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Cost-Benefit of Optimal Allocation of DSTATCOM in Distribution Networks Using Ant-Lion Optimization Algorithm

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Abstract

Distribution Static Compensators (DSTATCOMs) are considered to be one of the most cost-effective modern devices for reactive compensation in distribution networks. However, the DSTATCOMs sizing and their deployment position are important factors to consider in order to get the most out of their installation. This study proposes the use of the Ant-Lion Optimization Algorithm (ALOA) for the appropriate allocation of the DSTATCOM with the goal of maximization of the cost-benefit derived from the reduction in the cost of power purchased from the transmission grid less the DSTATCOM cost for the distribution networks in order to find its appropriate allocation. The suggested technique is tested on a Nigerian Dada 46-bus system as well as an IEEE 33 bus. The simulation results for the IEEE 33-bus system reveal that the cost benefits of $ 100,601, $ 108,212, and $ 89,422 were actualized for one, two, and three DSTATCOMs allocations, respectively, while the figures for the Dada 46-bus system were $ 482,166, $ 574,546, and $ 531,415, respectively. In terms of real power loss in the IEEE 33-bus, the suggested method was determined to be quite effective for DSTATCOM allocation when compared to similar studies in the literature.

Keywords

distribution network, DSTATCOM, Ant-Lion Optimization, cost-benefit, optimal allocation

1 Introduction

The distribution system, which serves as the connection linking the high-voltage transmission line to low-voltage energy users, is the final phase of the electricity grid. The distribution level accounts for around 70% of overall power losses in the power system while the remaining losses are attributed to other parts of the power system. [1]. This distribution network is considered as the weakest part of the power system and the power losses on constitute a significant percentage of the total energy generated [2]. Reduction of losses are one of the primary concerns to enhance the reliability, security and efficiency of power supply to avoid wastage of scarce resources for the distribution companies (Discos).

The reactive compensation methods are one of the solutions for reduction of power losses in the distribution network through installation devices such as synchronous condenser, capacitors, reactors, automatic voltage regulators (AVR) [3]. In the last few years, Distribution Flexible AC Transmission (DFACTS) have been introduced for integration into the distribution system for the purpose of reactive compensation [4]. FACTS was initially created for transmission networks, but it has recently been expanded to enhance power quality in distribution systems that operate at low or medium voltages. Due to sensitive equipment in most industrial, residential, commercial, and traction applications, distribution networks are experiencing a number of power quality issues. In distribution systems, these power quality issues are categorized as voltage and current quality issues [5]. Poor power factor, current harmonics, unbalanced currents, poor voltage control and increasing neutral current are regarded as current power quality issues. Some of the common DFACTS devices used to provide reactive compensation and mitigate the power quality problems include Static Synchronous Series Compensator (SSSC), Distribution Static Compensator (DSTATCOM) and Unified Power Flow Controller (UPFC) [6].

STATCOM connected to the radial distribution system for provision of reactive compensation and mitigation of

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multiple current power quality problems is known as distribution STATCOM (DSTATCOM). In distribution systems, DSTATCOM technology is currently an established technology for reactive power compensation, harmonic current correction and load balancing [7]. DSTATCOMs are also utilized in three-phase systems to control terminal voltage, decrease voltage flicker, and enhance voltage balancing [8]. Traditional technologies such as power capacitors and static VAR compensators have been utilized to alleviate some of these power quality issues, but DSTATCOM is the greatest and most efficient solution for addressing all current-based power quality issues compared to capacitor and SVC on distribution network [9]. DSTATCOM is predicted to play a vital role in radial distribution systems due to increased power system demand.

Obtaining the precise size and appropriate location of DSTATCOM is a technical aspect that must be resolved using an appropriate optimization technique as wrong placement and inappropriate size of DSTATCOM can have adverse effect on the operation of the distribution network [10]. Optimal allocation and size of DSTATCOM will allow DISCOs to save money by reducing power loss. In a bid to resolve this allocation issue, researchers have utilized various optimization techniques considering various objectives taking into account various constraints. Some of the optimization techniques include hybrid genetic and ant colony algorithm [11], Fuzzy logic–based rooted tree optimization algorithm [12], differential evolution algorithm [13], Harmony Search Algorithm (HSA) [14], Particle Swarm Optimization (PSO) algorithm [15], Cuckoo Search Algorithm [16] and several other population-based search optimization techniques. Furthermore, a comprehensive performance analysis has been conducted between various placement scenarios, which will assist in the planning and establishment of a competent decision-making process in order to arrive at the best plan possible depending on the utility long-term objectives.

[17] suggested an immune technique for DSTATCOM optimal allocation in distribution systems, with the purpose of minimizing power loss, DSTACOM investment cost, and voltage variation. [16] used the Cuckoo Search Optimization technique to address the simultaneous DG and DSTATCOM allocation problem with the objective of minimizing power loss. [18] proposed Multi-Verse Optimization for simultaneous DG and DSTATCOM integration, with the goal of lowering power loss, voltage deviation, and cost due to losses. [10] employed the New Voltage Stability Index (NVSI) and the Bat Algorithm to determine the ideal size and position of DSTATCOM in the distribution system in order to reduce power losses. [19] proposed a lightning search technique for simultaneous placement of DG and DSTATCOM with the following goals of minimizing the power loss, total voltage deviation and voltage stability index.

The focus of this research is to use Ant-Lion Optimization Algorithm (ALOA) for DSTATCOM allocation in the distribution system in order to maximize the cost savings as a result of minimal cost of power purchased from the substation minus the DSTATCOM cost. Previous aforementioned studies on DSTATCOM allocation have mostly focused on the goal of minimizing power loss. Even studies that included cost savings as one of their goals attributed the cost savings to the cost of energy saved owing to reduced power loss, rather than the cost of electricity purchased from the substation. It is necessary to investigate how the proper installation of DSTATCOM in the distribution system affect the cost of power acquired from the substation to have a vivid view of the overall economic advantage. This study, therefore, will utilize the ALOA technique to obtain the optimal size and location of DSTATCOM for maximization of the cost benefit based on reduced power purchased.

2 Mathematical modelling of D-STATCOM

The distribution line between buses 'A' and 'B' shows the placement of DSTATCOM at bus 'B'. r_A and x_A represent the line resistance and reactance, $P_A + jQ_A$ and $P_B + jQ_B$ represent load demands, v_A and v_B are the node voltages. Let $v_A \angle \Delta_A$, $i_A \angle \delta$ and $i_{DSTATCOM} \angle \left(\Delta'_B + \frac{\pi}{2} \right)$ represents the voltage of bus 'B' after the placement of DSTATCOM, voltage of bus 'A', current flow in line after DSTATCOM placement and injected current by DSTATCOM respectively from Fig. 1.

$$\begin{aligned} v'_B \angle \Delta'_B &= v_A \angle \Delta_A - \left(r_A + jx_A \right) i_A \angle \delta \\ &- \left(r_A + jx_A \right) i_{DSTATCOM} \angle \left(\Delta'_B + \frac{\pi}{2} \right) \end{aligned} \tag{1}$$

Separating the real and imaginary parts of Eq. (1) yields:

$$\begin{aligned} v'_B \operatorname{Cos} \Delta'_B &= RA\left(v_A \angle \Delta_A \right) - RA\left[\left(r_A + jx_A \right) i_A \angle \delta \right] \\ &+ x_A i_{DSTATCOM} x \operatorname{Sin}\left(\Delta'_B + \frac{\pi}{2} \right) \\ &- r_A i_{DSTATCOM} \operatorname{Cos}\left(\Delta'_B + \frac{\pi}{2} \right), \end{aligned} \tag{2}$$

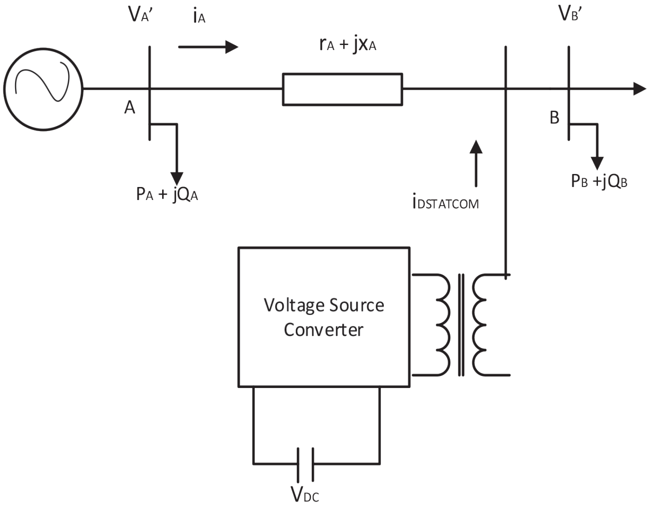

Fig. 1 Distribution line with DSTATCOM installation at the receiving bus

$$\begin{aligned} v_B' \operatorname{Sin} \Delta_B' &= \operatorname{Im}\left(v_A \angle \Delta_A\right) - \operatorname{Im}\left[\left(r_A + jx_A\right) i_A \angle \delta\right] \\ &- x_A i_{DSTATCOM}\, x \operatorname{Cos}\left(\Delta_B' + \frac{\pi}{2}\right) - r_A i_{DSTATCOM} \operatorname{Sin}\left(\Delta_B' + \frac{\pi}{2}\right). \end{aligned} \tag{3}$$

Let use the following notations:

$$K_1 = RA\left(v_A \angle \Delta_A\right) - RA\left[\left(r_A + jx_A\right) i_A \angle \delta\right],$$

$$K_2 = \operatorname{Im}\left(v_A \angle \Delta_A\right) - \operatorname{Im}\left[\left(r_A + jx_A\right) i_A \angle \delta\right],$$

$$\left.\begin{aligned} C_1 &= r_A \\ C_2 &= x_A \\ D &= v_B' \\ U &= i_{DSTATCOM} \\ W &= \Delta_B' + \frac{\pi}{2} \end{aligned}\right\}. \tag{4}$$

Equations (3) and (4) can be written as:

$$D \operatorname{Cos} W = K_1 + C_1 U \operatorname{Sin} W + C_2 U \operatorname{Cos} W, \tag{5}$$

$$D \operatorname{Sin} W = K_2 - C_2 U \operatorname{Sin} W - C_1 U \operatorname{Cos} W, \tag{6}$$

where K_1, K_2, C_1 and C_2 are constant.

From Eqs. (5) and (6), we have:

$$U = \frac{D \operatorname{Cos} W - K_1}{C_1 \operatorname{Sin} W - C_2 \operatorname{Cos} W}, \tag{7}$$

$$U = \frac{D \operatorname{Sin} W - K_2}{C_2 \operatorname{Sin} W - C_1 \operatorname{Cos} W}. \tag{8}$$

Eqs. (7) and (8) and taking $X = \operatorname{Sin} W$, we have:

$$\left(Q_1^2 + Q_2^2\right) X^2 - \left(Q_1 D C_1\right) X + \left(D^2 C_1^2 - Q_2^2\right) = 0, \tag{9}$$

where $Q_1 = K_1 C_2 - K_2 C_1$ and $Q_2 = K_1 C_1 - K_2 C_2$.

Solving Eq. (9) using quadratic formula gives:

$$X = \frac{2Q_1 D C_1 \pm \sqrt{\begin{aligned}&\left(2Q_1 D C_1\right)^2 \\ &-4\left(Q_1^2 + Q_2^2\right)\left(D^2 C_1^2 - Q_2^2\right)\end{aligned}}}{2\left(Q_1^2 + Q_2^2\right)}, \tag{10}$$

but:

$$v_B' = W = \operatorname{Sin}^{-1} X. \tag{11}$$

The injected voltage, current and reactive power at bus *B* are as follows:

$$v_B' = v_B' \angle \Delta_B', \tag{12}$$

$$i_{DSTATCOM} = i_{DSTATCOM} \angle \left(\Delta_B' + \frac{\pi}{2}\right), \tag{13}$$

$$jQ_{DSTATCOM} = v_B' i_{DSTATCOM}^*, \tag{14}$$

where '*' signifies complex conjugate.

3 Problem formulation

The problem formulation covers the distribution load flow technique used for the study and the formulation of the objective function based on the cost-benefit.

3.1 Distribution load flow analysis

The backward/forward sweep power flow approach described in [20] was applied on the distribution system for both standard IEEE 33-bus and Nigerian practical network Dada 46-bus distribution systems to conduct the power flow study. Because of its great computational performance, versatility, ease of use, and good convergence, forward/backward sweep was chosen [21].

3.2 Formulation of the objective function and constraints

For the planning period, the DSTATCOM investment cost ($DSTATCOM_{inv}$) is determined in Eq. (15):

$$DSTATCOM_{inv} = \sum_{i=1}^{NDS} k_{I,DSTATCOM} Q_{DSTATCOM}, \tag{15}$$

where $k_{I,DSTATCOM}$ is the investment cost of DSTATCOM units (\$/kVAr), $Q_{DSTATCOM}$ = size of DSTATCOM units at i^{th} bus in kVAr.

Number of DSTATCOMs installed in the distribution system is represented by NDS. The DSTATCOM maintenance cost ($DSTATCOM_M$) for the planned period is as follows:

$$DSTATCOM_M = MC_{DSTATCOM}, \tag{16}$$

where $MC_{DSTATCOM}$ is the DSTATCOM annual maintenance cost.

DSTATCOM's overall cost ($DSTATCOM_{cost}$) is computed as follows:

$$DSTATCOM_{cost} = DSTATCOM_{inv} + DSTATCOM_M. \tag{17}$$

The cost of reducing active power bought (C_{pw}) from the Disco is calculated as follows for the planning period:

$$C_{pw} = \Delta P_{pw} \cdot k_{pw,p} \cdot T \times \sum_{y=1}^{nyr} \left(\frac{1+\inf R}{1+\operatorname{int} R} \right)^{y}, \tag{18}$$

where ΔP_{pw} is the reduction in purchase active power from the Disco, $k_{pw,p}$ is the energy market price (\$/kWh), T is the total load duration for one year (8760 h), nyr is the planning years inf R and int R represent the interest and inflation rate respectively.

$$\begin{aligned} \Delta P_{pw} = & \left[\left(P_{(pw,\ \text{before } DSTATCOM)} + P_{(loss \text{ before } DSTATCOM)} \right) \right] \\ & - \left[\left(P_{(pw,\ \text{after } DSTATCOM)} + P_{(loss \text{ after } DSTATCOM)} \right) \right] \end{aligned} \tag{19}$$

The net economic benefit (Cost-Benefit) of DSTATCOM deployment is determined as:

$$\text{Cost-Benefit } (\$) = C_{pw} - DSTATCOM_{cost}. \tag{20}$$

The objective function is the maximization of the net savings subject to both equality and inequality constraints as follows:

- *Limit of bus voltage:* the voltage magnitude of each bus is subjected to the following limitations:

  $$V_{\min} \le |V_i| \le V_{\max}. \tag{21}$$

- DSTATCOM *Capacity limit*: the sizes of DSTATCOM units must be within the permitted size limit, which is listed below:

  $$Q_{\min}^{DSTATCOM} \le Q^{DSTATCOM} \le Q_{\max}^{DSTATCOM}, \tag{22}$$

  where Q_{min} and Q_{max} are the DSTATCOM are the limits on reactive power injection or absorption (minimum and maximum), respectively.

4 Solution technique

4.1 Ant-Lion Optimization Algorithm

The Ant-Lion Optimization (ALO) method was proposed by [22] and draws its inspiration from the hunting mechanism for ant lions. This method consists of a random walk exploration followed by a random selection of agents. Traps are used to exploit the situation. ALO inspired us to apply a location in DSTATCOM that had never been used before, according to the authors' knowledge. Random walk of agents, constructing traps, trapping of ants in traps, obtaining prey, and repairing traps are the five fundamental processes of hunting. Local optimization may be eliminated using the ALO optimizer's roulette wheel and random ant walks. The following is a mathematical representation of the ALO algorithm. The steps of ALO Algorithm are as follows [22].

4.1.1 Random walk of ants

Equation (23) shows the random walk of ants:

$$X(t) = \begin{bmatrix} 0, Cum_{sum}\left(2r(t1)-1\right), \\ Cum_{sum}\left(2r(t2)-1\right), \ldots, Cum_{sum}\left(2r(tn)-1\right) \end{bmatrix}, \tag{23}$$

where Cum_{sum} is calculating cumulative sum, n is maximum number of iterations, t is step of random walk:

$$r(t) = \begin{cases} 1 \text{ if } rand > 0.5 \\ 0 \text{ if } rand \le 0.5 \end{cases}, \tag{24}$$

where *rand* is a random number generator that ranges from 0 to 1. Within the search space, a random walk may be performed using Eq. (25):

$$X_i^t = \frac{\left(X_i^t - a_i\right) \times \left(d_i^t - c_i^t\right)}{\left(b_i - a_i\right)} + c_i^t. \tag{25}$$

The lowest and maximum values of the random walk of the i^{th} variable are a_i, b_i. The lowest and maximum of the i^{th} variable in the i^{th} iteration are c_i^t, d_i^t. The ant's current location as well as the accompanying fitness function matrix are shown in Eq. (26):

$$\boldsymbol{M}_{\boldsymbol{Ant}} = \begin{pmatrix} A_{1,1} & A_{1,2} & \cdots & \cdots & A_{1,d} \\ A_{2,1} & A_{2,2} & \cdots & \cdots & A_{2,d} \\ \vdots & & \vdots & & \vdots \\ A_{n,1} & A_{n,2} & \cdots & \cdots & A_{n,d} \end{pmatrix}, \tag{26}$$

$$\boldsymbol{M}_{\boldsymbol{OAL}} = \begin{bmatrix} C_f\left(\left[A_{11}, A_{12}, \dots A_{1d}\right)\right. \\ f\left(\left[A_{21}, A_{22}, \dots A_{2d}\right)\right. \\ \vdots \\ f\left(\left[A_{n1}, A_{n2}, \dots A_{nd}\right)\right. \end{bmatrix}, \tag{27}$$

where $\boldsymbol{M}_{\boldsymbol{OAL}}$ matrix denotes the fitness values of ant lions' position.

4.1.2 Construction of a trap

A roulette wheel is used to increase the chances of collecting ants. This system determines which ant lions are the most fit.

4.1.3 Ant-lion pit trapping

The mathematical equations for trapping are given by:

$$C_t^i = \text{Ant-lion}_j^t + c^t, \tag{28}$$

$$D_t^i = \text{Ant-lion}_j^t + d^t, \tag{29}$$

where C_t^i, D_t^i are the lowest and maximum values of all variables at the i^{th} iteration, respectively. The lowest and maximum of all variables for i^{th} ant are c^t, and d^t. Ant-lion_j^t is the picked ant lion's ant location.

4.1.4 Ants slithering approaching ant lions

Ant lions blast sand outwards to entice ants to approach them. Iteration can be used to model the mathematical model for the aforementioned operation. The ant's current location as well as the accompanying fitness function matrix are shown in Eqs. (30) and (31):

$$\boldsymbol{C^t} = \frac{c^t}{I}, \tag{30}$$

$$\boldsymbol{D^t} = \frac{d^t}{I}, \tag{31}$$

where $I = 10^{\omega}\, t/T$, t is current iteration and T is maximum number of iterations.

4.1.5 Rebuilding the pit and catching prey

The final stage of ant lion hunting behavior is trapping an ant that has reached the bottom of the pit and then updating its position to the most recent position using Eq. (32):

$$\text{Ant-lion}_j^t = \text{Ant}_i^t \text{ if } \left(\text{Ant}_i^t\right) > f\left(\text{Ant-lion}_j^t\right). \tag{32}$$

4.1.6 Elitism

In order to maintain the best solution, it is critical in the evolution algorithm. This may be expressed in Eq. (33):

$$\text{Ant}_i^t = \frac{R_A^t + R_E^t}{2}, \tag{33}$$

where R_A^t, R_E^t are random walks near by the Ant-lion by roulette wheel, elite at i^{th} iteration.

4.2 Application of ALOA for sizing of DSTATCOM

The proposed ALOA method, which calculates optimum DSTATCOM allocation by maximizing the cost-benefit objective function represented in Eq. (20), follows these steps:

1. Step 1: Data for the distribution system's input lines and loads, the number of DSTATCOMs to be installed, DSTATCOM capacity limitations, bus voltage restrictions, distribution line capacity (maximum permissible power flow), restraints, and ALO parameters.
2. Step 2: Perform an initial load flow study for the radial distribution network prior to integrating DSTATCOM for the basic scenario.
3. Step 3: Create a basic firefly population. Each solution has two parts: the first portion reflects the DSTATCOM's position, and the second part represents the DSTATCOM's size. The DSTATCOM solution set is formulated as follows:

$$X = \begin{bmatrix} l_1^1 & l_1^1 & DSTATCOM_1^1 & DSTATCOM_2^1 \\ l_1^2 & l_2^2 & DSTATCOM_1^2 & DSTATCOM_2^2 \\ \vdots & \vdots & \vdots & \vdots \\ l_1^n & l_2^n & DSTATCOM_1^n & DSTATCOM_2^n \end{bmatrix}. \tag{34}$$

4. Step 4: Using distribution load flow, evaluate the individual solutions of the matrix $\boldsymbol{X}$, compute the real power loss P_{loss}, node voltages (V_{bus}) and the objective function in Eq. (20).
5. Step 5: Determine the fitness function is obtained as follows:

$$FF=\left\{\begin{array}{l}\text{Cost-benefit}_{\max}\\ +\sum_{i=1}^{n_b}(\text{penalty factor})\times\left(V_i-V_{\max}\right)^2\\ +\sum_{i=1}^{n_b}(\text{penalty factor})\times\left(V_i-V_{\min}\right)^2\\ +\sum_{i=1}^{n_b}(\text{penalty factor})\times\left(\text{Flow}_i-\text{Flow}_i^{\max}\right)^2\end{array}\right\}, \quad (35)$$

the penalty factor is taken as:

$$\text{penalty factor} =\left\{\begin{array}{cc}0 & \begin{array}{c}\text{if constraints}\\ \text{are not violated}\end{array}\\ -10\times\text{cost-benefit}_{max}\times\text{iteration}^2 & \begin{array}{c}\text{if constraints}\\ \text{are violated}\end{array}\end{array}\right\} \quad (36)$$

6. Step 6: The current best answer is DSTATCOM data with the highest fitness function.
7. Step 7: Update the location of the ant lions using Eqs. (24) to (34).
8. Step 8: Calculate losses, net economic savings, and fitness function for the upgraded population.
9. Step 9: If the fitness function found is higher, replace the existing best solution with it; otherwise, return to Step 7.
10. Step 10: The iteration is terminated after the maximum iterations has been reached and the final result is displayed.

5 Result and discussion

To show the efficacy and performance of the proposed technique, it was evaluated on standard IEEE 33-bus and Dada 46-bus radial distribution systems. The IEEE 33-bus has total real and reactive power demands of 3.715 MW and 2.3 MVAr, respectively, whereas the Dada 46-bus has total real and reactive power demands of 4.12 MW and 2.05 MVAr, respectively. The standard IEEE 33-bus and Dada 46-bus have base cases of 12.66 kV and 11 kV, respectively. All network buses' power is expected to be supplied by the substation located at node 1. Figs. 2 and 3 depict single line diagrams of the IEEE 33-bus and the Dada 46-bus, respectively. The suggested approach is implemented using MATLAB software version R2020a on a Core i3 laptop running at 2.50 GHz with 4GB of installed memory. Table 1 shows system commercial information as well as other cost metrics related with DSTATCOM collected from [14, 23]. In order to evaluate the efficiency of the suggested technique while considering the cost-benefit in Eq. (20), four distinct cases were investigated:

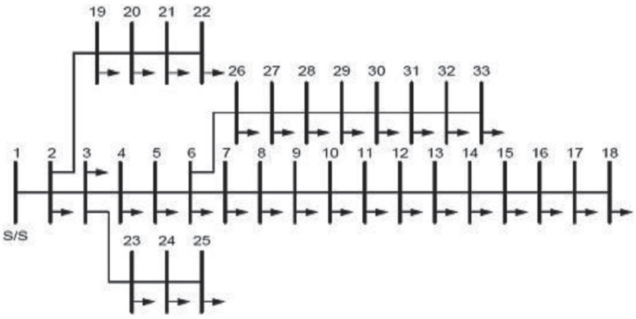

Fig. 2 Standard IEEE 33-Bus System

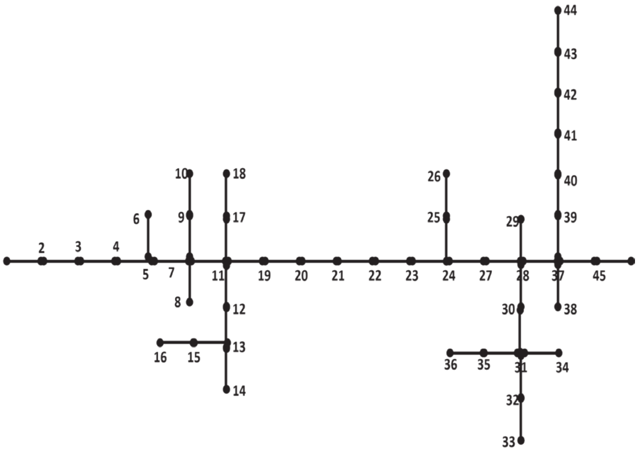

Fig. 3 Dada 46-Bus Distribution System

Table 1 Cost specifications

Parameter	Value
$k_{I,DSTATCOM}$ (\$/kVAr)	50
$MC_{DSTATCOM}$(\$/yr)	10% of $k_{I\,DSTATCOM}$
Inf R (%)	9
Int R (%)	12.5
nyr (in years)	10
$k_{pw,p}$(\$/MWh)	49

1. Case 1: base case without DSTATCOM allocation;
2. Case 2: optimal allocation of single DSTATCOM;
3. Case 3: optimal allocation of two DSTATCOMs;
4. Case 4: optimal allocation of three DSTATCOMs.

5.1 Case 1: System without DSTATCOM

The cost of the power purchased from the transmission grid for the considered period including the power loss (Ploss) before integration of DSTATCOM are $ 14,155,648.42 and 211 kW respectively for IEEE 33-bus system and the values are $ 18,197,543.96 and 927 kW, respectively for Dada 46-bus system.

5.2 Case 2: System with one DSTATCOM

After optimal installation of one DSTATCOM, the cost of the DSTATCOM ($DSTATCOM_{COST}$), the reduced energy cost purchased (C_{pw}) from the transmission grid and the overall cost benefit for the number of planning years are \$ 115,736, \$ 216,337 and \$ 100,601, respectively for IEEE 33-bus distribution system and the values are \$ 138,000, \$ 620,165.95 and \$ 482,165.92, respectively for Dada 46-bus system. From Tables 2 and 3, it is crystal clear that the cost of energy purchased from the transmission grid were reduced from \$ 14,155,648 to \$ 13,939,311.46 and from \$ 18,197,543.96 to \$ 17,577,378, respectively for the IEEE 33-bus and Dada 46-bus distribution systems. The decrease in the cost of the energy power purchased were due to significant reduction of Ploss in the distribution systems due to the optimal installation of one DSTATCOM. This eventually resulted to an appreciable cost benefits of \$ 100,601 and \$ 482,165.92, respectively for the IEEE 33-bus and Dada 46-bus distribution systems despite of the costs incurred for the installation of the DSTATCOM.

5.3 Case 3: System with two DSTATCOMs

The DSTATCOM cost, the reduction in the cost of energy purchased from the transmission grid and overall cost benefit after optimal installation of two DSTATCOMs are \$ 140,576, \$ 248,787.50 and \$ 108,211.50, respectively for IEEE 33-bus system and the values are \$ 161,000, \$ 735,545.66 and \$ 574,545.66, respectively for Dada 46-bus system. From Tables 2 and 3, it is shown that the cost of energy purchased from the transmission grid were reduced from \$ 14,155,648 to \$ 13,906,860.91 and from \$ 18,197,543.96 to \$ 17,461,998.29, respectively for the IEEE 33-bus and Dada 46-bus distribution systems. The cost-benefits were actualized due to significant reduction of Ploss in the distribution systems. This implies that the margin reduced cost of energy purchased from the transmission grid are greater than the cost of installation of the two DSTATCOMs thereby resulting in the cost benefits.

5.4 Case 4: System with three DSTATCOMs

For IEEE 33 bus system, the DTSTATCOM cost, the reduction in energy purchased from the grid and cost

Table 2 Optimal results obtained for IEEE 33-bus distribution system

	No DSTATCOM	1 DSTATCOM	2 DSTATCOMs	3 DSTATCOMs
Optimal Size in kVAr (bus locattion)	–	1258(30)*	4659(12)*, 1063(30)*	308(13)*, 544(24)*, 1037(30)*
Ploss (kW)	210.99	151.36	141.83	138.25
Qloss (kVAr)	143.13	103.98	96.50	94.30
$DSTATCOM_{inv}$ (\$) × 10^5	–	0.6290	0.7640	0.9445
$DSTATCOM_M$ (\$) × 10^5	–	0.5284	0.6418	0.7934
$DSTATCOM_{COST}$ (\$) × 10^6	–	0.1157	0.1406	0.1738
C_{pp} (\$) × 10^6	14.16	13.94	13.91	13.89
C_{pw} (\$) × 10^6	–	0.2163	0.2488	0.2631
Cost-benefit (\$) × 10^6	–	0.1006	0.1082	0.0894
$V_{\min}$ (p.u.)	0.9038	0.9165	0.9303	0.9317

* The numbers in the parenthesis are the bus location of the DSTATCOM

Table 3 Optimal results obtained for Dada 46-bus distribution system

	No DSTATCOM	1 DSTATCOM	2 DSTATCOMs	3 DSTATCOMs
Optimal Size in kVAr (bus location)	–	1500(28)*	1300(11)*, 450(37)*	1260(28)*, 510(4)*, 488(11)*
Ploss (kW)	926.50	755.26	723.22	722.22
Qloss (kVAr)	–	145.06	138.91	138.72
$DSTATCOM_{inv}$ (\$) × 10^5	–	0.7500	0.8750	1.1120
$DSTATCOM_M$ (\$) × 10^5	–	0.6300	0.7350	0.9484
$DSTATCOM_{COST}$ (\$) × 10^6	–	0.1380	0.1610	0.2077
C_{pp} (\$) × 10^6	18.20	17.58	17.46	17.46
C_{pw} (\$) × 10^6	–	0.6202	0.7355	0.7392
Cost-benefit (\$) × 10^6	–	0.4822	0.5745	0.5314
$V_{\min}$ (p.u.)	0.8437	0.8552	0.8590	0.8593

* The numbers in the parenthesis are the bus location of the DSTATCOM

benefits for optimal installation of three DSTATCOMs for the number of planning years are $ 173,788, $ 263,210 and $ 89,422, respectively. Likewise for Dada 46-bus system, the values are $ 207,836, $ 739,151.28 and $ 531,415.28 respectively. The recorded cost benefits were due to significant reduction of Ploss resulting in reduced cost of energy purchased from Transmission Company (Transco).

5.5 Comparative study of results for the different cases

From the overall results for the different cases as shown in the Tables 2 and 3, it is clear that case 3 which involves optimal installation of two DSTATCOMs gave the best results for the consideration of the cost benefit as the objective function. It is observed that the cost benefit improved or increased gradually with the number of DSTATCOM optimally installed until after the allocation of three DSTATCOMs. Even though the Ploss reduction were highest for the optimal installation of three DSTATCOMs but the cumulative effect of the cost of the three DSTATCOMs is higher in relation to the reduced cost of energy purchased from the Transco in comparison to that of two DSTATCOMs allocation. The Ploss, Qloss and voltage profile of the four instances are shown in Figs. 4 to 7 for both the IEEE 33-bus and the Dada 46-bus, respectively. Figs. 4 and 5 show that as the number of DSTATCOMs installed in the distribution system increases, the ploss decreases, whereas Figs. 6 and 7 show that the voltage profile of the distribution improves with optimal DSTATCOM integration and continues to improve as the number of DSTATCOM penetration increases.

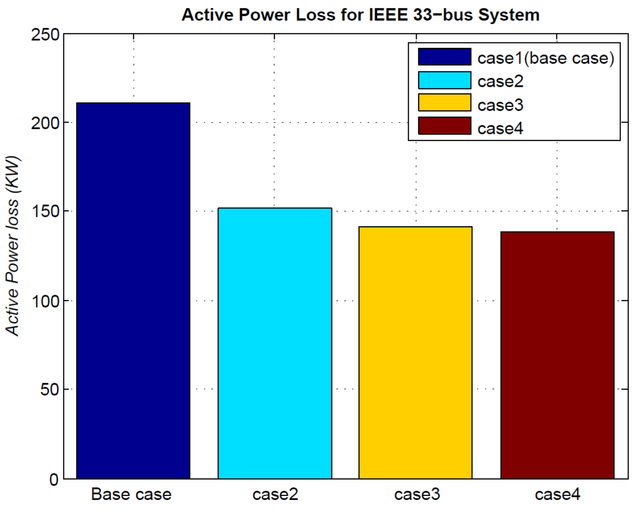

Fig. 4 Real power loss for IEEE 33-Bus system

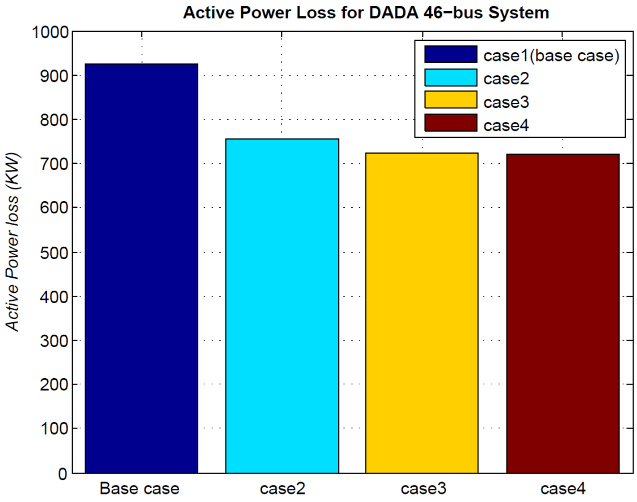

Fig. 5 Real power loss for Dada 46-Bus system

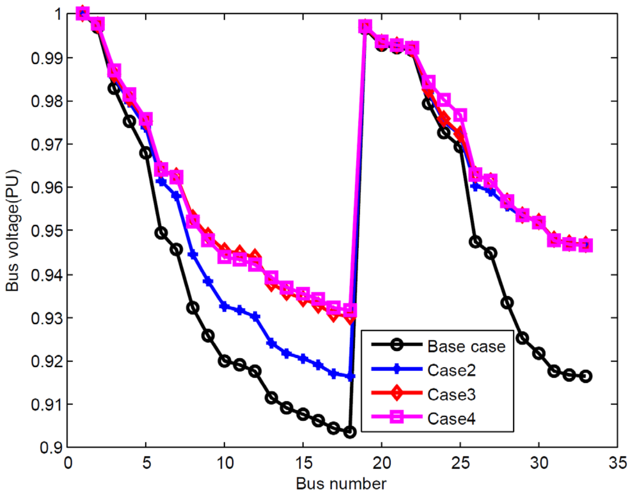

Fig. 6 Voltage profile for IEEE 33 bus system

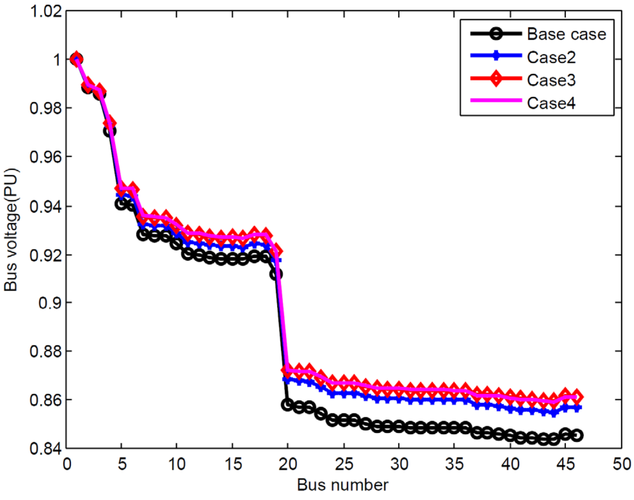

Fig. 7 Voltage profile for Dada 46 bus system

5.6 Comparative Study for IEEE 33-bus distribution system

A comparison is presented with publication [14, 21, 23-27] that uses the same case study to illustrate the computing efficiency of the suggested method compared to other offered techniques. However, for optimal allocation of the DSTATCOM planning problem, the research in [14, 21, 23–27] used various ideas and aims. Furthermore, the cost used in prior DSTATCOM research only considers cost savings in terms of decreased power loss, not the cost of energy acquired through the transmission system. As a result, for all of the situations analyzed, comparisons can only be made based on the Ploss reduction, as shown in Table 4. The technique is also likened to the shunt capacitor (SC), as both DSTATCOM and SC are reactive power compensators with similar characteristics on the total power loss of distribution system. From Table 4, it is shown that the proposed technique is in line with other existing techniques for the different cases considered and provides enhanced power loss reduction.

6 Conclusion

In this study, the ALOA method was used to determine the best placement and sizes for DSTATCOM in a conventional and real distribution network for maximization of the cost savings due to lower power purchased minus DSTATCOM costs. The influence of the number of DSTATCOM on the cost benefit, total active power loss, and voltage profile of the radial distribution networks was also evaluated. As a result, the strategy can save a large amount of energy over the course of a number of planning years. The results reveal that optimal allocation two DSTATCOM units gave the best cost-benefit over allocation installation of one and two DSTATCOM units. The study demonstrated the possibility of DSTATCOM allocation using ALOA to further improve the steady state operation and performance of distribution systems. Further work can consider optimal penetration of DG units with DSTATCOM placements.

Table 4 Comparative study for IEEE 33-bus distribution system

Case	Technique	Year	Description	DSTATCOM/SC in MVAr (bus)	Ploss (kW)	%Ploss
Base case	–	–	–	–	210.98	–
1 DSTATCOM/SC	Analytical [24]	2013	1SC	1(33)*	164.60	21.98
	IA [17]	2014	1DSTATCOM	0.96(12)*	171.81	18.57
	CSO [25]	2017	1DSTATCOM	0.14(23)*	175.01	17.05
	MVO [18]	2018	1DSTATCOM	0.13(30)*	151.39	28.24
	CSA [16]	2020	1SC	0.12(30)*	151.52	28.18
	BA [10]	2021	DSTATCOM	0.11(30)*	151.52	28.18
	ALOA	2022	DSTATCOM	0.13(30)*	151.36	28.86
2 DSTATCOMs/SCs	Analytical [24]	2013	2SC	0.85(7)*, 0.86(29)*	146.64	30.50
	WIPSO-GSA [26]	2018	2SC	0.47(12)*, 1.06(30)*	141.84	32.77
	CSA [16]	2020	2SC	1.0(30)*, 0.40(13)*	142.07	32.66
	ALOA	2022	2DSTATCOM	0.47(12)*, 1.06(30)*	141.83	32.78
3 DSTATCOMs/SCs	Analytical [24]	2013	3SC	0.85(7)*, 0.25(29)*, 0.9(30)*	144.04	31.73
	GSA [27]	2015	3SC	0.45(13)*, 0.8(15)*, 0.35(26)*	134.50	36.25
	BFOA [28]	2015	3SC	0.35(18)*, 0.82(30)*, 0.28(33*)	144.04	31.23
	LSA [19]	2017	3DSTATCOM	0.34(14)*, 0.52(24)*, 1.01(30)*	138.35	34.43
	WIPSO-GSA [23]	2018	3SC	0.69(6)*, 0.31(14)*, 0.77(30)*	134.01	36.48
	CSA [16]	2020	3SC	450(11)*, 400(24)*, 950(30)*	138.65	34.28
	ALOA	2022	3DSTATCOM	0.31(13)*, 0.54(24)*, 1.04(30)*	138.25	34.47

* The numbers in the parenthesis are the bus location of the DSTATCOM

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