_{min}) subject to the operating constraints. Design period of one year is taken at full load condition for the purpose of analysis and comparison. The number of buses for compensation is taken as three in this work. Various constant assumed and applied in the calculations are [18]: annual cost per unit of power losses (K_p) = 525.6 \$/kW, purchase cost of capacitor C_{cap} = 25 \$/kW, installation cost C_{inst} = 1600 \$/location and operating cost C_{ope} = 300 \$/year per location.

3.1 The Standard IEEE 33-Bus Radial Distribution System

The IEEE 33-bus system is a standardized radial distribution system used by most researchers for the purpose of comparison with similar works. The total real power loads and reactive loads on the 33 radial distribution system are 3.715 MW and 2.3 Mvar respectively. The line and load data are gotten from [19]. The test system has a total thirty-three buses with thirty branches as shown in Fig. 1.

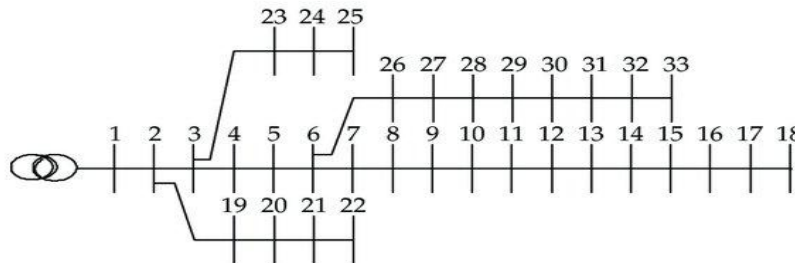


Fig. 1. Standard IEEE 33 bus system

First stage result: After running the first stage of the methodology, the base case gave a total power loss of 210.99 kW and total annual cost function of \$110, 896.34. The Loss Sensitivity Factors (LSFs) are calculated from the base case load flow for each transmission line and are shown in Table 1. Fig. 2 shows the LSFs for the 33 bus where the 'ranking' column in Table 1 shows the order in which the possible potential buses will be considered for optimization by the second stage of the algorithm. The buses requiring compensation are the ones shown in the bar graph.

Second Stage Result: The simulation result after running the second stage of the algorithm are tabulated in Table 2 while the voltage profile and the Voltage Stability Index before and after compensation are illustrated in Figs. 3 and 4 respectively. The optimal nodes and capacitor

sizes obtained by the proposed algorithm are 11, 24 and 30 and 450 kVar, 400 kVar and 950 kVar respectively. The total power loss and annual cost of operation of the system for the optimum case are 138.65 kW and 78, 839.03 \$. The net saving per year is 32, 057.31 \$. The percentage loss reduction and cost saving per year are 34.28% and 28.91% respectively compared to the base case. The minimum voltage of the system is improved from 0.9038 p.u. to 0.9321 p.u. while the minimum value of VSI is 0.7554. From Figs. 3 and 4, the voltage profile and VSI values of the system were poor for the base case and improved after the compensation.

The results of the proposed approach of the standard IEEE 33-bus are compared with the results of other methods and shown in Table 3. The results show the efficiency of the proposed method in finding optimal capacitor allocation.

Table 1. LSFs for the standard IEEE 33-bus system

Line No	From Bus (p)	To Bus (q)	V_p	V_q	LSF	Norm(i)= $\frac{V_q(i)}{0.95}$	Ranking
1	1	2	1	0.9970	2.74	1.0495	-
2	2	3	0.9970	0.9829	13.27	1.0346	-
3	3	4	0.9829	0.9754	7.65	1.0267	-
4	4	5	0.9754	0.9679	7.68	1.0188	-
5	5	6	0.9679	0.9495	16.81	0.9995	1
6	6	7	0.9495	0.9459	1.33	0.9957	14
7	7	8	0.9459	0.9323	10.09	0.9814	8
8	8	9	0.9323	0.9260	4.65	0.9748	4
9	9	10	0.9260	0.9201	4.45	0.9685	5
10	10	11	0.9201	0.9192	0.79	0.9675	18
11	11	12	0.9192	0.9177	1.33	0.9660	13
12	12	13	0.9177	0.9115	4.53	0.9595	6
13	13	14	0.9115	0.9092	1.39	0.9570	17
14	14	15	0.9092	0.9078	0.81	0.9556	16
15	15	16	0.9078	0.9064	0.91	0.9541	15
16	16	17	0.9064	0.9044	1.18	0.9520	12
17	17	18	0.9044	0.9038	0.45	0.9514	19
18	2	19	0.9970	0.9965	0.33	1.0489	-
19	19	20	0.9965	0.9929	2.29	1.0452	-
20	20	21	0.9929	0.9922	0.42	1.0444	-
21	21	22	0.9922	0.9916	0.36	1.0434	-
22	3	23	0.9829	0.9793	2.65	1.0308	-
23	23	24	0.9793	0.9726	4.75	1.0238	-
24	24	25	0.9726	0.9693	2.38	1.0203	-
25	6	26	0.9495	0.9475	2.67	0.9974	9
26	26	27	0.9475	0.9450	3.68	0.9947	7
27	27	28	0.9450	0.9335	13.67	0.9826	2
28	28	29	0.9335	0.9253	10.33	0.9740	3
29	29	30	0.9253	0.9218	6.05	0.9703	11
30	30	31	0.9218	0.9176	3.04	0.9659	10
31	31	32	0.9176	0.9167	0.65	0.9649	20
32	32	33	0.9164	0.9164	0.20	0.9646	21

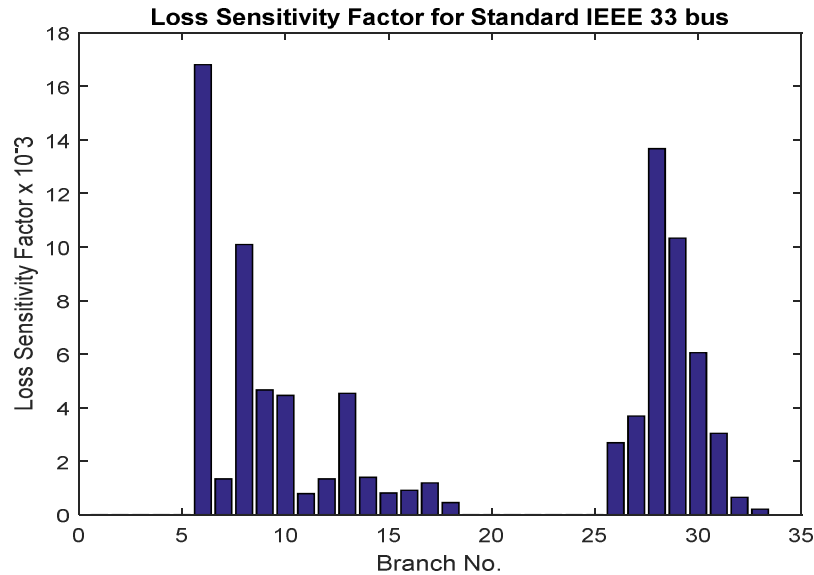


Fig. 2. LSFs for standard IEEE 33 bus system

Table 2. Summary of results for standard IEEE 33-bus before and after compensation

	Base Case	After Compensation
Optimal Bus	-----	30, 24, 11
Capacitor size (kVar)	-----	950, 400, 450
Power loss (kW)	210.99	138.65
Qloss (kVar)	143.13	94.41
Annual Cost (\$)	110, 896.34	78, 839.03
Net Savings (\$)	-----	32,057.31
Min Voltage	0.9038 (18)	0.9321 (18)
Min VSI	0.6689	0.7554
Ploss Reduction (kW)	-----	72.34
% Ploss Reduction	-----	34.28
% Net Savings	-----	28.91

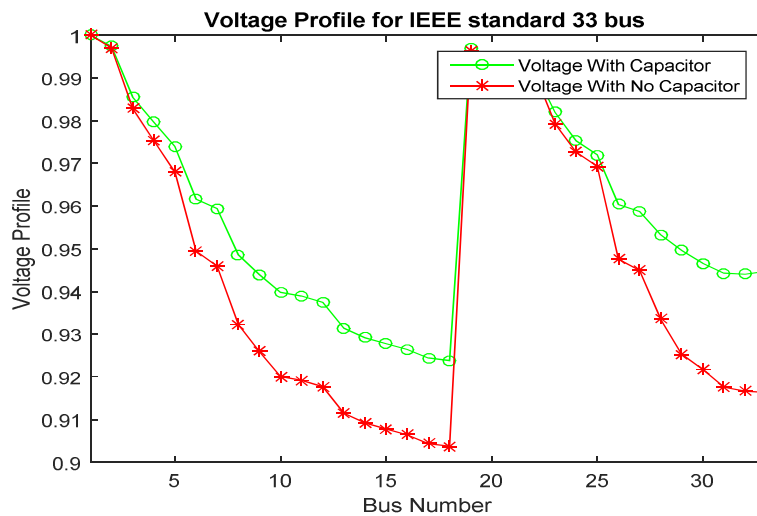


Fig. 3. Voltage profile for the standard IEEE 33-bus

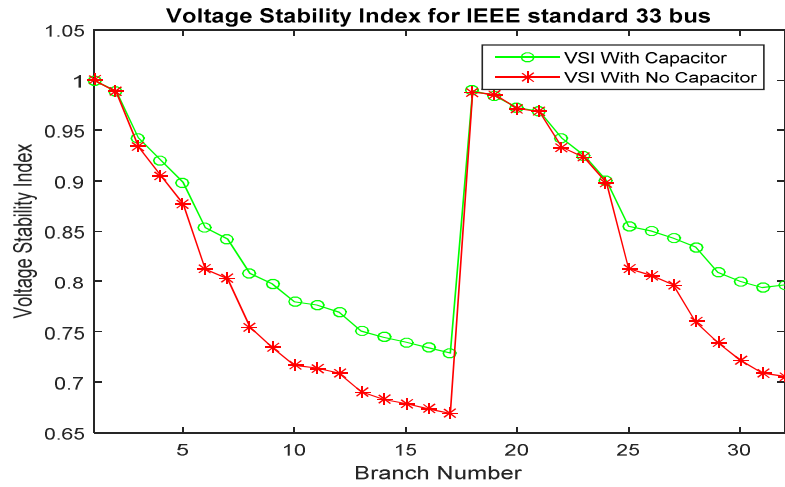


Fig. 4. VSI values for the standard IEEE 33-bus

Table 3. Optimal CBs allocation in the 33-bus system

Optimization Technique	CBs size (kVar) and location	Base Ploss (kW)	Ploss (kW)	Ploss Reduction (kW)
GSA [8]	450(13), 800(15), 350(26)	202.6	134.5	68.1
CSA [20]	600(11), 300(33), 450(24), 600(30)	202.6	131.5	71.1
BFOA [7]	349.6(18), 820.6(30), 277.3(33)	202.6	144.04	58.56
IMDE [21]	475(14), 1037(30)	202.6	139.7	62.9
WCA [9]	397.3(14), 451.1(24), 1000(30)	202.6	130.91	71.69
SSA [22]	450(10), 450(23), 1050(29)	202.6	132.35	70.25
Proposed method	450(11), 400(24), 950(30)	210.99	138.65	72.34

3.2 The Ayepe 34-Bus Radial Distribution System

Ayepe 11-kV feeder is an outgoing feeder from Ayepe 15MVA, 33/11-kV injection substation located at Osogbo, Osun state, Nigeria. Ayepe 11-kv feeder has thirty-four buses with thirty-

three branches with a total real power loads and reactive power loads and reactive power of 4.15 MW and 2.04 Mvar respectively. The line and the load data are gotten from [22]. The single line diagram of the Ayepe 34-Bus feeder is as shown in Fig. 2.

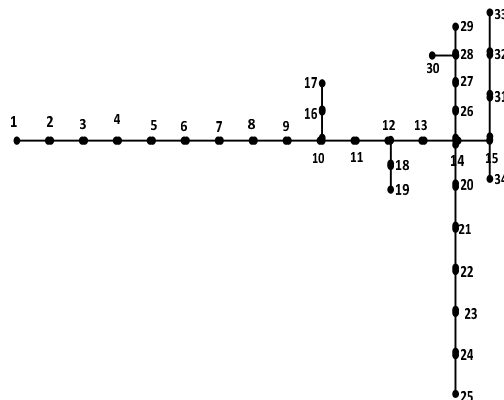


Fig. 5. Single line diagram of Ayepe 34-bus distribution system

First stage result: After running the first stage of the methodology, the base case gave that the total power loss as 762.64 kW and the total annual cost function of the power losses as \$ 400, 840.00. The Loss Sensitivity Factors (LSFs) are calculated from the base case load flow for each transmission line and are shown in Table 4. Fig. 6 shows the LSFs for the 34-bus where the 'ranking' column shows the order in which the possible potential buses will be considered for optimization by the second stage of the algorithm. The buses requiring compensation are the ones shown in the bar graph.

Second Stage Result: The simulation result after running the second stage of the algorithm are tabulated in Table 5 while the voltage profile and the Voltage Stability Index before and after

compensation are illustrated in Figs. 7 and 8 respectively. The optimal nodes and capacitor sizes obtained by the proposed algorithm are 10, 21 and 31 and 800 kVar, 550 kVar and 500 kVar respectively. The total power loss and annual cost of operation of the system for the optimum case are 588.09 kW and 315, 054.49 \$. The net saving per year is 85, 788.51 \$. The percentage loss reduction and cost saving per year are 22.89% and 21.40% respectively compared to the base case. The minimum voltage of the system is improved from 0.8295 p.u. to 0.8481 p.u. while the minimum value of VSI is improved from 0.4746 to 0.5181. From Figs. 7 and 8, the voltage profile and VSI values of the system were poor for the base case and improved after the compensation.

Table 4. LSFs for the Ayepe 34-bus radial distribution system

Line No	From Bus (p)	To Bus (q)	V_p	V_q	LSF	Norm(i)= $\frac{V_q(i)}{0.95}$	Ranking
1	1	2	1.0000	0.9826	-	1.0343	-
2	2	3	0.9826	0.9743	-	1.0256	-
3	3	4	0.9743	0.9505	1.39	1.0005	13
4	4	5	0.9505	0.9227	4.91	0.9713	8
5	5	6	0.9227	0.9130	24.82	0.9611	1
6	6	7	0.9130	0.8971	9.01	0.9443	7
7	7	8	0.8971	0.8832	15.27	0.9297	3
8	8	9	0.8832	0.8693	14.19	0.9151	4
9	9	10	0.8693	0.8544	13.79	0.8994	5
10	10	11	0.8544	0.8515	17.51	0.8963	2
11	11	12	0.8515	0.8441	2.97	0.8886	10
12	12	13	0.8441	0.8367	4.42	0.8807	9
13	13	14	0.8367	0.8365	10.32	0.8805	6
14	14	15	0.8365	0.8322	0.06	0.8760	29
15	10	16	0.8544	0.8542	1.88	0.8992	12
16	16	17	0.8542	0.8538	0.14	0.8987	27
17	12	18	0.8441	0.8429	0.94	0.8873	17
18	18	19	0.8429	0.8424	0.56	0.8867	21
19	14	20	0.8365	0.8342	1.89	0.8781	11
20	20	21	0.8342	0.8325	2.05	0.8763	15
21	21	22	0.8325	0.8320	1.24	0.8758	16
22	22	23	0.8320	0.8312	0.40	0.8749	23
23	23	24	0.8312	0.8299	0.57	0.8736	20
24	24	25	0.8299	0.8295	0.46	0.8732	22
25	14	26	0.8365	0.8357	2.27	0.8797	14
26	26	27	0.8357	0.8347	0.791	0.8786	19
27	27	28	0.8347	0.8337	0.794	0.8776	18
28	28	29	0.8337	0.8336	0.302	0.8775	25
29	28	30	0.8337	0.8336	0.05	0.8775	30
30	15	31	0.8544	0.8318	0.14	0.8756	26
31	31	32	0.8318	0.8317	0.34	0.8755	24
32	32	33	0.8317	0.8317	0.04	0.8760	31
33	15	34	0.8544	0.8322	0.07	0.8760	28

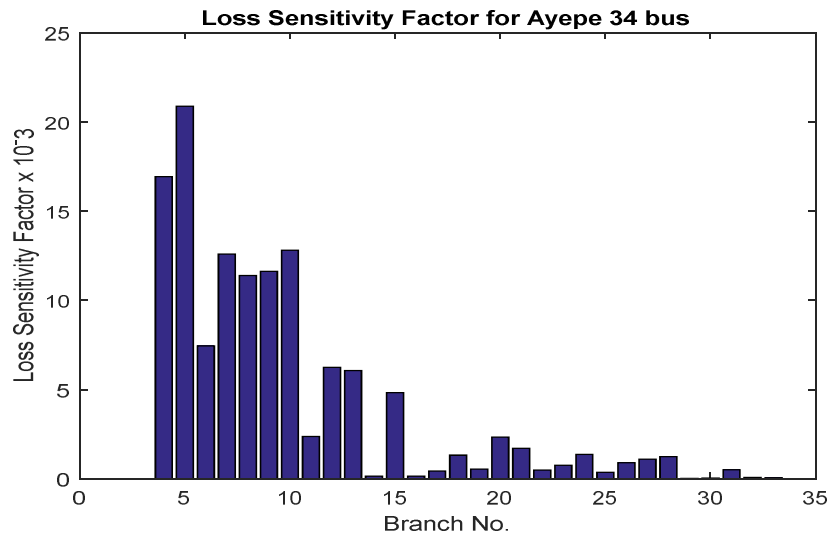


Fig. 6. LSFs for Ayepe 34-bus distribution system

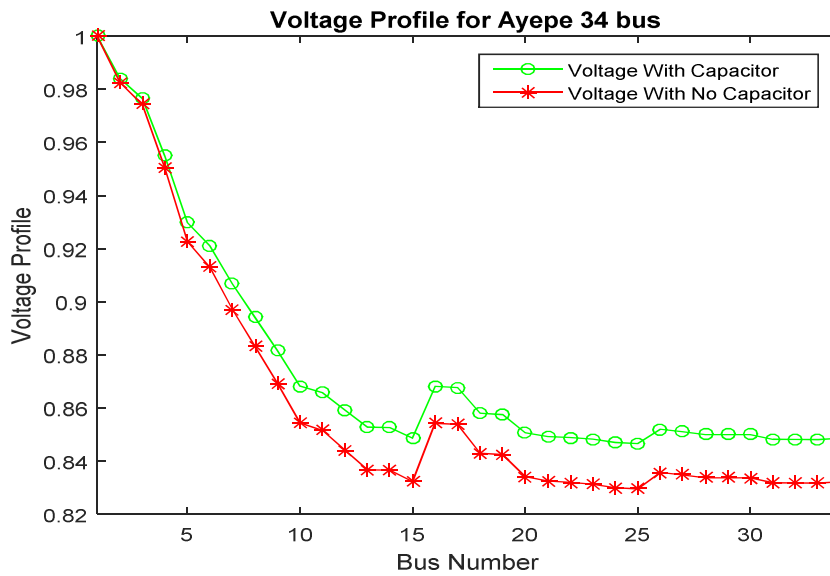


Fig. 7. Voltage profile for the Ayepe 34-bus system

Table 5. Summary of results for Ayepe 34-bus before and after compensation

	Base Case	After Compensation
Optimal Bus	-----	31, 21, 10
Capacitor size (kVar)	-----	500, 550, 800
Power loss (kW)	762.64	588.09
Qloss (kVar)	146.37	112.87
Annual Cost (\$)	400,840.00	315 054.49
Net Savings (\$)	-----	85,788.51
Min Voltage	0.8295(25)	0.8481(25)
Min VSI	0.4746	0.5181
Ploss Reduction (kW)	-----	174.55
% Ploss Reduction	-----	22.89
% Net Savings	-----	21.40

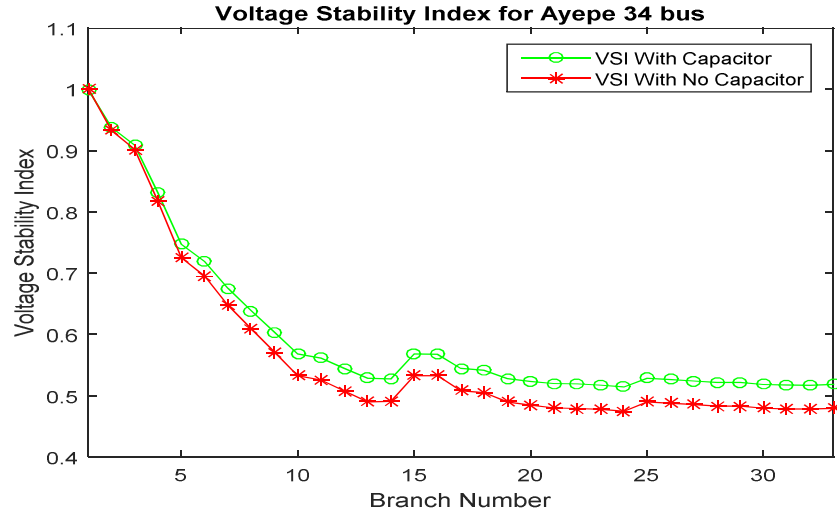


Fig. 8. VSI values for the Ayepe 34-bus system

4. CONCLUSION

A two stage method using Loss Sensitivity Factors and Cuckoo Search Algorithm has been proposed to solve optimal placement and sizing of capacitors with the objective of minimizing the cost due to power loss and reactive power compensation, maximizing the voltage stability index and minimizing the total reactive power loss. The proposed method is applied to two distribution systems and the obtained results for the standard system were compared with other optimization techniques. It is demonstrated that the proposed method is capable of saving significant amount of total annual cost, reducing total power losses, attain improvement in voltage profile by comparing the simulation results before and after compensation. The methodology is also tested on a real distribution network to illustrate the practical applicability of the solution.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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