American Journal of Electrical Power and Energy Systems
2023; 12(4): 68-76
http://www.sciencepublishinggroup.com/j/epes
doi: 10.11648/j.epes.20231204.12
ISSN: 2326-912X (Print); ISSN: 2326-9200 (Online)

Impact Assessment of Optimal Integration of Combined DG and D-STATCOM Allocation for Active Distribution System Enhancement with Loading Variations

Musa Mustapha[1, 2, *], Ganiyu Ayinde Bakare[2], Yau Shuaibu Haruna[2], Babagana Mallambe Mustapha[1, 2], Musa Baba Lawan[1], Abdulkadir Abubakar Sadiq[2]

[1]Department of Electrical and Electronics Engineering, University of Maiduguri, Maiduguri, Nigeria

[2]Department of Electrical and Electronics Engineering, Abubakar Tafawa Balewa University, Bauchi, Nigeria

Email address:

musamustyy@unimaid.edu.ng (Musa Mustapha), gabakare@atbu.edu.ng (Ganiyu Ayinde Bakare), ysharuna@atbu.edu.ng (Yau Shuaibu Haruna), bgmustaphaee@yahoo.com (Babagana Mallambe Mustapha), babalawan24@unimaid.edu.ng (Musa Baba Lawan), engrsadiqgam@gmai.com (Abdulkadir Abubakar Sadiq)

[*]Corresponding author

To cite this article:

Musa Mustapha, Ganiyu Ayinde Bakare, Yau Shuaibu Haruna, Babagana Mallambe Mustapha, Musa Baba Lawan, Abdulkadir Abubakar Sadiq. Impact Assessment of Optimal Integration of Combined DG and D-STATCOM Allocation for Active Distribution System Enhancement with Loading Variations. *American Journal of Electrical Power and Energy Systems*. Vol. 12, No. 4, 2023, pp. 68-76.
doi: 10.11648/j.epes.20231204.12

Received: July 11, 2023; **Accepted**: July 26, 2023; **Published**: August 4, 2023

Abstract: Renewable Distributed Generation (RDG) is a promising alternative to conventional power generation methods because it reduces power losses and dependence on central power generation. However, when DG is deployed, it doesn't always provide the reactive power needed for proper voltage regulation leading to low voltage on some buses. To achieve the maximum benefits of a DG unit, a combined DG and D-STATCOM allocation is evaluated. The selection of the optimal capacity and position of these compensators requires appropriate optimization methods to be solved. The real and reactive power loss reduction and voltage profile improvement was selected as objective function and the Artificial Bee Colony (ABC) optimization algorithm was used to solve the optimal allocation problem under variable load conditions. Four case studies, including combined DG / D-STATCOM at the same location (Case III) and combined DG / D-STATCOM at separate locations (case IV), were considered under different load factors of normal, light and peak loading conditions. The performance analysis of these approaches was tested on the standard IEEE 33-bus radial distribution system. The MATLAB 2021b environment was used for the simulations. The outcomes showed that applying optimal DG and D-STACOM at separate locations resulted in a better percentage real power loss reduction of (76.34%, 75.95%, and 75.41%) compared to combined DG/D-STATCOM at the same location, which recorded (72.41%, 71.62% and 71.12%) under normal, light and peak loading conditions. Similarly, optimal DG/DSTATCOM at separate locations recorded better reactive power loss reduction (72.71%, 72.71%, and 72.11%) compared to DG/D-STATCOM at the same location, which recorded (66.57%, 66.57%, and 65.98%) under the said loading conditions. However, DG/D-STATCOM at the same location offered slightly better voltage profile improvement.

Keywords: Distribution Static Compensator (D-STATCOM), Distributed Generation (DG), Artificial Bee Colony, Distribution System

1. Introduction

The conventional power system structure consists of three main sections: generation, transmission and distribution systems, and are clearly distinguished by either step-up or step-down power transformers. The system was not initially designed with the intention of distributed generation (DG) integration. However, growth in load demand requires building new generating stations and extension of distribution and transmission systems, which is undesirable from an economic and environmental point of view. Especially when many countries are trying to meet the greenhouse gas emissions reduction targets set by the Kyoto Protocol [1, 2]. Hence, the power system planning and expansion have led to the evolution of the power system driven by the penetration of renewable energy sources, low carbon policies and decentralization to fulfill the growth in load demand.

Recently, there has been a lot of focus on RDG sources as the have the potential to replace traditional energy sources. However, incorporating DG systems into utility grid can cause reactive power issues, which can compromise the stability of the network. As more large-scale DGs are connected to the power distribution network, this integration challenge is expected to escalate, leading to technical issues that may affect the power quality of the entire network system [3]. Identifying the optimal locations and capacity of DGs in the power distribution system has become a challenge [4]. However, Enormous benefits can be achieved from DGs if carefully selected, sized, and placed in electrical power systems. This can help ensure that DGs are used effectively and efficiently, and provide the most significant possible benefits to utilities, consumers, and the environment [5]. Several studies are present in the literature that reviewed optimization techniques for optimal DG placement and sizing in power distribution system for power loss minimization and voltage stability [6, 5].

Custom Power Devices (CPD) plays a vital role in improving the power quality and reliability of the distribution system (DS). Among the CPD devices, D-STATCOM is the most reliable due to its good performance and excellent features [7]. Its features make it simple for reactive power and unbalanced load compensation in keeping with the network requirements. But the benefit of these compensators also depends heavily on their positions and ratings in the power DS [8]. Sirjani and Jordehi discussed a reviewed article on the optimal allocation of D-STATCOM in the electrical power distribution system [9].

Several research papers have been published that explain various methods used in the optimal allocation of DG or D-STATCOM independently in distribution networks. Biogeography-Based Optimization [10], Shuffled Frog Leap Algorithm [11] Swarm Month Flame Optimization [12] etc. were used for optimal deployment of DG in the DS. Similarly, the Weighted Artificial Fish Swarm Algorithm [13], Voltage Stability Index and Bat algorithm [14], Immune Algorithm [15], Ant Colony Algorithm [16], Firefly algorithm [17] etc. were used for optimal allocation of D-STATCOM in power DS.

Studies show that while researchers have mainly focused on placing DG or D-STATCOM individually, implementing combined DG/D-STATCOM has the potential to further reduce system losses and improve voltage stability Some researchers have attempted simultaneous allocation of DG and D-STATCOM in the DS. Penguins Optimization Algorithm was utilized for simultaneous placement of DG and D-STATCOM with an objective of total power loss reduction [18]. Gravitational Search Algorithm was used for D-STATCOM and DG allocation on the IEEE- 33 bus RDS. The objective was to minimize active power loss and improve voltage profile in [19]. Similarly, voltage stability index and variation technique were employed voltage to place DG and D-STATCOM optimally on radial DS, with the objective of minimizing power loss and harmonic distortion [20]. Modified Multi-objective Particle Swarm Optimization was utilized to determine the optimal location of PV and wind DG with D-STATCOM [21]. This resulted in improve voltage stability, reliability as well as reduce pollution. Artificial Fish Swarm Optimization method was utilized to allocate DG and D-STATCOM optimally, aimed to reduce power loss and improve voltage profile on the IEEE 14 and 33 bus RDS [22].

The Artificial Bee Colony (ABC) swarm optimization algorithm is population-based stochastic optimization method that have successfully handle nonlinear and discrete optimal problems. Extensive studies proved that ABC is still far more efficient than GA, DE, and the PSO optimization methods and requires fewer control parameters to be tuned [23]. Also, it is easy to use, fast, and compatible with power system controller design, allowing for simple and quick convergence. Such features have motivated the use of ABC to solve different kinds of engineering problems such as constrained multi-objective problem [24] DGs allocation [25] bioinformatics [26], soft computing [27], DG and capacitor placement with network reconfiguration [28] etc.

From the literature survey, researchers have used the optimal placement of these compensators to solve power loss and voltage issues in the distribution system. However, integrating DG into the system can make voltage regulation more complex over long distances, especially when dealing with varying loads. This can result in voltage drops and fluctuating reactive power flow, affecting the system's ability to maintain voltage stability and potentially increasing power losses. Based on the available literature, authors have prioritized the optimal deployment of combined DG and D-STATCOM by focusing on the system's normal loading but have not taken into account multi-level loads in the radial distribution system. Therefore, this study addresses these issues by examining the optimal allocation of combined DG and D-STATCOM, comparing their placement at the same or separate locations using the ABC optimization method. The study also considers multi-level loads (normal, light, and peak) to determine the impact of load variations on DG and D-STATCOM's size and verify how optimal solutions should adapt to the changing load conditions.

The rest of the article is as follows: the problem formulation and the objective functions are explained in Section 2. The methodology considered is described in Section 3. Simulation results are presented and explained in Section 4, followed by the conclusion of the manuscript in Section 5.

2. Problem Formulation

2.1. Power Flow Analysis

The traditional methods for analyzing power flow work well for transmission systems, but they are not as effective for distribution systems because of the radial structure of the networks. To address this, the Bus Injection to Branch Current (BIBC) matrix and forward sweep load flow approach was used to determine line losses and bus voltages. Figure 1 illustrates a schematic representation of a basic two-bus power distribution system.

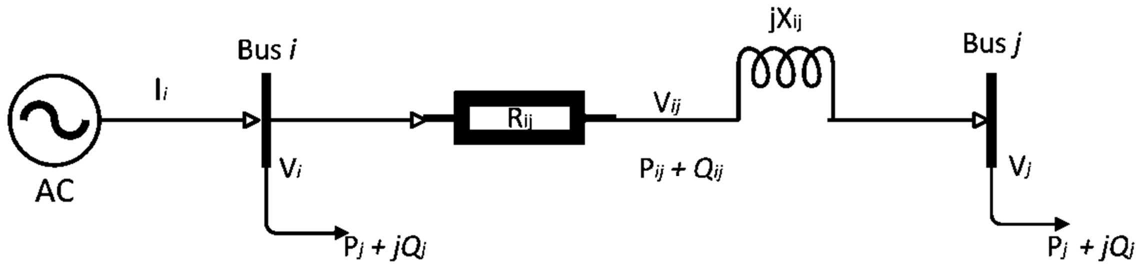

Figure 1. *Schematic representation of a simple 2-bus distribution network.*

The network power flow computation is conducted using the equations obtained from Figure 1.

2.1.1. Computation of the Load Current

The computation of the load current at bus *i* is expressed as:

$$I_i = \left(\frac{P_i + jQ_i}{V_i}\right)^* = \left(\frac{P_i - jQ_i}{V_i^*}\right) \text{ for i = 1, 2……….. } N_{Bus} \quad (1)$$

Where; N_{Bus} represents the total number of buses,
I_i Is the load currents
P_i & jQ_i are the bus *i* active and reactive power demand
V_i^* Is the bus *i* voltage conjugate

2.1.2. BIBC Matric Formulation

Kirchhoff's Current Law (KCL) is applied to the network to establish the relationship between load currents (I_i) and branch currents (I_{ij}). The network branch currents are expressed in matrix form as;

$$[I_{ij}] = [BIBC] * [I_i] \quad (2)$$

Where; BIBC is the load current injection to the branch current matrix and contains only 0 and 1 values.

2.1.3. Forward Sweep

To calculate the bus voltages at the receiving end, simply subtract the corresponding branch voltage drop from the sending end voltage values. This is possible because the voltage values of the source buses are already known. The forward sweep formula is expressed as;

$$V_j = V_i - I_{ij} * \left(R_{ij} + jX_{ij}\right) \quad (3)$$

2.1.4. Power Losses

Eq. (4) and (5) are used to calculate the real and reactive power losses.

$$P_{ij(Loss)} = \left|I_{ij}\right|^2 * R_{ij} \quad (4)$$

$$Q_{ij(Loss)} = \left|I_{ij}\right|^2 * jX_{ij} \quad (5)$$

By summing up all of the power losses of each individual branches, the overall real and reactive power losses of the system are expressed in (6) and (7)

$$P_{T(Loss)} = \sum_{i=1}^{NBus} P_{ij(Loss)} \quad (6)$$

$$Q_{T(Loss)} = \sum_{i=1}^{NBus} Q_{ij(Loss)} \quad (7)$$

Refer [19, 16] for the DG and D-STATCOM Models.

2.2. Objective Function

The combined DG/D-STATCOM placement aims to minimize power losses and improve voltage profile. The optimal position and capacity of compensators are selected to achieve this goal.

The power loss reduction by DG/D-STATCOM deployment is computed as;

$$J_1 = \frac{P_{T,loss,ij\ after\ DG/D-STATCOM}}{P_{T,loss,ij\ before\ DG/D-STATCOM}} \quad (8)$$

Where the $P_{T,loss,ij\ after\ DG/D-STATCOM}$ is total power loss reduction after DG/D-STATCOM placement & $P_{T,loss,ij\ beforeDG/D-STATCOM}$ is the system overall power loss of the distribution system before DG/D-STATCOM placement.

Minimization of Bus Voltage Deviation

Optimal placement of DG and D-STATCOM in the distribution system improves the voltage profile of the system. The concept of the voltage deviation index is represented as;

$$\Delta V_D = \left(\frac{V_{i,ref} - V_i}{V_{i,ref}}\right)^2 \quad (9)$$

Where $V_{i,ref}$ & V_i are the bus *i* reference and the actual voltage. Hence, the average voltage deviation is the summation of normalized ΔV_D for all buses, given in (10).

$$J_2 = \Delta V_{D-avg} = \sum_{i=1}^{NBus} \left(V_{VD}^{norm}\right)_{after\ DG/D-STATCOM} \quad (10)$$

Where NBus is the overall number of buses.

The objective function is mathematically formulated in eq. (11) as;

$$\text{Min } (F_1) = Min\,(\alpha_1 J_1 + \alpha_2 J_2) \quad (11)$$

The fitness function is given as

$$\text{Fitness} = \frac{1}{1+objectibe\ function} \quad (12)$$

Where α_1 & α_2 are the weight factors used for constraints handling. The objective function is defined with the succeeding constraints;

Power balance equality constraints

$$\sum_{i=1}^{NBus} P_{DG/DSTATCOM(i)} = \sum_{i=1}^{NBus} P_{Di} + P_L \quad (13)$$

$$\sum_{i=1}^{NBus} Q_{DG/DSTATCOM(i)} = \sum_{i=1}^{NBus} Q_{Di} + Q_L \quad (14)$$

Where $P_{DG/DSTATCOM}$& $Q_{DG/DSTATCOM}$ are the active and reactive power generated at bus *i* with the DG/D-STATCOM; P_{Di}, Q_{Di} are the overall active and reactive power demand of the load, P_L, Q_L are the system active and reactive power losses respectively.

The inequality constraints are the voltage magnitude, DG and D-STATCOM limits given as:

$$V_i^{min} \le V_i \le V_i^{max} \text{ for i= 1,….. NBus} \quad (15)$$

$$P_{DG,min} \le P_{(i)DG/D-STATCOM} \le P_{DG,max} \text{i = 2…... NBus} \quad (16)$$

$$Q_{DG,min} \le Q_{(i)DG/D-STATCOM} \le Q_{DG,max} \text{i = 2…... NBus} \quad (17)$$

Here, max and min represent the maximum and minimum of the parameter values.

In this work, the PV DG source supplies active power only and reactive power is supplied by the D-STATCOM.

3. Methodology

3.1. Artificial Bee Colony Optimization Algorithm

The Artificial Bee Colony (ABC) algorithm is a metaheuristic search technique that was introduced by Karaboga in 2005 [29]. It was based on the behavior of honey bees. Bee colonies have a well social structure and are divided into three distinct groups; employed bees, onlooker bees and scout bees. The employed bee exploit food source and share information on the nectar amount with the onlooker bee. The onlookers use a dance called wrangle dance to assess the food source of employee bees. If the number of visiting bees doesn't increase, the food source is abandoned, indicating low quality. In that case, the employed bee becomes a scout. In a bee colony, there are scout bees that search for new food sources to avoid overexploiting one location. These scout bees conduct a random search to explore the environment and find new food sources (solution). A detailed description of the ABC algorithm can be found [30]. The flowchart of the ABC algorithm is represented in Figure 2.

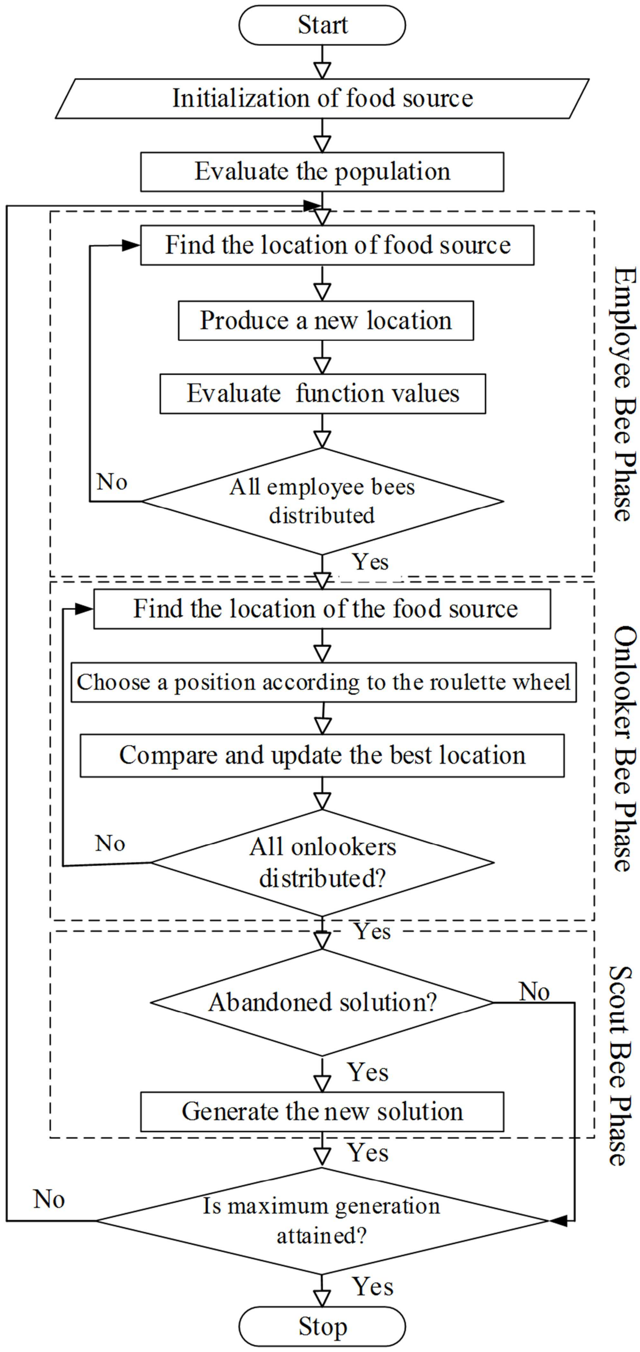

Figure 2. *Flowchart for the ABC optimization algorithm [31].*

3.2. Implementation of Optimal Combined DG and D-STATCOM Allocation

The flowchart for the implementing of the optimal allocation of combined DG and D-STATCOM using the ABC algorithm is presented in Figure 3.

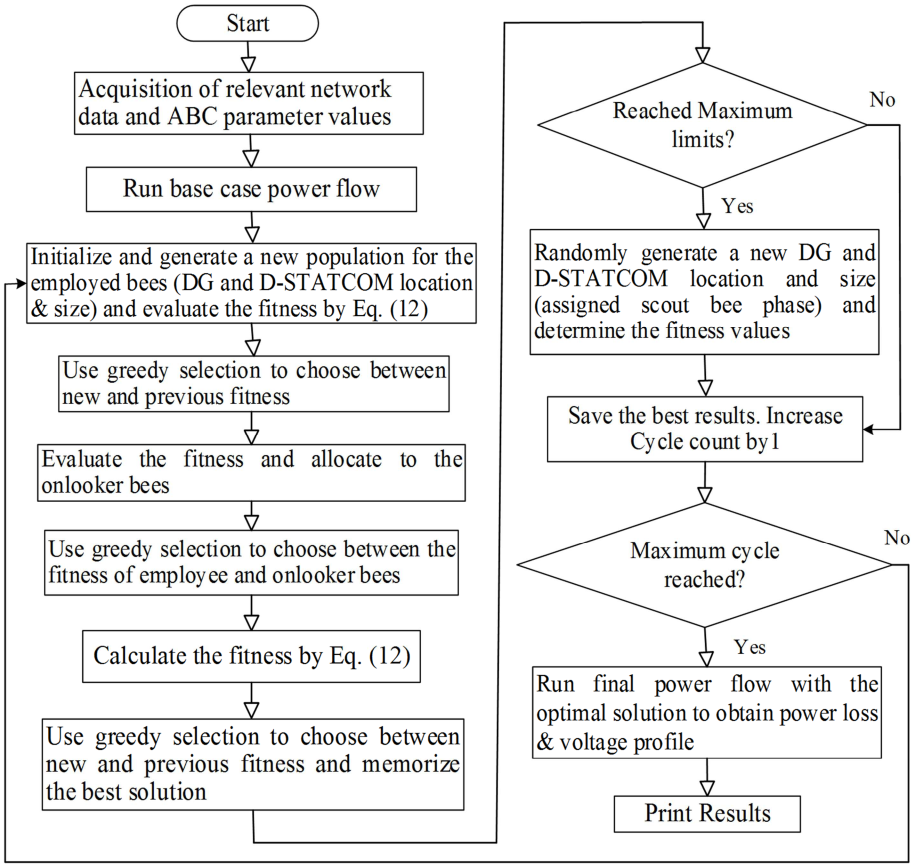

Figure 3. *Flowchart of the optimal deployment of combined DG and D-STATCOM using ABC Algorithm.*

4. Simulation Results and Discussion

The algorithm for the optimal allocation of DG and D-STATCOM was developed in the MATLAB environment (R2021b version) and its effectiveness was evaluated on the IEEE 33-bus radial distribution system. The total network requirements for active and reactive power of the test system are 3715kW and 2300kVAR at a nominal voltage of 12.66 kV under normal loading conditions. Similarly, the system loading decreased by 25% and raised by 30% to consider light and peak system loading conditions. The total network requirements for active and reactive power of the test system under light and peak loading conditions are 2786.25kW, 1725kVAR and 4829.5kW, 2990kVAR, respectively. The one-line diagram, line data and bus data of the standard IEEE 33-bus test system can be found [32]. Here, four case studies were considered for simulation as follows;

Case I: The base case without DG and D-STATCOM compensation.

Case II: The system with optimal DG placement.

Case III: The system with DG and D-STATCOM optimally sited in the same location.

Case IV: The system with DG and D-STATCOM optimally sited at separate locations.

Tables 1, 2 and 3 summarizes the simulation results of the test system under normal light and peak loading conditions respectively. The results of the simulation for the test system under normal loading are displayed in Table 1. After conducting a power flow analysis of the network's base case, the system active and reactive power loss was found to be 201.7749kW, 134.9912kVAR. The ABC method was applied to determine the optimal position and size of DG, combined DG/D-STATCOM at the same location as well at separate locations (case II, III, and IV), respectively. The result show that DG was optimally placed at bus 25, with a size 2711kW (case II), the total active and reactive power loss decrease from the initial value to 101.3768kW, 72.9192kVAR. This corresponds to percentage power loss reduction of 49.76% and 45.98%, respectively. In case III, the placement of both DG/D-STATCOM at the same location resulted in a further substantial improvement in the percentage reduction of real and reactive power loss to 72% and 66.57%, respectively. The optimal capacity and position of DG and D-STATCOM was found to be 2717kW and 1800kVAR at bus 25, as presented in Table 1. However, when DG and D-STATCOM were optimally sited at separate positions in case IV, it was observed that the system's power loss reduction was slightly better than in case III which further improved to 76.33% and 72.70% respectively. The study found that bus 5 and 30 were the optimal positions of DG and D-STATCOM, with capacity of 2713kW, and 1200kVAR respectively. Interestingly, the D-STATCOM size decreased from 1800 kVAR in case III to 1200 kVAR in case IV, as captured in Table 1.

Table 2 presents the simulation results of the test system under light loading conditions. In the base case, the system's active and reactive power loss was 113.4984kW, 75.9326kVAR. The result shows that by optimally placing DG at bus 5, the total active and reactive power loss reduction decreased from the initial value to 57.4619kW, 41.0045kVAR. This corresponds to an improvement percentage power loss reduction of 49.76% and 45.98%, respectively. Comparing case III and case IV, it was revealed that case IV offered better real and reactive percentage power loss reduction of 76.34% and 72.71%, compared to case III which recorded 72% and 66.57%, respectively. The results also revealed that the optimal locations for DG and D-STATCOM in case IV were selected at bus 5 and 30 with a capacity of 2028kW and 900kVAR, respectively.

The simulation results for the test system during peak loading conditions is shown in Table 3. In The base case system, active and reactive power loss was 340.9995kW, 228.1352kVAR, respectively. with DG optimally placed at bus 5 in Case II, the percentage of total active and reactive power loss reduction improved to 48.87% and 45.31%, respectively. Comparing case III and IV, case IV offered better real and reactive percentage power loss reduction of 75.41% and 72.11%72.71%, while case III recorded 71.12% and 65.98%, respectively. The analysis also shows that the size of the D-STATCOM decreased from 2300 kVAR in case III to 1500 kVAR in case IV as captured in Table 3.

Table 1. *Performance evaluation of the simulation results considering normal loading.*

Case Study (Light Load Factor =1.0)	Base Case	Optimal DG allocation	DG/D-STATCOM allocation in the same location	DG/D-STATCOM allocation at separate positions
DG capacity (Position)	-	2711kW (25)	-	-
DG and D-STATCOM capacity (Positions)	-	-	2717kW, 1800kVAR (25)	2713kW, 1200kVAR (5, 30)
Total active and reactive power loss (kW, kVAR)	201.7749, 134.9912	101.3768, 72.9192	56.4783, 45.1269	47.748, 36.8369
Percentage active and reactive power loss reduction	-	49.76% 45.98%	72% 66.57%	76.34% 72.71%
Minimum bus voltage p.u, (location)	0.9134 (18)	0.950 (18)	0.9661 (18)	0.9838 (18)
Performance voltage deviation index	0.119168	0.03098	0.01216	0.012669

Table 2. *Performance evaluation of the simulation results considering light loading.*

Case Study (Light Load Factor =0.75)	Base Case	Optimal DG allocation	DG/D-STATCOM allocation in the same location	DG/D-STATCOM allocation at separate positions
DG capacity (Position)	-	2030kW (5)	-	-
DG and D-STATCOM capacity (Positions)	-	-	2033kW, 1348kVAR (5)	2028kW, 900kVAR (5, 30)
Total active and reactive power loss (kW, kVAR)	113.4984, 75.9326	57.4619, 41.0045	32.2068, 25.3869	27.2958, 20.7201
Percentage active and reactive power loss reduction	-	49.37% 46%	71.62% 66.57%	75.95% 72.71%
Minimum bus voltage p.u, (location)	0.9352 (33)	0.9629 (18)	0.9748 (18)	0.9707 (18)
Performance voltage deviation index	0.067009	0.017503	0.006789	0.006904

Table 3. *Performance evaluation of the simulation results considering peak loading.*

Case Study (Light Load Factor =1.3)	Base Case	Optimal DG allocation	DG/D-STATCOM allocation in the same location	DG/D-STATCOM allocation at separate positions
DG capacity (Position)	-	3000kW (5)	-	-
DG and D-STATCOM capacity (Positions)	-	-	3000kW, 2300kVAR (5)	3000kW, 1500kVAR (5, 30)
Total active and reactive power loss (kW, kVAR)	340.9995, 228.1352	174.3492, 124.7714	98.4864, 77.8244	83.8441, 63.6336
Percentage active and reactive power loss reduction	-	48.87% 45.31%	71.12% 65.98%	75.41% 72.11%
Minimum bus voltage p.u, (location)	0.8875 (33)	0.929 (33)	0.9486 (33)	0.9703 (33)
Performance voltage deviation index	0.201289	0.067776	0.030119	0.031093

The voltage deviation index measures how far the bus voltage deviates from the nominal voltage. A lower index value indicates better network performance. Based on the results presented in Tables 1, 2, and 3, it was found that case III, which involves placing the DG/D-STATCOM at the same location, had the lowest voltage deviation index values of 0.01216, 0.006789, and 0.030119, under normal, light, and heavy loading conditions, respectively.

Figures 4, 5, and 6 display the performance outcome of the bus voltage profile effect in solving cases I to IV of the test system network under normal, light, and peak loading conditions.

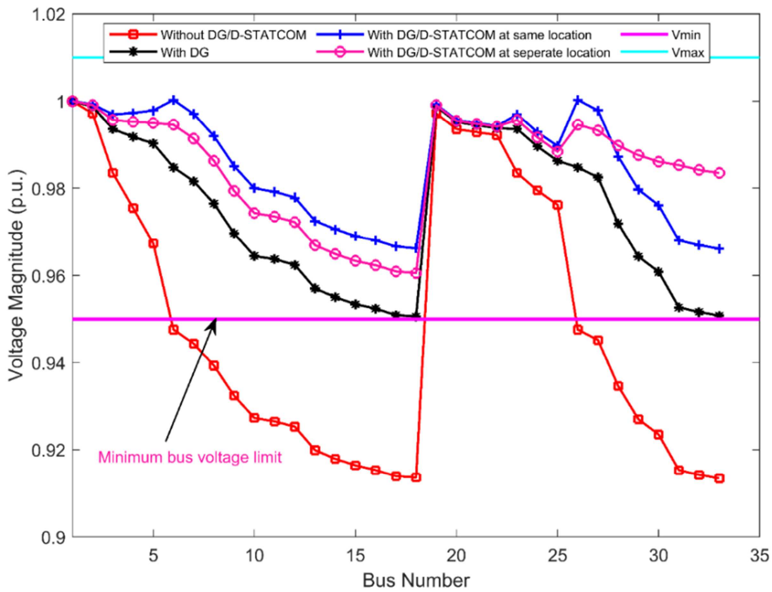

Figure 4. *Comparison of voltage profile for the cases I-IV under normal loading condition.*

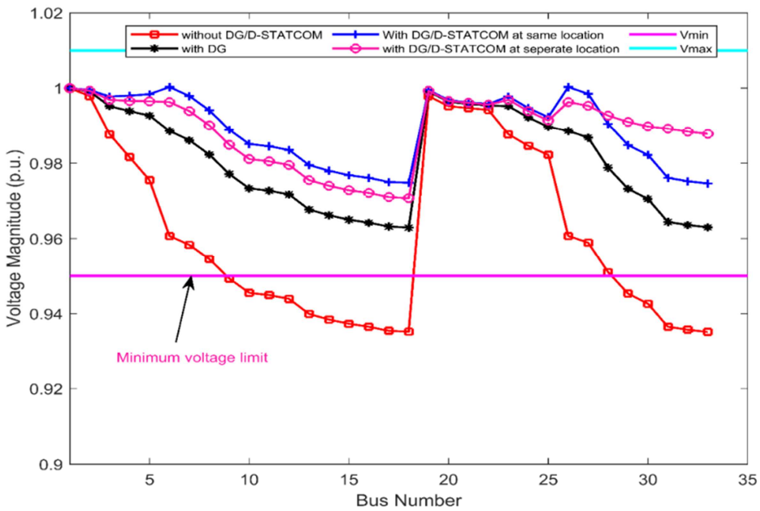

Figure 5. *Comparison of voltage profile for the cases I-IV under light loading condition.*

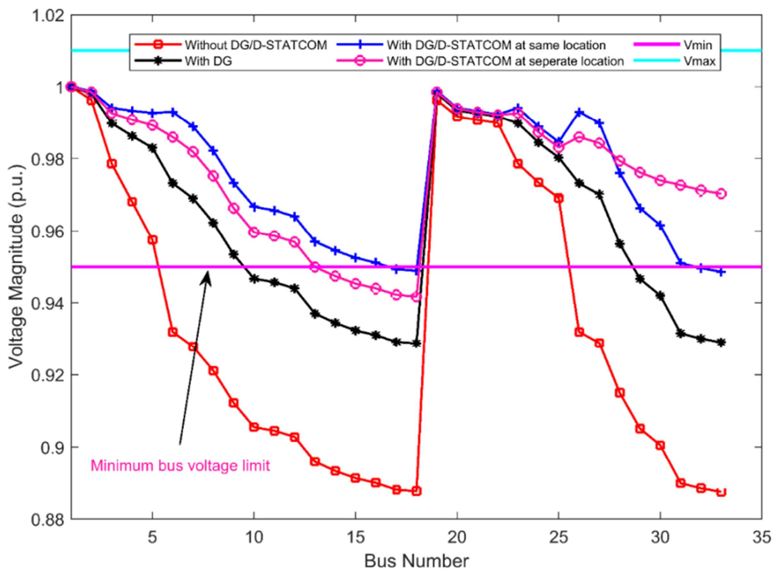

Figure 6. *Comparison of voltage profile for the cases I-IV under peak loading condition.*

The performance outcome of the bus voltage profiles for solving cases I - IV under normal, light and peak loading conditions are displayed in Figures 4, 5 and 6 respectively. The figures compare the impact of each case on the system bus voltage.

The normal loading condition in Figure 4 revealed that placing the DG in an optimal position improved the bus voltage profile significantly compared to the base case (Case I), even though some nodes were on the step line. To ensure proper functioning, a minimum bus voltage of 0.95p.u was set. Comparing Cases III and IV, it was found that both had better voltage profiles than Case II. However, Case III showed a slight improvement in the voltage profile compared to Case IV, as shown in Figure 4.

Figure 5 revealed that optimal placement of the combined DG and D-STATCOM (case III) during light loading significantly improved the voltage profile compared to other cases. Moreover, the bus voltage was better during light loading than under normal loading conditions.

In Figure 6, the voltage profile at different buses during peak load is compared. The results show that as the load increases, the voltage violations at the buses become more noticeable, exceeding the permissible operating limit. Additionally, placing both DG and D-STATCOM at the same position resulted in a better improvement in voltage profile compared to other cases.

The above analysis concludes that the placement of combined DG and D-STATCOM reduces the total system loss and enhance the voltage profile in the system. Interestingly, it was discovered that when DG and D-STATCOM are placed at different locations, it resulted in a better reduction of power loss compared to when they were placed in the same location. Nevertheless, the voltage profile was slightly better when both DG and D-STATCOM were placed on the same bus, as opposed to being placed on separate buses.

5. Conclusion

This paper examines the ABC-based optimal deployment of combined DG and D-STATCOM with different load factors of (normal, light and medium loads) in radial DS. These compensating devices can be optimally placed in the same or separate locations. The study revealed that optimal placement of combined DG and D-STATCOM at separate locations (case IV) is more effective in reducing the total power loss than placement at the same location (case III). The findings also revealed that optimal DG and D-STATCOM placement at different locations resulted in better performance with lower compensators ratings compared to placement at the same location. However, combined DG and D-STATCOM placement in the same location has resulted in a slight improvement in the voltage profile compared to placing them at separate locations. The findings are presented in a table for easy comparison. Also, the study has demonstrated that the ABC algorithm can solve complex nonlinear optimization problems with many decision variables. Future research should consider these compensators' installation and operational costs in real-time radial distribution systems. Additionally, exploring newer optimization methods could also be beneficial.

Acknowledgments

The primary author expresses gratitude to Tertiary Education Trust Fund (TETFUND) Nigeria for providing financial assistance through a scholarship. Furthermore, the authors appreciate the unwavering support of the University of Maiduguri.

References

[1] Marwali, Mohammad N., Jin-woo Jung, and Ali Keyhani (2004). Control of Distributed Generation Systems — Part II : Load Sharing Control. *IEEE Transactions on Power Electronics* 19 (6). doi: 10.1109/TPEL.2004.836634.

[2] Zeineldin, H. H., Ehab F. El-Saadany, and M. M. A. Salama (2006). "Impact of DG Interface Control on Islanding Detection and Nondetection Zones. *IEEE Transactions on Power Delivery* 21 (3) doi: 10.1109/TPWRD.2005.858773.

[3] J. Machowski, J. W. Bialek, J. R. Bumby (2011). Power System Dynamics: Stability and Control. Second Edion. doi: 10.1007/978-1-4471-2291-3_5.

[4] Pandi, V. Ravikumar, H. H. Zeineldin, and Weidong Xiao (2012). Distributed Generation Resources Considering Harmonic and Protection Coordination Limits. *IEEE Transactions on Power Systems*. 8 (2) doi: 10.1109/TPWRS.2012.2209687.

[5] Shuaibu Hassan, Abdurrahman, Yanxia Sun, and Zenghui Wang (2020). Optimization Techniques Applied for Optimal Planning and Integration of Renewable Energy Sources Based on Distributed Generation: *Recent Trends. Cogent Engineering* 7 (1). doi: 10.1080/23311916.2020.1766394.

[6] Sultana, U., Azhar B. Khairuddin, M. M. Aman, A. S. Mokhtar, and N. Zareen (2016). A Review of Optimum DG Placement Based on Minimization of Power Losses and Voltage Stability Enhancement of Distribution System. *Renewable and Sustainable Energy Reviews* 63: 363–78. doi: 10.1016/j.rser.2016.05.056.

[7] Gupta, Atma Ram, and Ashwani Kumar (2015). Energy Savings Using D-STATCOM Placement in Radial Distribution System. *Procedia Computer Science* (70) 558–64. doi: 10.1016/j.procs.2015.10.100.

[8] Gupta, Atma Ram, and Ashwani Kumar (2019). Deployment of Distributed Generation with D-FACTS in Distribution System: A Comprehensive Analytical Review. *IETE Journal of Research* 68 (3). doi: 10.1080/03772063.2019.1644206.

[9] Sirjani, Reza, and Ahmad Rezaee Jordehi (2017). Optimal Placement and Sizing of Distribution Static Compensator (D-STATCOM) in Electric Distribution Networks: A Review. *Renewable and Sustainable Energy Reviews* 77 (October 2016). doi: 10.1016/j.rser.2017.04.035.

[10] Duong, Minh Quan, Thai Dinh Pham, Thang Trung Nguyen, Anh Tuan Doan, and Hai Van Tran. (2019). Determination of Optimal Location and Sizing of Solar Photovoltaic Distribution Generation Units in Radial Distribution Systems. *Energies* 12 (1). doi: 10.3390/en12010174.

[11] Zadehbagheri, Mahmoud (2013). Optimal DG Placement in Distribution Networks Using Shuffled Frog Leap Algorithm. in Proceedings of *4th International Graduate Conference on Engineering, Science and Humanities* IGCESH.

[12] Tan, Zhukui, Ming Zeng, and Liming Sun (2021). Optimal Placement and Sizing of Distributed Generators Based on Swarm Moth Flame Optimization. *Frontiers in Energy Research*. 9. doi: 10.3389/fenrg.2021.676305.

[13] Umar Musa, Ganiyu Ayinde Bakare, Mohammed Aminu Shehu, and Umar Abubakar (2017). D-STATCOM Placement in Distribution Systems Using Weighted Artificial Fish Swarm Algorithm. *IEEE 3rd International Conference on Electro-Technology for National Development (NIGERCON).*

[14] Yuvaraj, T., K. Ravi, and K. R. Devabalaji. (2015). D-STATCOM Allocation in Distribution Networks Considering Load Variations Using Bat Algorithm." *Ain Shams Engineering Journal* 8 (3). doi: 10.1016/j.asej.2015.08.006.

[15] Taher, Seyed Abbas, and Seyed Ahmadreza Afsari (2014). Optimal Location and Sizing of DSTATCOM in Distribution Systems by Immune Algorithm. *International Journal of Electrical Power and Energy Systems* 60: 34–44. doi: 10.1016/j.ijepes.2014.02.020.

[16] Oloulade, A., A. Moukengue Imano, A. Viannou, and H. Tamadaho (2018). Optimization of the Number, Size and Placement of D-STATCOM in Radial Distribution Network Using Ant Colony Algorithm. American Journal of Engineering Research and Reviews 1–13. doi: 10.28933/AJOERR.

[17] Mela Lashiru Lele, Aliyu Usman Otaru, Ganiyu Ayinde Bakare and Musa Mustapha (2022). Application of Firefly Algorithm to the Optimal Siting and Sizing of D-STATCOM in Distribution Networks. *IEEE 4th International Conference on Disruptive Technologies for Sustainable Development, NIGERCON 2022* - Proceedings.

[18] Prabu, J., and S. Muthuveerapan (2016). Optimum Placement and Sizing Determination of Distributed Generation and DSTATCOM Using Penguins Search. *International Journal of Innovative Research in Science, Engineering and Technology* 6675–80. doi: 10.15680/IJIRSET.2016.0505010.

[19] Salkuti, Surender Reddy. (2022). An Efficient Allocation of D-STATCOM and DG with Network Reconfiguration in Distribution Networks. *International Journal of Advanced Technology and Engineering Exploration* 9 (88). doi: http://dx.doi.org/10.19101/IJATEE.2021.874812

[20] Gupta, Atma Ram (2018). Effect of Optimal Allocation of Multiple DG and D-STATCOM in Radial Distribution System for Minimizing Losses and THD. *2017 7th International Symposium on Embedded Computing and System Design, ISED*. doi: 10.1109/ISED.2017.8303936.

[21] Sannigrahi, Surajit, Sriparna Roy Ghatak, and Parimal Acharjee (2019). Multi-Objective Optimisation-Based Active Distribution System Planning with Reconfiguration, Intermittent RES, and D-STATCOM. *IET Renewable Power Generation* 13 (13). doi: 10.1049/iet-rpg.2018.6060.

[22] Hariprasad, C H, R. Kayalvizhi, N. Karthik (2022). Optimum Restructuring of Radial Distribution Network with Integration of DG and D-STATCOM Using Artificial Fish Swarm Optimization Technique. *IEEE International Conference on Sustainable Energy and Future Electric Transportation.*

[23] Tejaswini, V., and D. Susitra. (2020). Optimal Placement of D-STATCOM Using Artificial Bee Colony Algorithm. *International Journal of Advanced Science and Technology* 29 (6 Special Issue).

[24] Kaswan Kuldeep, Singh, Choudhary, Sunita Sharrma, Kapil (2017). Applications of Artificial Bee Colony Optimization Technique Survey. *2nd International Conference on Computing for Sustainable Global Development (INDIACom*).

[25] Nabil, Mohd, Bin Muhtazaruddin, Jamani Jasrul, Jamian, and Goro Fujita. (2014). Determination of Optimal Output Power and Location for Multiple Distributed Generation Sources Simultaneously by Using Artificial Bee Colony. *IEEJ Transactions on Electrical and Electronics* Engineering 9 (4): 351–59. doi: 10.1002/tee.21979.

[26] Altwaijry, Najwa, Malak Almasoud, Areej Almalki, and Isra Al-Turaiki (2020). Multiple Sequence Alignment Using a Multiobjective Artificial Bee Colony Algorithm. ICCAIS 2020 - *3rd International Conference on Computer Applications and Information Security*. doi: 10.1109/ICCAIS48893.2020.9096734.

[27] Ghambari, Soheila, and Amin Rahati. (2018). An Improved Artificial Bee Colony Algorithm and Its Application to Reliability Optimization Problems. *Applied Soft Computing* (62) 736-767. doi: 10.1016/j.asoc.2017.10.040.

[28] Muhtazaruddin, M. N. B., Bani, N. A., Mohd Aris, S. A., Jalil, S. Z. A., Mad Kaidi, H., Abd Fatah, A. Y., Jamian, J. J., Muhammad-Sukki, F. And Abu-Bakar, S. H. (2017). Distribution Power Loss Minimization via Distributed Generation, Capacitor and Network Reconfiguration. *International conference on electrical, electronic, communication and control engineering, (ICEECC2016).* Johor Bahru, Malaysia.

[29] Karaboga, D., and B. Bastur (2008). On the Performance of Artificial Bee Colony (ABC) Algorithm. *Applied Soft Computing Journal* 8 (1). doi: 10.1016/j.asoc.2007.05.007.

[30] Linh, Nguyen Tung, and Dam Xuan Dong (2013). Optimal Location and Size of Distributed Generation in Distribution System by Artificial Bees Colony Algorithm. *International Journal of Information and Electronics Engineering* 3 (1): doi: 10.7763/IJIEE.2013.V3.267.

[31] Kefayat, M., A. Lashkar Ara, and S. A. Nabavi Niaki (2015). A Hybrid of Ant Colony Optimization and Artificial Bee Colony Algorithm for Probabilistic Optimal Placement and Sizing of Distributed Energy Resources. *Energy Conversion and Management.* (92) 149-161. doi: 10.1016/j.enconman.2014.12.037.

[32] Vita, Vasiliki (2017). Development of a Decision-Making Algorithm for the Optimum Size and Placement of Distributed Generation Units in Distribution Networks. *Energies* 10 (9) doi: 10.3390/en10091433.