Optimal Sizing and Placement of Shunt Capacitors on the Distribution System Using Whale Optimization Algorithm

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ABSTRACT: This paper aims at power loss minimization and reduction of cost due to losses in the distribution network as well as improvement of the network voltage stability and profile via optimal shunt capacitor allocation. The optimal shunt capacitor allocation was obtained using Whale Optimization Algorithm considering technical (real power loss and VSI) and economic objective functions as sub-optimal allocation may result in undesired effects on the network. The obtained optimal sizes of the shunt capacitors were placed on the obtained location of the distribution networks to ascertain the behavior of the networks before and after their placements taking power loss, cost due to losses, and voltage stability index as the performance metrics. A comparison of these performance metrics under four cases, namely base case (case one), installation of one SC (case two), installation of two SCs (case three), and installation of three SCs (case four) were demonstrated using standard IEEE 33-bus and Dada 46-bus distribution networks. The results gave a percentage loss reduction of 33.74% with 27.60% annual net saving for the IEEE 33-bus network and 22.24% loss reduction with 25.60% annual net saving for the Dada 46-bus network. Hence, reduction in the total power losses and costs. Also, the voltage profile and voltage stability index were significantly improved.

KEYWORDS: Distribution system, Shunt capacitors, Whale Optimization Algorithm, Real power, Voltage stability index.

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I. INTRODUCTION

Most distribution networks are usually radial due to many numbers of branches and nodes, the weakly meshed configuration of the network, and dynamic change in imposed load. The radial distribution network is mostly preferred to the ring distribution network because of its low construction cost (Michline and Ganesh, 2014). A radial distribution network is fed from the substation, which is supplied by the generation stations via the transmission system. The electricity consumers are supplied from the substation via the distribution network. The distribution networks have high resistance to reactance ratio, resulting in bus voltage magnitude violations and power losses (Moradi and Abedini, 2010). Among the power system sub-systems, the distribution system has the largest power losses when compared with the remaining sections such as transmission and generation. The distribution network power loss contribution is 13% of the generated total power (Rao and Ramakingaraju, 2011).

To reduce this power loss to enhance the network operation, several methods have been introduced such as system reconfiguration (Baran and Wu, 1998; Gomes *et al*., 2005; Olamaei *et al*., 2008; Zhigang 2008; Huang 2012; Mirhoseini *et al*., 2014; Verma and Singh, 2018), shunt capacitor placement (Jovica and Mirko, 2014; Sirjani and Shareef, 2014; Abdelaziz *et al.,* 2016; Salimon *et al*., 2020; Walter *et al*., 2020) series compensation (Ghosh and Ledwich, 2002), distributed generation placement (Vatani *et al*., 2016; Priyadarshini *et al*., 2017; Grisales-Noreña *et al*., 2019; Adepoju *et al*., 2019; Kola *et al*., 2019; Trieu *et al*., 2020), phase balancing (Hooshmanda and Soltanib, 2012; Soltani *et al*, 2018) and location of the energy storage system (Grisales-Noreña *et al*., 2020).

Optimal capacitor sizing and location are more economical and easier to implement (Abdelaziz *et al*., 2010). Capacitors compensate for reactive power in the distribution network and are commonly utilized to enhance voltage profile, reduce power loss and boost distribution network capacity (Ponnavaiko and Prakasa-Rao, 1989). However, its effectiveness in compensation for the losses in the distribution system largely depends on its optimal placement and size. When it is wrongly placed or sized, it will increase distribution network losses. Therefore, efficient and optimal planning for reactive compensation through the installation of a shunt capacitor is required to deal with both the technical and economic challenges associated with the radial distribution network. The technical advantages of compensation include reduced power losses, improved power factor, etc., compensating for reactive power on the supply side, and efficient use of the network components (El-ela *et al*., 2018; Abou El-Ela *et al.*, 2016). Minimizing operating costs due to power losses is key to the economic benefits associated with the installation of shunt capacitors.

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Quite a lot of papers have been written to optimally locate and size shunt capacitors by researchers over the years with the objectives of reducing losses and voltage magnitude violations. Analytical numeric programming optimization techniques such as the local variation method (Ponnavaiko and Prakasa-Rao, 1989) and mixed-integer programming technique (Baran and Wu, 1985; Khodr *et al*., 2008) have been used over the years as an analytical approach in solving the problem. The major drawbacks of the analytical methods in solving the shunt capacitor allocation problem are the complex calculations required and impedance matrix formulation. To surmount these problems, several artificial intelligent methods have been recently utilized by researchers.

Numerous optimization techniques have been used by researchers to solve shunt capacitor problem allocations with diverse objective functions. These optimization techniques include Genetic Algorithm (Reddy and Sydulu, 2007), Particle Swarm Optimization (Prakash and Sydulu, 2007; Ziari *et al.*, 2010), Direct Search Algorithm (Raju *et al*., 2012), Teaching Learning Based Optimization (Sultana and Roy, 2014), Plant Growth Simulation Algorithm (Rao *et al*., 2011), Cuckoo Search Algorithm (El-fergany and Abdelaziz, 2013; Salimon *et al.*, 2020), Harmony Search Algorithm (Sirjani and Shareef, 2014), clustering-based optimization (Jovica and Mirko, 2014), bat algorithm (Injeti *et al*., 2015), gravitational search algorithm (Shuaib, 2015), bacterial foraging optimization algorithm (Khodabakhshian and Andisghar, 2016), crow search algorithm (Askarzadeh, 2016), flower pollinated algorithm (Abdelaziz *et al*., 2016), spring search algorithm (Sambaiah and Jayabarathi, 2019), vortex search discrete version algorithm (Walter *et al*., 2020), and several others. In a bid to obtain better optimal results, several modified and hybrid approaches have been developed (Kishore *et al*., 2018; Al-Ammar *et al*., 2018; Kannan *et al*., 2015). However, most of these algorithms suffer the drawbacks of having numerous input parameters, the tendency of being trapped in local optimum, and may not reach the optimal solution.

In other to surmount the drawbacks, Whale Optimization Algorithm (WOA) was applied, in this paper, to proffer solutions to the problems of optimal sizing and placement of shunt capacitors. The WOA has been chosen due to its few parameters, lack of local optima entrapment, easy implementation, fast convergence, and strong global search capability. Though Prakash and Lakshminarayana (2017) had utilized the WOA technique for allocation of multiple capacitors in the distribution network with the objectives of minimizing the operating cost and power loss, the work did not analyze how the number of optimally allocated shunt capacitors affects the technical and economic benefits derivable from capacitive reactive compensation. The number of shunt capacitors that will yield the maximum technical benefit (minimal power loss) may not give the best economic benefit (net savings as a result of reduction of cost due to losses). Expending scarce resources on the installation of large number of shunt capacitors in other to obtain the least possible power loss may not yield the best optimal economic benefit. Hence, it is imperative to investigate how the number of shunt capacitors optimally installed affects the technical (power loss) and economic benefits (net annual savings).

This paper seeks to solve the shunt capacitor allocation problem using WOA to determine how the number of shunt capacitors optimally allocated affects both the technical and economic benefits. The proposed method, considering various cases of optimal installation of one to three shunt capacitors, was tested on both standardized and Nigerian practical distribution networks.

II. PROBLEM FORMULATION

In this section, the power flow, power systems under study, objective function, constraints, whale optimization technique, and the application of the proposed method are presented.

A. Power Flow Analysis

The forward/backward sweep load flow technique as given by Salimon *et al.* (2019), was adopted to carry out the power flow analysis on IEEE 33-bus and Dada 46-bus distribution networks. It was chosen in preference to conventional load flow techniques, due to its high computational performance, ease, and good convergence (Adepoju *et al.*, 2019).

B. Power System under Study

Two distribution networks are employed in this study for testing the proposed method. Line and load data of the IEEE 33-bus network, as illustrated by Figure 1, are obtained from (Shuaib *et al*., 2015). The total active and reactive loads are 3715 kW and 2300 kVAR, respectively. Dada 46-bus is a practical Nigerian distribution network of Ibadan Electricity Distribution Company (IBEDC), as illustrated in Figure 2. The total active and reactive loads are 6250 kW and 3155 kVAR, respectively.

C. Objective Functions

Three objective functions comprising of two technical and economic benefits are considered in this research. The first objective function is aimed at reducing the overall distribution network power loss, which is expressed as in Eq. (1):

$$F_1 = \min\left(\frac{TRP_{after}}{TRP_{before}}\right) \tag{1}$$

$$TRP_{before} = \sum_{i=1}^{B_n} {I_{i(before)}}^2 R_{i,i+1} \tag{2}$$

$$TRP_{after} = \sum_{i=1}^{B_n} {I_{i(after)}}^2 R_{i,i+1} \tag{3}$$

where, $I_{i(before)}$ and $I_{i(after)}$ = current injected at bus 'i' before and after the capacitor placement respectively, B_n = total bus number, $R_{i,i+1}$ = line resistance between buses i and i+1, TRP_{before} and TRP_{after} = total active power loss without and with capacitor placement, respectively.

The second objective function is to reduce the cost due to losses. It is as given in Eq. (4) (Salimon *et al*., 2020).

$$F_2 = \min\left(\frac{TAC_{after}}{TAC_{before}}\right) \tag{4}$$

where, $$TAC_{before} = C_{pu} * P_{\text{loss}} \tag{5}$$

$$TAC_{after} = C_{pu} * P_{\text{loss}} + \text{CQC} \tag{6}$$

and $$\text{CQC} = \alpha * \left[\left(C_{install} * N_{cp}\right) + \left(C_{cap}\sum_{i=1}^{N_{cp}} Qsize_i\right)\right] + C_{opn} * N_{cp} \tag{7}$$

where, TAC_{before} and TAC_{after} are costs of power losses before compensation respectively and the overall annual cost after capacitor placement of, CQC is reactive power compensation cost due to placement of capacitor, C_{pu} is annual cost per unit loss, P_{loss} is total real power loss, α is depreciation factor, $C_{install}$ is capacitor installation cost, N_{cp} is number of capacitors installed, C_{cap} is purchasing cost of the capacitor, C_{opn} is operating cost, $Qsize_i$ is capacitor size and i= 1,2…N_{cp}.

Voltage stability index is the third objective function. It reveals the weak buses that need compensation in other to avoid the collapse of the network. It can be expressed as given in Eq. (8) (Tan *et al.*, 2012).

$$VSI_i = |V^*|^4 - 4[P_i * X_i - Q_i * R_i]^2 - 4[P_i * X_i + Q_i * R_i]|V^*|^2 \quad (8)$$

$$\text{inv}VSI_i = \frac{1}{VSI_i} \quad (9)$$

where invVSI_i is the inverse of the VSI as given in Eqn. (8)
It can be expressed as an objective function as given:

$$F_3 = \min(\text{inv}VSI_i) \quad (10)$$

The objective functions are combined using the weighting factors approach as expressed in Eq. (11).

$$\text{OF}= w_1 * F_1 + w_2 * F_2 + w_3 * F_3 \quad (11)$$

where, w_1 = 0.6, w_2 = 0.2 and w_3 = 0.2

D. Constraints

The following constraints are used in the optimal shunt capacitor sizing and placement in radial distribution network:
Shunt capacitor limit:

$$Q_{min} \le Q_{size} \le Q_{max} \quad (12)$$

where, Q_{min} = minimum capacitor size, Q_{max} = maximum capacitor size, and Q_{size} = selected capacitor size for reactive power compensation.

Bus Voltage:

$$V_{min} \le V_i \le V_{max} \quad (13)$$

where, V_{min}, = minimum voltage limit, V_{max} = maximum voltage limit and V_i = selected voltage.

Total reactive power (Q_{ci}) injected:

$$\sum_j^i Q_{ci} < Q_{total} \quad (14)$$

where, Q_{total} = total reactive load.

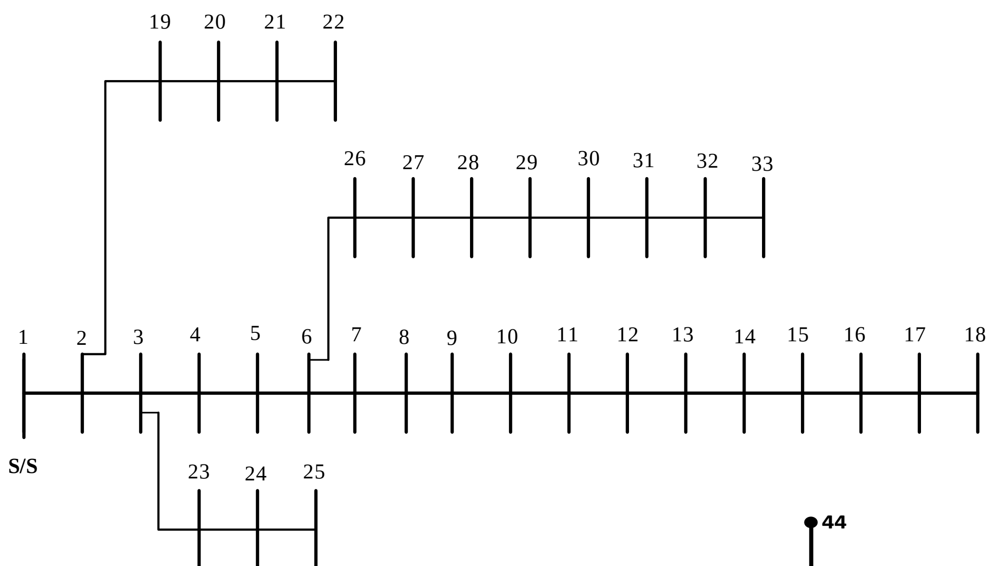

Figure 1: IEEE 33-bus test system.

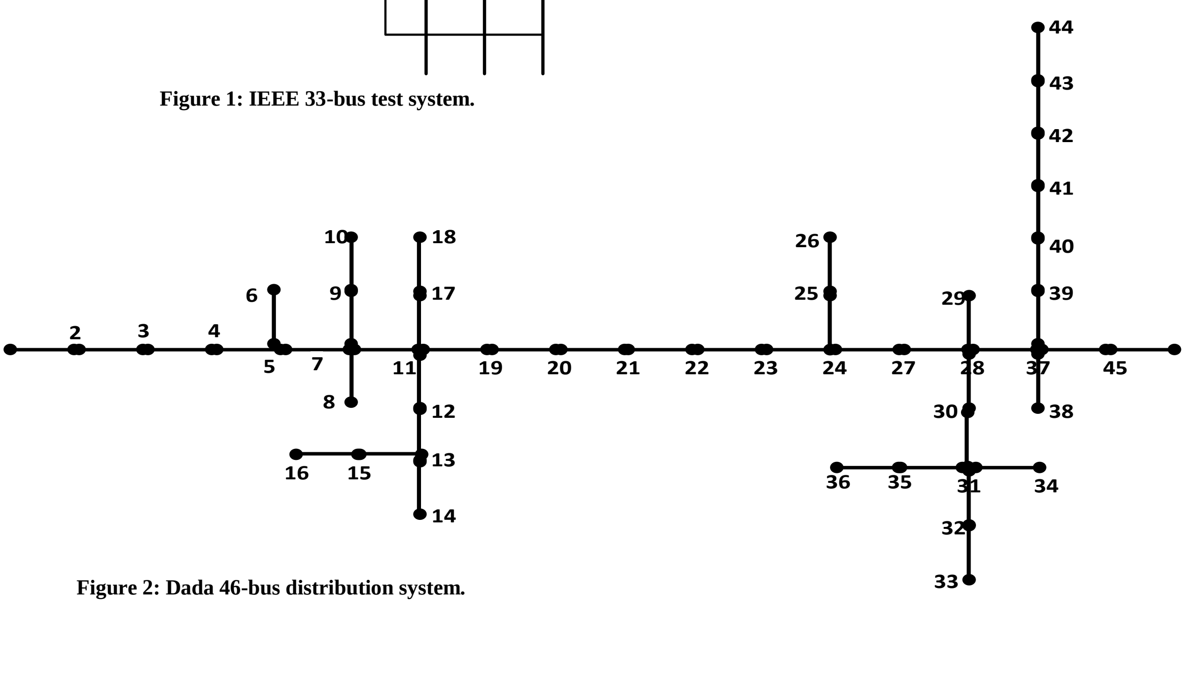

Figure 2: Dada 46-bus distribution system.

E. Whale Optimization Algorithm

Whale Optimization Algorithm (WOA) is a nature-inspired optimization technique proposed by Mirjalili and Lewis in 2016. The algorithm was drawn from the inspiration of how humpback whales catch their prey. They are highly intelligent animals that live alone or in a group. They are characterized by a hunting method called Bubble-net feeding. Bubble net feeding is a property that is only exhibited by humpback whales which can be mathematically modelled as presented below:

Encircling Prey

These behaviors are modelled as given by Seyedali and Andrew (2016) and are presented in Eqs. (15) – (16).

$$\vec{D} = |\vec{C}.\overrightarrow{X^*}(t) - \vec{X}(t)| \tag{15}$$

$$\vec{X}(t+1) = \overrightarrow{X^*}(t) - \vec{A}.\vec{D} \tag{16}$$

$$\vec{A} = 2\vec{a}.\vec{r} - \vec{a} \tag{17}$$

$$\vec{C} = 2.\vec{r} \tag{18}$$

where, t = current iteration, vector $\vec{A}$ and $\vec{C}$ = coefficient vectors, $\overrightarrow{X^*}(t)$= position vector of the best solution, $\vec{r}$ = random vector between [0,1], $\vec{a}$ = a value that decreases linearly from 2 to 0.

Spiral Bubble-net Feeding

This behavior modeling is also known as the exploitation phase. It can be modelled based on two designed approaches namely spiral-updating-position and shrinking-encircling-mechanism. In the latter, the behavior is obtained by reducing $\vec{a}$ in Eq. (17). Spiral updating position is given as:

$$\vec{X}(t+1) = \overrightarrow{D'}.e^{bl}.\cos(2\pi l) + \overrightarrow{X^*}(t) \tag{19}$$

$$\overrightarrow{D'} = \left|\overrightarrow{X^*}(t) - \vec{X}(t)\right| \tag{20}$$

$$\vec{X}(t+1) = \begin{cases} \overrightarrow{X^*}(t) - \vec{A}.\vec{D} & if\ p < 0.5 \\ \overrightarrow{D'}.e^{bl}.\cos(2\pi l) + \overrightarrow{X^*}(t) & if\ p \geq 0.5 \end{cases} \tag{21}$$

where, b = constant that defines the spiral shape, l = random number between [-1,1],
p = random number between [0,1].

Search for prey

This modelling is also referred to as the exploitation phase. It can be modelled as given in Eqns. (22) and (23).

$$\vec{D} = |\vec{C}.\overrightarrow{X_{rand}} - \vec{X}| \tag{22}$$

$$\vec{X}(t+1) = \overrightarrow{X_{rand}} - \vec{A}.\vec{D} \tag{23}$$

where, $\overrightarrow{X_{rand}}$ = current population random position vector.

III. METHODOLOGY

The procedural steps taken for the incorporation of WOA based technique for shunt capacitor allocation are illustrated in the flowchart in Figure 3 and are given as:

Step 1: input the bus and data and WOA parameters such as: dimension [dim= 6], search agent number [Search Agents no = 50], iteration maximum number [Max_iteration = 200].

Step 2: Generate the population, i.e. the number of search agents to be optimized, which gives Shunt capacitor locations and sizes. Set leader position vector, score, and the search agent position. Thus, the solution is formulated as follows

$$Search\ Agent\ Position = \begin{bmatrix} SC_1^1 & L_1^1 & SC_2^1 & L_2^1 & SC_3^1 & L_3^1 \\ SC_1^2 & L_1^2 & SC_2^2 & L_2^2 & SC_3^2 & L_3^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ SC_1^n & L_1^n & SC_2^n & L_2^n & SC_3^n & L_3^n \end{bmatrix} \tag{24}$$

Step 3: Return the search agents that go beyond the boundary limits and Perform load flow analysis with the forward/backward sweep algorithm.

Step 4: Calculate each search agent fitness using weighted objective functions as given in Eq. (11), find the initial best agent, and update the leader and search agent positions with Eqs. (17) to (21).

Step 5: If the position vector is less than 0.5 (i.e. p<0.5) go to step 9, else if the position vector is greater than or equal to 0.5, go to step 11.

Step 6: If |A| ≥ 1, compute the new search agent and update the position vector with Eqs. (22) and (23). Else if |A| < 1, update the position vector with Eqs. (15) and (16).

Step 7: If the counter reaches the specified maximum iteration, return to 13, else return to 4.

Step 8: Print the best score and positions which signifies shunt capacitor size(s) and location(s) respectively.

Step 9: Stop.

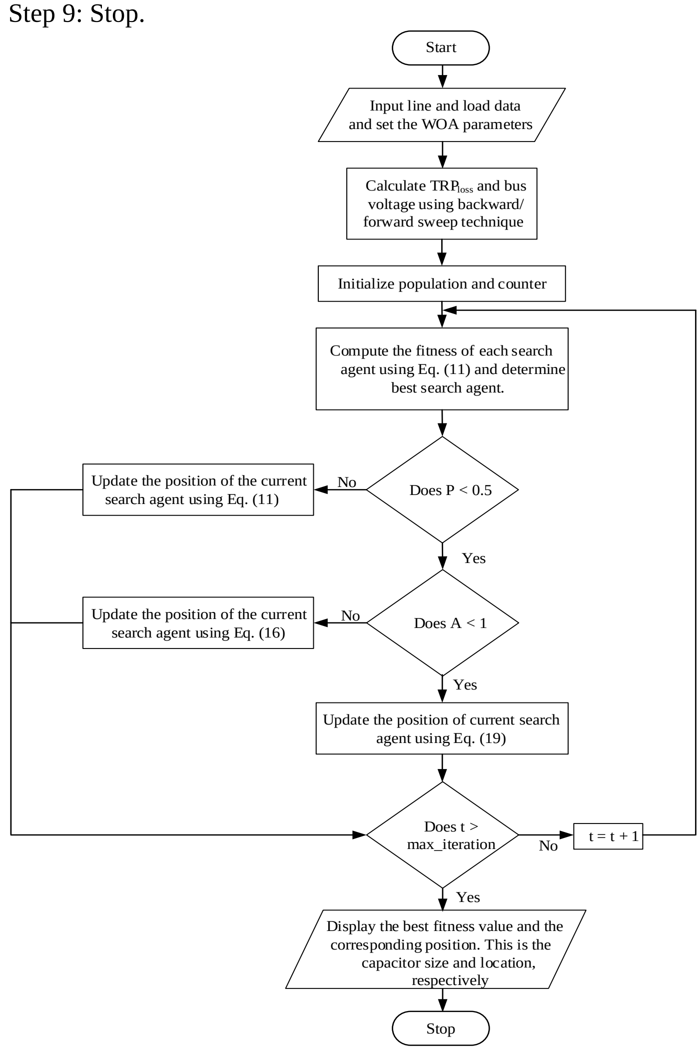

Figure 3: The flowchart of the proposed method.

IV. RESULTS AND DISCUSSION

The WOA was implemented on IEEE 33-bus and Dada 46-bus distribution networks to obtain the optimal sizes and location of shunt capacitors and simulations were performed using MATLAB. The constants used as given by Salimon *et al*. (2020) are: purchasing cost of the capacitor (C_{cap})= 24 $/kVAR, installation capacitor cost ($C_{install}$) = 1600 $/location, operating cost (C_{opn}) = 300 $/year/location, annual cost per unit of power loss (C_{pu}) = 525.6 $/kW and depreciation factor (α) = 10%. N_{cp} is the number of capacitors.

In this research, four (4) cases were considered viz;

Case 1: base case without shunt capacitor allocation.

Case 2: power loss minimization considering one (1) shunt capacitor allocation.

Case 3: power loss minimization considering only two (2) shunt capacitor allocations.

Case 4: power loss minimization considering only three (3) shunt capacitor allocations.

The simulation results are presented and discussed in the sub-sections below.

A. *IEEE 33-Bus Distribution Network.*

Simulation results for the four cases are presented in Table 1, Figures 4 and 5 present the characteristics of the voltage profile and stability index, respectively for each case. From the table, it is observed that the active and reactive power losses of the base case are 211 kW and 143 kVAR, respectively while the least voltage magnitude is 0.9038 p.u. at bus 18. Also, the cost of the losses per annum (i.e. the annual cost) is $110,898.34. The optimal size and location after running the algorithm for case 2 is 1259 kVAR at bus 30. After the optimal placement of the capacitor size, the active power loss, reactive power loss, annual cost, and minimum voltage magnitude got after the power flow analysis are 151.4 kW, 104 kVAR, $ 83 183.34, and 0.9165 p.u. at bus 18 respectively. For case 3, the optimal sizes and bus locations are 996 KVAR at bus 30 and 411 KVAR at bus 14. After the power flow, the active power loss, reactive power loss, annual cost, and the minimum voltage magnitude are 142.3 kW, 96.8 kVAR, $79235.64, and 0.9276 p.u. at bus 18, respectively. For case 4, the optimal sizes and bus locations are 1223 kVAR at bus 30, 511 kVAR at bus 24, and 435 kVAR at bus 11 with the active power loss of 139.8 kW, reactive power loss of 95.4 kVAR, the annual cost of $80286.64 and the minimum voltage magnitude of 0.9315 at bus 18.

From Table 2, the active and reactive power loss reductions for cases 2, 3, and 4 are 59.59 kW (28.26%), 68.68 kW (32.55%), and 71.18 kW (33.74%), respectively compared with case 1. Annual net savings for cases 2, 3 and 4 are $ 83 183.34 (24.99%), $ 79 235.64 (28.55%) and $ 80 286.64 (27.60%) compared with case 1. The power loss was least with the installation of three shunt capacitors (case three) while the best economic benefit (net annual savings due to the reduction of cost due to power losses) was obtained with the optimal installation of two shunt capacitors (case two). This is because the net increment in the reduction of the power losses decreases as the number of shunt capacitors increases. Hence, the additional cost of the third capacitor is greater than the cost-saving due to the minimization of power losses as a result of the third capacitor.

From Figures 4 and 5, it is observed that there are voltage profile and stability index improvements after optimal capacitor placement. The difference in the level of improvement depends on the number of capacitors that are optimally installed. An increase in the number of capacitors results in an increase in the level of improvement for voltage profile and stability index. It was observed that case 4 has the best voltage profile and VSI compare to the other cases. This justifies the effect of the number of shunt capacitors optimally installed in the distribution network.

Table 2 presents the results for case 4 as compared with existing methods in the open literatures, such as GSA, TSM, FRCGA, PSO, BFOA, and SSA (Das *et al*., 1995, Abul'Wafa, 2013, Abul'Wafa, 2014, Askarzadeh, 2016, Khodabakhshian and Andisghar, 2016, Sambaiah and Jayabarathi, 2019). Table 2 demonstrates the efficacy of the proposed technique in optimal shunt capacitor allocations when compared to other techniques as the minimization in the losses with respect to the base case is higher compared to the other techniques.

B. *Dada 46-bus Distribution Network.*

The results of the four cases are presented in Table 3, while Figures 6 and 7 present the voltage profile and stability index. From the table , the active power loss, reactive power loss, annual cost and least voltage magnitude for the base case are 926.50 kW, 177.92 kVAR, $ 486 968.40, and 0.8437 (44), respectively. The optimal shunt capacitor location and size after running the algorithm for case 2 is 1498 kVAR at bus 28. After the optimal placement of the capacitor size, the active and reactive power losses, annual cost, and minimum voltage magnitude obtained are 755.37 kW, 145.08 kVAR, $401227.47, 0.8552 (44), respectively.

Table 1. Result for the standard IEEE 33-bus test system.

	Base case	Case 2	Case 3	Case 4
SC size (kVAR)	---	1259	996, 411	1223, 511, 435
Bus location	---	30	30, 14	30, 24, 11
Real Power loss (kW)	210.99	151.40	142.31	139.81
Reactive Power Loss (kVAR)	143.13	104.00	96.75	95.41
Min. Voltage (p.u.) (bus)	0.9038 (18)	0.9165 (18)	0.9276 (18)	0.9315 (18)
Min. VSI (bus)	0.6685 (17)	0.7070 (17)	0.7418 (17)	0.7543 (17)
Loss Reduction (kW)	---	59.60	68.66	71.19
% Power Loss Reduction	---	28.26	32.55	33.74
Annual cost ($)	110896.34	83183.34	79235.64	80286.64
Net savings ($)	----	27713.00	31660.71	30609.71
% Net savings	----	24.99	28.55	27.60

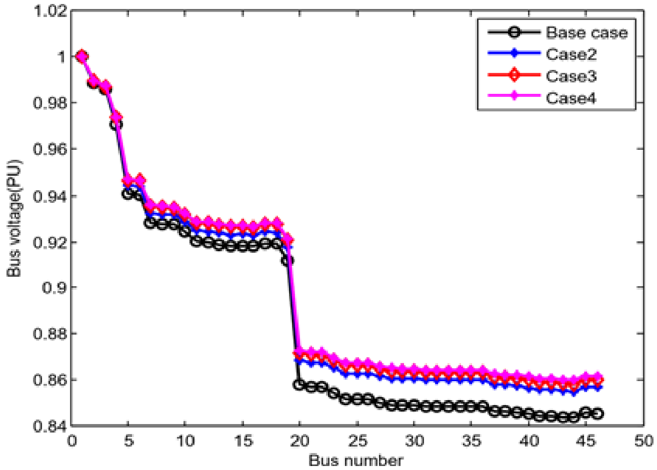

Figure 4: IEEE 33-bus network voltage profile.

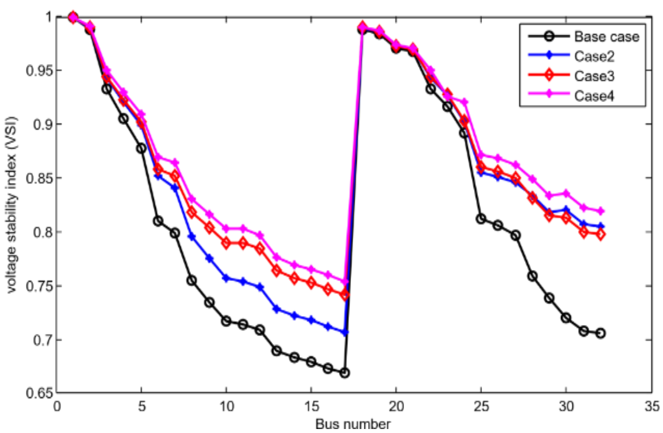

Figure 5: IEEE 33-bus network VSI.

For case 3, the optimal sizes and locations are 1434 kVAR at bus 27 and 1438 kVAR at bus 12. After power flow solutions, the active and reactive power losses, annual cost, and minimum voltage magnitude are 725.15 kW, 139.28 kVAR, $389 238.84, and 0.8584 (44), respectively. For case 4, the optimal sizes and bus locations are 1432 kVAR at bus 11, 960 kVAR at bus 25, and 674 kVAR at bus 39 with the active power loss of 720.46 kW, reactive power loss of 138.38 kVAR, the annual cost of $387718.78 and least voltage magnitude of 0.8600 at bus 44.

From Table 3, the active and reactive power loss reductions for cases 2, 3, and 4 are 171.13 kW (18.47%), 201.35 kW (21.73%), and 206.04 kW (22.24%), respectively compared with case 1. Annual net savings for cases 2, 3 and 4 are $85740.93 (21.37%), $97729.56 (25.11%) and $99249.62 (25.60%) with respect to case 1. The results for cases 1, 2, 3, and 4 show a reduction in real and reactive power losses, and annual cost after optimal the incorporation of shunt capacitor(s). It is crystal clear from the results that technical and economic benefits increased as the number of installed shunt capacitors is increased from 1 to 3.

Figures 6 and 7 show voltage profile and stability index improvements after shunt capacitor location and the difference in the level of improvement depend on the number of capacitors that are optimally installed. An increase in the number of capacitors increases the level of improvement for voltage profile and stability index as observed in Figures 6 and 7. It was observed that case 4 has the best voltage profile and stability index compared to the rest, followed by case 3 and then case 2. This justifies the effect of the shunt capacitor number that is optimally installed in the distribution network.

Table 2: Comparison of results for IEEE 33-bus network.

Method	SC size (kVAR) and location	Base Ploss (kW)	Ploss (kW)	Ploss Minimization (kW)
GSA	450(9), 800(29), 900(30)	210.99	171.78	39.21
TSM	850(7), 25(29), 900(30)	210.99	144.04	66.95
FRCGA	25(28), 475(6), 300(29),175(8), 400(30), 350(9)	210.99	141.24	69.75
PSO	900(2), 450(7), 450(11), 300(15), 450(29)	202.60	132.48	70.12
BFOA	349.6(18), 820.6(30), 277.3(33)	202.60	144.04	58.56
SSA	450(10),450(23), 1050(29)	202.60	132.35	70.25
Proposed method	1223(30), 511(24), 435(11)	210.99	139.80	71.19

Table 3: Results for the Dada 46-bus system.

	Base case	Case 2	Case 3	Case 4
SC size (kVAR)	-	1498	1434, 1438	1432, 960, 674
Bus	-	28	27, 12	11, 25,39
Real Power Loss (kW)	926.50	755.37	725.15	720.46
Reactive Power Loss (kVAR)	177.92	145.08	139.28	138.38
Min. Voltage (p.u.)	0.8437 (44)	0.8552 (44)	0.8584 (44)	0.8600 (44)
Min. VSI	0.5072 (43)	0.5355 (43)	0.5436 (43)	0.5476 (43)
Loss Reduction(KW)	-	171.13	201.35	206.04
% Power Loss reduction	-	18.47	21.73	22.24
Annual cost ($)	486968.40	401 227.5	389 238.8	387 718.8
Net savings ($)	-	85 740.93	97 729.56	99 249.62
% Net savings	-	21.37	25.11	25.60

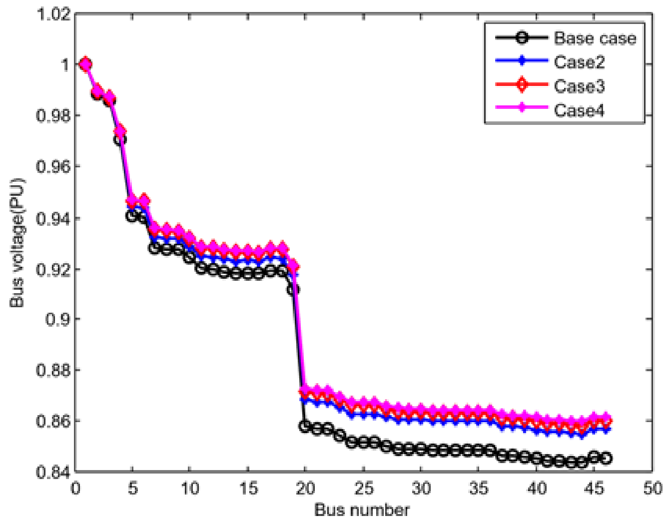

Figure 6: Dada 46-bus network voltage profile.

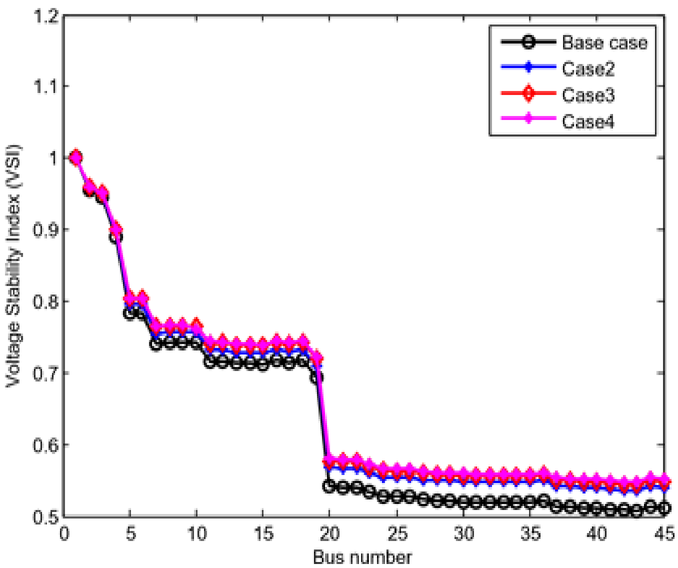

Figure 7: Dada 46-bus network VSI.

V. CONCLUSION

WOA has been presented for the optimal allocation of shunt capacitors in distribution networks. The method was applied to the IEEE 33-bus network and practical Dada 46-bus distribution network, to minimize the total power losses and annual cost, and also to improve voltage profile and stability index. The results were presented and compared with existing methods. The proposed technique gives viable results for the systems considered by reducing the total real power loss by 33.74% compared to the base case with 27% annual net saving for IEEE 33-bus network and 33.74% real power loss reduction with 27% annual net saving for Dada 46-bus network with improvements on voltage profile and voltage stability index. Further work can consider the simultaneous inclusion of distributed generation (DG) alongside the shunt capacitors for greater technical and economic benefits.

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