Enhancing Reactive Power Compensation in Distribution Systems through Optimal Integration of D-STATCOM using the Pelican Optimization Algorithm

A. F. S. Yussif[1*], T. Seini[1], B. Ayasu[2], E. A. Nyantakyi[3]
[1,2,3]Department of Electrical and Electronic Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana
[1]Department of Physical Sciences, University for Development Studies, Tamale, Ghana
[*]corresponding author's email: seini.coe@gmail.com

Abstract – *This paper presents a study that introduces the Pelican Optimization Algorithm (POA) as an innovative approach for the strategic deployment of Distribution Static Synchronous Compensators (D-STATCOM) in distribution systems. The primary objectives are to reduce losses and enhance voltage profiles in radial distribution systems. The proposed approach is validated on both the IEEE 33-bus and IEEE 69-bus systems through comprehensive simulations using MATLAB software. The results demonstrate exceptional performance, showcasing a remarkable 29.40% and 32.30% reduction in active power losses for the respective systems. Furthermore, a comparative analysis against recent methods from the literature highlights the superior efficacy of the POA algorithm, revealing reductions of 29.15% and 32.00% in active power losses for the IEEE 33-bus and IEEE 69-bus systems. These findings substantiate the efficiency of the POA algorithm in strategically positioning and sizing D-STATCOM, making significant strides toward minimizing losses and improving voltage profiles in distribution systems. In summary, this study provides valuable insights into the field of power systems optimization, offering a pioneering solution for the effective deployment of D-STATCOM to enhance the overall performance of distribution networks.*

***Keywords**: D-STATCOM, distribution system, loss reduction, optimization, Pelican Optimization Algorithm (POA)*

Article History
Received 10 December 2023
Received in revised form 12 March 2024
Accepted 19 March 2024

I. Introduction

The escalating demand for electricity has underscored the paramount importance of ensuring the efficiency and reliability of distribution systems [1]. This imperative is further intensified by the integration of renewable energy sources, evolving load patterns, and the imperative to mitigate environmental impact, necessitating the evolution of sophisticated methodologies to optimize the operation of power distribution networks [2]. A pivotal facet of this optimization process revolves around strategically determining the placement and dimensions of devices aimed at augmenting system performance [3]. In this realm of devices, the Distribution Static Compensator (D-STATCOM) has emerged as a formidable instrument for bolstering system voltage stability, curtailing power losses, and elevating the overall quality of power supply within radial distribution systems [4]. Nevertheless, it is imperative to underscore that the efficacy of the D-STATCOM is intricately linked to its judicious placement and sizing within the distribution system [5]. The optimization of this aspect becomes paramount in navigating the intricate landscape of modern power distribution, where a delicate balance must be struck to accommodate diverse energy sources, adapt to fluctuating demand, and uphold environmental considerations, all while meeting the burgeoning need for electricity with unwavering reliability. As the quest for sustainable and resilient power distribution intensifies, the strategic deployment and dimensioning of devices, particularly the D-STATCOM, emerge as linchpins in shaping the future landscape of efficient and eco-friendly electrical grids.

The recent trajectory of research has been directed toward the utilization of metaheuristic algorithm-based approaches to optimize the placement and sizing of Distribution Static Compensators (D-STATCOM) for maximal advantages [6]. A notable example is the work of Baseem Khan et al., who introduced a bacterial search algorithm-based (BSA) approach aimed at optimizing the integration of D-STATCOM within distribution systems to enhance overall system efficiency [7]. Similarly, S. F. Mekhamer et al. pioneered a grey wolf optimization algorithm-based (GWOA) technique for the optimization of D-STATCOM placement in distribution systems, demonstrating a commitment to advancing methodologies in this domain [8]. Furthermore, Devabalaji Kaliaperumal Rukmani et al. employed the Cuckoo Search Optimization algorithm to strategically place and size multiple D-STATCOMs within radial distribution systems [9]. Despite these advancements, it is noteworthy that many of these algorithms exhibit limitations, particularly when applied to large optimization systems, leading to the generation of suboptimal solutions [10]-[11]. This limitation raises concerns about the effectiveness of existing techniques in distribution systems characterized by varying sizes, as the attained solutions may not guarantee global optimality [12]-[13]. Consequently, there is a pertinent need to explore alternative algorithms that may offer more robust and globally optimal solutions for the intricate task of optimizing the placement and sizing of D-STATCOMs in distribution systems, thereby advancing the state-of-the-art in this crucial area of power system optimization.

In this research, a pioneering strategy is introduced to tackle the intricate challenge of determining the optimal placement and dimensions of a Distribution Static Compensator (D-STATCOM) within a radial distribution system. The innovative approach leverages the Pelican Optimization Algorithm, a metaheuristic inspired by the foraging behavior of pelicans, to effectively address this complex optimization problem [14]. The fundamental goals of this study revolve around the dual objective of minimizing both active and reactive power losses within the distribution network, while concurrently improving the voltage profile. By achieving these objectives, the aim is to establish an efficient and reliable power supply within the distribution system [15]. The utilization of the Pelican Optimization Algorithm signifies a departure from conventional methods, offering a promising avenue for optimizing the placement and sizing of D-STATCOM devices in radial distribution systems, with the ultimate goal of enhancing the overall performance and resilience of the power supply network.

The evaluation of the efficacy of the proposed method is conducted on the IEEE 33-bus and 69-bus radial distribution systems, selected as test platforms for this purpose [16]-[17]. The decision to employ these particular systems is underpinned by their established status as widely recognized testbeds within the realm of power systems research, serving as benchmarks for evaluating the performance of various optimization techniques [18]. Through the utilization of these benchmark systems, our study seeks to offer substantial contributions and insights into the practical application of metaheuristic algorithms for addressing real-world challenges in power distribution. By leveraging the IEEE 33-bus and 69-bus configurations, our research endeavors to enhance the understanding of how these metaheuristic approaches can effectively optimize the placement and sizing of Distribution Static Compensators (D-STATCOM) in radial distribution systems, providing valuable knowledge and paving the way for advancements in the field of power system optimization. The deliberate choice of these well-established test platforms aligns with our commitment to rigorously assess and validate the proposed approach in a context that mirrors the complexities of real-world power distribution scenarios.

This paper provides a thorough examination of the optimization problem formulation, elucidating the intricacies involved in designing the Pelican Optimization Algorithm and its incorporation into the placement and sizing of the D-STATCOM device. Additionally, a detailed presentation of the results obtained is offered, highlighting the noteworthy reductions in both active and reactive power losses, along with enhancements in the voltage profile of the distribution systems. Furthermore, a comparative analysis is undertaken, juxtaposing the outcomes of the proposed method with existing works in the literature [8]. This comparative assessment serves to underscore the superior performance of the developed approach, affirming its efficacy in optimizing the placement and dimensions of the D-STATCOM for enhanced efficiency and reliability in power distribution systems.

The subsequent sections of this paper are organized as follows: Section II provides a detailed exposition of the problem formulation, encompassing the mathematical representation of the D-STATCOM placement and sizing issue. In Section III, the Pelican Optimization Algorithm is expounded upon, elucidating its adaptive characteristics and proficiency in navigating the solution space. Section IV articulates the simulation setup and presents results pertaining to loss reduction and voltage enhancement. A comprehensive comparative analysis with other optimization methods from the literature is offered in Section V. Finally, Section VI concludes the paper by summarizing contributions and outlining potential avenues for future research.

II. Problem Formulation

The Distribution Static Synchronous Compensator (D-STATCOM) is a crucial power electronics device that significantly enhances the quality of electrical power systems [19]. At its core lies a Voltage Source Inverter (VSI) guided by a sophisticated algorithm, generating compensatory currents to alleviate power quality issues like voltage sags, swells, flicker, and harmonics [20]. Certain DSTATCOMs integrate energy storage components for swift response and heightened reliability [21]. Continuous monitoring of grid parameters is facilitated through sensors and measurement devices, with DSTATCOMs seamlessly integrated into the grid's control and communication network for remote monitoring and coordination with other grid equipment [22]. This comprehensive modeling approach ensures the DSTATCOM's capability to sustain efficient, high-quality, and dependable electricity distribution. The mathematical intricacies of the D-STATCOM are meticulously outlined in [23].

In the context of this study, the D-STATCOM is conceptualized as a shunt-connected reactive load with reverse reactive power flow, injecting reactive power into the distribution system at the connected bus [24]. The primary focus is on furnishing flexible reactive power compensation through the D-STATCOM, with the active power component assumed to be zero [7]. Fig. 1 vividly illustrates the seamless integration of the D-STATCOM at bus j within a given distribution system, exemplifying its role and impact in optimizing power quality and distribution.

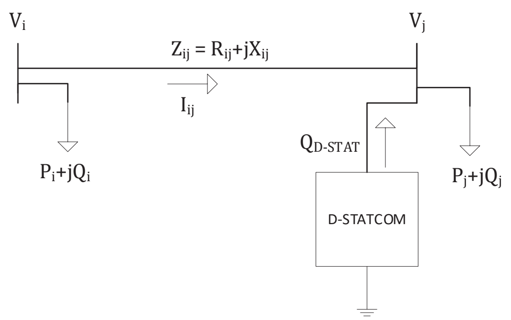

Fig. 1. Illustration of D-STATCOM integrated at bus j

By incorporating the D-STATCOM at bus *j*, the reactive power at this location undergoes a transformation to *Qjnew*, as outlined in equation (1) [25]. This conceptual framework assumes a shared functionality among all shunt reactive compensators, emphasizing their collective responsibility in infusing reactive power into the power system at the respective connected bus [26]. The integration of the D-STATCOM plays a pivotal role in altering the reactive power dynamics, with the expressed value denoted as *Qjnew*, as detailed in equation (1). It is essential to underscore the common purpose shared by shunt reactive compensators, underscoring their role in augmenting reactive power levels within the power system at the connected bus [26].

$$Q_{jnew} = Q_j - Q_{D-STAT} \tag{1}$$

Where; Q_{jnew} is the new reactive demand at bus *j* after integrating the compensator, Q_j is the reactive power at bus *j* before the integration, and $Q_{D\text{-}STAT}$ is the D-STATCOM size (amount of reactive power injected).

$$Q_{D-STATCOM}^{min} \leq Q_{D-STATCOM} \leq Q_{D-STATCOM}^{max} \tag{2}$$

This study concentrates on enhancing power delivery efficiency by effectively minimizing power losses and enhancing system voltage. The problem is articulated by formulating an objective function grounded in both the collective active power losses and overall voltage deviations of the system. Specifically, the objective function is derived from the total active power losses of the system, as delineated in equation (3). The primary goal is to systematically address and mitigate power inefficiencies while concurrently improving voltage stability across the system. The formulation of the objective function integrates both active power loss reduction and voltage deviation minimization as crucial elements in achieving enhanced power delivery efficiency.

$$f_1 = \sum_1^{N-1} P_{ij} \tag{3}$$

$$P_{ij} = R_{ij} \times I_{ij}^2 \tag{4}$$

Where R_{ij}, and I_{ij} are the line resistance and line current respectively.

The sum of the system voltage deviations at the various busses is expressed in (5) as the second component of the problem formulation.

$$f_2 = \sum_{i=1}^{N} |V_{ref} - V_i| \tag{5}$$

Where; V_{ref} is the reference voltage taken as 1p.u, V_i represents the voltage at bus *i*, and *N* represents the total number of buses.

$$V_i^{min} \leq V_i \leq V_i^{max} \tag{6}$$

The objective function is expressed as the algebraic sum of (1) and (5) in their per-unit forms to ensure equal treatment. It is therefore expressed in (7) as follows.

$$F_{obj} = \frac{f_{1(comp)}}{f_{1(base)}} + \frac{f_{2(comp)}}{f_{2(base)}} \tag{7}$$

Where; $f_{1(comp)}$ and $f_{2(comp)}$ represent the total system active power losses and the total voltage deviation with the D-STATCOM connected. And $f_{1(base)}$ and $f_{2(base)}$ represent the total system active power losses and the total voltage deviation without the D-STATCOM connected.

The Pelican Optimization Algorithm (POA) is employed for the optimal placement and sizing (in KVAr) of the D-STATCOM in a radial distribution system. The objective is to minimize the value defined in equation (7). To assess the power distribution system parameters, a backward/forward sweep load flow (BFLF) analysis [27] is conducted. This approach integrates the POA to strategically position and size the D-STATCOM within the radial distribution system, with the aim of enhancing system performance and minimizing the specified objective function according to the parameters derived from the BFLF analysis.

A. Backward/Forward Sweep Load Flow (BFLF)

The determination of distribution system parameters is facilitated through the implementation of the Backward/Forward Sweep Load Flow (BFLF) method, a well-suited approach for analyzing power distribution networks. Its efficiency lies in faster convergence and relatively lower computational complexity [28], making it particularly applicable in this study. The BFLF algorithm is an iterative process comprising key steps: initialization involves presetting all bus voltages to 1p.u. Following that, the Backward Sweep calculates current flows from the end node back to the source node. Subsequently, the Forward Sweep recalculates new bus voltages, updating previous values from the source node towards the end nodes. This iterative Backward/Forward process is repeated until convergence is achieved. For a comprehensive understanding of the mathematical intricacies of the BFLF in distribution systems, refer to [29]. This method offers a systematic and computationally efficient means of load flow analysis, ensuring accurate determination of distribution system parameters crucial for subsequent optimization efforts.

The BFLF algorithm method steps are summarized below:

1. Initialization: first, all the bus voltages are preset to 1p.u.
2. Backward Sweep: the current flows are calculated starting from the end node backward towards the source node.
3. Forward Sweep: new bus voltages are calculated to update the previous voltages starting from the source node forward towards the end nodes.
4. Steps 2 and 3 are repeated till convergence is obtained.

III. The Pelican Optimization Algorithm (POA)

The Pelican Optimization Algorithm (POA) is an innovative optimization approach inspired by the collective behavior of pelicans; water birds known for their collaborative hunting strategy. Derived from the pelicans' hunting behavior, POA addresses optimization problems by simulating the cooperative and competitive dynamics within a pelican group aiming to catch fish [30]. In this algorithm, pelicans play a pivotal role as integral members of the population, each representing a potential solution to the optimization problem. These individuals contribute values for the problem's variables based on their positions within the search space.

At the outset of the algorithm, the population members are initialized with random values falling within the predefined lower and upper bounds of the optimization problem, as outlined in equation (8). The randomness in the initial values introduces diversity into the population, reflecting the varied strategies employed by pelicans in their collective hunting endeavors. As the algorithm progresses, the pelican-inspired optimization process unfolds, incorporating collaboration and competition among population members to iteratively refine the solutions. The algorithm leverages the inherent adaptability observed in pelican groups, where individual members continuously adjust their strategies in response to the evolving collective dynamics, ultimately contributing to the algorithm's ability to efficiently navigate and converge toward optimal solutions in the search space.

$$x_{ij} = l_j + \left(u_j - l_j\right).rand\,, \quad i = 1,2,\dots,N \quad j = 1,2,\dots,m \tag{8}$$

In the context of this description, the symbol x_{ij} denotes the value of the *j*th variable associated with the *i*th candidate solution. The parameters *N* and *m* correspond to the population size and the number of problem variables, respectively. Additionally, l_j and u_j signify the lower and upper bounds of the search interval for variable *j.* The term "*rand"* represents a randomly generated value within the interval [0, 1]. These components collectively define the characteristics of the candidate solutions, population size, variable count, and the search space constraints essential for the optimization algorithm.

The POA emulates the tactics of pelicans during prey attacks to refine candidate solutions. This simulated hunting strategy unfolds in two distinct stages (exploration phase, and exploitation phase), replicating the sequential approach employed by pelicans in their pursuit and capture of their prey.

i. Exploration Phase (moving towards pray)
ii. Exploitation Phase (Winging on the water surface)

Exploration Phase:

The pelican movement towards the location of prey is mimicked to develop an exploration update operator presented in (9) as follows.

$$x_{ij}^{P1} = \begin{cases} x_{ij} + rand.\left(p_j - I.x_{ij}\right), & F_p < F_i \\ x_{ij} + rand.\left(x_{ij} - p_j\right), & else \end{cases} \tag{9}$$

The new state of the i^{th} pelican in the j^{th} dimension during the exploration is denoted by x_{ij}^{P1} The variable, I is a random integer of either 1 or 2, while p_j represents the prey's location in the jth dimension, and F_p is its corresponding objective function value. Throughout the exploration phase, the optimal pelican is tracked using (10) as the updating technique.

$$X_i = \begin{cases} X_i^{P1}, & F_i^{P1} < F_i \\ X_i, & else \end{cases} \quad (10)$$

Where; X_i^{P1} is the new status of the pelican in the i^{th} dimension, and F_i^{P1} is its objective function value based on the exploration phase. X_i is the present status of the pelican in the ith dimension, while F_i is its objective function value.

Exploitation Phase:

The mathematical representation of the exploitation phase update operator, as defined in equation (11), emulates the pelicans' behavior of extending their wings across the water surface to extract prey, specifically fish. This model captures the essence of how pelicans efficiently manipulate their wings during the hunting process.

$$x_{ij}^{P2} = x_{ij} + R.\left(1 - \frac{t}{T}\right).(2.rand - 1).x_{ij} \quad (11)$$

Where; x_{ij}^{P2} signifies the updated state of the i^{th} pelican along the j^{th} dimension. The constant R, maintaining a fixed value of 0.2, remains a key factor which was determined in reference [30]. Additionally, t and T denote the iteration count and the maximum number of iterations, respectively. Notably, the exploitation process mirrors the exploration phase, employing an identical updating mechanism illustrated in equation (12). This ensures consistency in computational procedures.

$$X_i = \begin{cases} X_i^{P2}, & F_i^{P2} < F_i \\ X_i, & else \end{cases} \quad (12)$$

Where; X_i^{P2} is the new status of the pelican in the i^{th} dimension, and F_i^{P2} is its objective function value determined based on the exploitation phase.

The implementation process of the POA is systematically presented in the flowchart in Fig. 2. The process represents the standard guide for adoption for application in any optimization problem.

It is relevant to note that, just like most other metaheuristic algorithms, the POA stoppage criteria is based on the maximum number of iterations which is predetermined to be 1000 iterations in [30]. However, it has been established that the POA produces good convergence results within the iteration range of 100 to 1000 iterations depending on the optimization problem. Hence it is recommendable to set the maximum iteration to 1000 as the stoppage and convergence criteria when applying the POA to solve optimization problem.

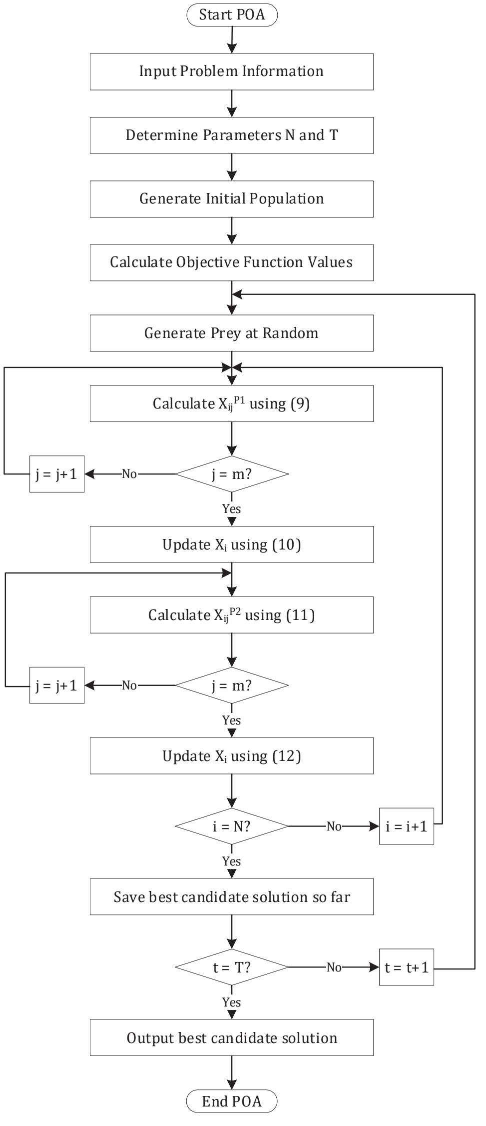

Fig. 2. Implementation Flowchart of POA

IV. Results and Discussion

In this segment, we assess the proposed POA-based methodology by implementing it on the widely recognized IEEE 33-bus and IEEE 69-bus systems. The primary aim of this evaluation is to integrate a singular D-STATCOM into the system, aiming to mitigate overall losses and enhance the voltage profile. The examination is carried out using MATLAB R2019a software on an HP Pavilion laptop featuring 4 gigabytes of RAM and an AMD processor operating at a clock speed of 2.0 GHz. The specified POA parameters for this evaluation include setting the number of search agents to 30 and establishing a maximum iteration limit of 1000 as the convergence and stoppage criteria. The assessment involves scrutinizing the impact of these parameters and the D-STATCOM integration on system performance, focusing on loss reduction and voltage profile enhancement. The chosen IEEE bus systems serve as robust test cases to validate the effectiveness of the proposed POA approach in optimizing power system performance.

The radial distribution network of the IEEE 33-bus system is characterized by 33 nodes, 32 power lines, a base voltage rating of 12.66 kV, and an overall capacity of 100 MVA [16]. This system supports a collective load demand of 3.72 MW and 2.3 MVAr, with a combined active power loss of 202.67 kW and reactive power loss of 135.14 kVAr. Detailed information about the IEEE 33-bus system can be explored in [16], providing a thorough understanding of its configuration and operational parameters. For a visual depiction, refer to Fig. 3, which provides an illustrative representation of the IEEE 33-bus system, capturing its essential components and configuration.

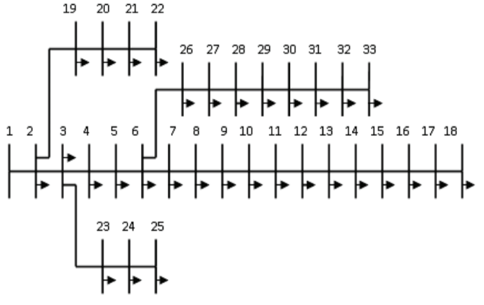

Fig. 3. Single Line Diagram of IEEE 33-bus System

Table I presents the results of the conducted experiment on the IEEE 33-bus system. The table provides details on the dimensions and locations of the D-STATCOM, overall active power losses, the percentage reduction in active power losses, total reactive power losses, the percentage reduction in total reactive power losses, and the minimum bus voltage within the system. These findings offer a comprehensive overview of the impact of integrating the D-STATCOM on various key parameters, shedding light on its effectiveness in minimizing both active and reactive power losses while maintaining voltage stability across the system.

TABLE I
RESULTS OF POA APPROACH ON IEEE 33-BUS SYSTEM

IEEE 33-bus	Base Case	Proposed POA
Size / kVAr (location)	-	1237 (30)
Real Power /P Loss, (kW)	202.67	143.1
% P Loss Reduction	-	29.40
Reactive Power (Q) Loss (kVAr)	135.14	96.0
% Q Loss Reduction	-	28.96
Min. Voltage	0.91309	0.926

As per the information presented in Table I, the application of the proposed POA method successfully positioned a singular D-STATCOM at bus 30, providing compensation with a capacity of 1237 kVAr. This strategic placement resulted in a significant reduction in the overall active power loss within the system, diminishing it to 143.1 kW and marking a substantial 29.40% decrease. Simultaneously, the total reactive power loss experienced a noteworthy decrease, reaching 96.0 kVAr, reflecting a substantial reduction of 28.96%. The system's voltage profile exhibited a commendable enhancement, with the minimum voltage registering at 0.926 p.u, as visually represented in Fig. 4. These outcomes underscore the effectiveness of the proposed POA method in optimizing system performance by mitigating power losses and improving voltage stability.

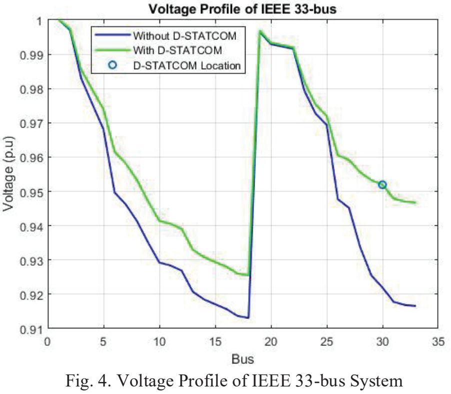

Fig. 4. Voltage Profile of IEEE 33-bus System

In order to assess the efficacy of the POA methodology introduced in this investigation, a comprehensive comparison has been conducted with recent advancements in the optimal placement of D-STATCOM. This comparative analysis, presented in Table II, evaluates the performance of the POA approach in relation to both the modified Grey Wolf Optimization Algorithm (mGWOA) and the Bat Algorithm (BA) technique [8]. This comparison aims to provide insights into the relative effectiveness of the POA approach by juxtaposing its outcomes with those of well-established optimization algorithms in the field.

TABLE II
RESULTS OF POA COMPARED WITH OTHER TECHNIQUES

IEEE 33-bus	Base Case	BA	mGWOA	Proposed POA
Size / kVAr (location)	-	1150 (30)	1252.5 (30)	1237 (30)
Real Power /P Loss,(kW)	202.67	138.45	143.5	143.1
% P Loss Reduction	-	28.97	29.15	29.40
Reactive Power (Q) Loss (kVAr)	135.14	96.47	96.0	96.0
% Q Loss Reduction	-	28.67	29.0	29.0
Min. Voltage	0.913	0.924	0.930	0.931

The innovative POA method showcased remarkable effectiveness when compared to the alternative techniques, exhibiting a notable 29.40% decrease in active power losses and a substantial 29.00% reduction in reactive power losses through the application of a total compensation capacity of 1,237 kVAr. In contrast, the mGWOA method demonstrated a 29.15% decrease in total active power losses and a 29% reduction in reactive power losses, employing a total compensation capacity of 1252.5 kVAr. Similarly, the BA approach yielded a 28.97% reduction in total active power losses and a 28.67% reduction in reactive power losses, utilizing a total compensation capacity of 1150 kVAr. Noteworthy is the fact that the proposed POA method surpassed existing methods in the literature, achieving a higher percentage reduction in power losses despite employing a smaller reactive compensation capacity. This underscores the efficiency of the POA approach in optimizing power distribution systems, offering superior performance in terms of minimizing both active and reactive power losses compared to the mGWOA and BA techniques. The findings highlight the potential of the POA method as a valuable tool for enhancing the overall efficiency and reliability of power networks.

The effectiveness of the newly introduced POA methodology was further assessed through its application to the IEEE 69-bus system, a radial distribution network characterized by 69 buses and 68 lines. This system operates with a base voltage of 12.66 kV and possesses a power capacity of 100 MVA. Detailed information about the IEEE 69-bus system can be explored in [18], providing a thorough understanding of its configuration and operational parameters. For a more illustrative depiction, refer to Fig. 5, which presents a visual representation of the IEEE 69-bus system. This evaluation on a real-world power distribution network enhances the applicability and reliability of the proposed POA approach, offering insights into its performance within a complex and established electrical infrastructure. The IEEE 69-bus system serves as a robust testbed, allowing for a comprehensive analysis of the POA method's capabilities and potential contributions to optimizing power distribution networks.

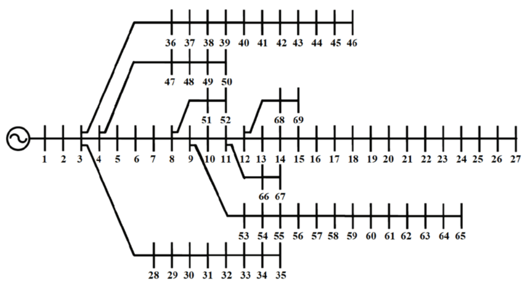

Fig. 5. Single Line Diagram of IEEE 69-bus System

The outcomes of the proposed POA methodology's performance on the IEEE 69-bus system are encapsulated in Table III. This table illustrates the optimization results specifically in the placement of a singular D-STATCOM, aiming to achieve optimal system performance.

TABLE III
RESULTS OF POA APPROACH ON IEEE 69-BUS SYSTEM

IEEE 69-bus	Base Case	Proposed POA
Size / kVAr (location)	-	1227 (61)
Real Power /P Loss, (kW)	225	152.35
% P Loss Reduction	-	32.3%
Reactive Power (Q) Loss (kVAr)	102.14	70.72
% Q Loss Reduction	-	30.76
Min. Voltage	0.90919	0.931

The application of the POA method successfully determined the optimal placement of a D-STATCOM at bus 61, accompanied by an ideal reactive capacity of 1227 kVAr. This strategic placement yielded a substantial decrease in the overall active power losses of the system, reducing them to 152.35 kW and marking a notable 32.3% reduction. Additionally, the total reactive power loss saw a significant decrease to 70.72 kVAr, reflecting a 30.76% improvement. The positive impact extended to the system's voltage profile, showcasing universal enhancements. The minimum voltage reached 0.931 p.u, indicating an improvement in the overall voltage stability and reliability of the power distribution system. The findings are visually represented in Fig. 6, providing a graphical illustration of the improved voltage profile resulting from the effective application of the POA method in optimizing the placement of the D-STATCOM within the IEEE 69-bus system. These results underscore the efficacy of the POA approach in not only minimizing power losses but also enhancing the overall operational performance and stability of the electrical network.

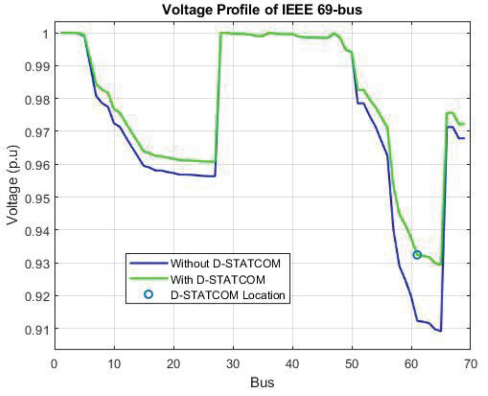

Fig. 6. Voltage profile of IEEE 69-bus system

For a more comprehensive assessment of this study's efficacy, the POA method is juxtaposed with the Cuckoo Search Algorithm (CSA) and the Bat Algorithm approach outlined in a recent research study [8]. Table IV encapsulates the outcomes, providing a clear comparative analysis. This contrast aims to deepen our insights into the performance of the POA method in relation to other established optimization algorithms, specifically the CSA and Bat Algorithm. The tabulated results offer a transparent and concise presentation, facilitating a nuanced understanding of how the POA method compares to alternative approaches in optimizing power distribution systems.

TABLE IV
RESULTS OF POA COMPARED WITH OTHER TECHNIQUES

IEEE 69-bus	Base Case	BA	CSA	Proposed POA
Size / kVAr (location)	-	1150 (61)	1200 (61)	1227 (61)
Real Power /P Loss, (kW)	225	153.36	152.95	152.35
% P Loss Reduction	-	31.84	32.00	32.3
Reactive Power (Q) Loss (kVAr)	102.14	71.26	71.05	70.72
% Q Loss Reduction	-	30.27	30.40	30.76
Min. Voltage	0.90919	0.927	0.928	0.930

The POA methodology showcased remarkable efficiency compared to alternative techniques, realizing a substantial 32.30% decrease in overall active power losses and a noteworthy 30.76% reduction in total reactive power losses. This superior performance was achieved through the application of a total reactive compensation of 1227 kVAr at bus 61. In contrast, the CSA approach exhibited a 32.00% reduction in total active power losses and a 30.40% reduction in total reactive power losses, employing a total reactive compensation of 1200 kVAr at the same bus. Meanwhile, the BA approach demonstrated comparatively less competitive outcomes, with a 31.84% reduction in total active power losses and a 30.27% reduction in total reactive power losses, utilizing a total reactive compensation of 1150 kVAr at bus 61. These findings underscore the potency of the POA methodology in minimizing power losses, particularly in comparison to the CSA and BA approaches, thereby emphasizing its efficacy in optimizing the placement of reactive power compensation devices within power distribution systems. The nuanced comparison provides valuable insights into the relative advantages of the POA method over existing optimization algorithms, substantiating its potential as a robust tool in enhancing the efficiency and reliability of power networks.

V. Conclusion and Recommendation

This research introduces an innovative approach utilizing the Placement Optimization Algorithm (POA) to strategically determine the location and sizing of D-STATCOM within distribution systems, with the primary objective of minimizing losses and enhancing the overall system voltage profile. The proposed methodology underwent rigorous testing on both the IEEE 33-bus and IEEE 69-bus systems, leveraging the MATLAB software (R2019b). Impressively, the method yielded remarkable reductions of 29.40% and 32.30% in active power losses for the respective systems, signifying a substantial enhancement in power efficiency. Through comparative analysis with recent methodologies found in the literature, which achieved reductions of 29.15% and 32.00% in active power losses for the IEEE 33-bus and IEEE 69-bus systems, the superior performance of the POA approach became evident. These findings not only underscore the effectiveness of the POA algorithm but also emphasize its competitive edge in optimizing the integration of D-STATCOM and other shunt reactive compensators within radial distribution systems. The results affirm the capability of the proposed POA methodology to significantly contribute to the advancement of power distribution systems, offering a robust solution for minimizing losses and improving voltage profiles, thereby enhancing the overall efficiency and reliability of such systems.

As a result, the Pelican Optimization Algorithm (POA) is highly recommended for diverse applications in power system optimization. This includes the effective integration of distributed generators, strategic placement of sectionalizing switches, and optimal reconfiguration of distribution systems to augment power delivery.

Acknowledgements

The authors wish to acknowledge the editorial team and reviewers of this journal for their good work.

Conflict of Interest

The authors declare no conflict of interest in the publication process of the research article.

Author Contributions

A. F. S. Yussif conceptualized the study, performed the analysis, and drafted the original paper. T. Seini performed the simulation and was also involved in drafting the paper as well as fully supervised the research. B. Ayasu and E. A. Nyantakyi reviewed and edited the paper. All authors have approved the final version.

References

[1] Z. Rui, L. Kecheng, L. Xiaoming, D. Jingyuan, and L. Anchang, "The research on multi-dimensional evaluation index system of distribution network loss," China Int. Conf. Electr. Distrib. CICED, vol. 2021-April, no. 202004300000033, pp. 747–751, 2021, doi: 10.1109/CICED50259.2021.9556681.

[2] S. E. Razavi, E. Rahim, M. S. Javadi, A. E. Nezhad, M. Lotf, M. Shafie-khah, and J. P. S. Catalao, "Impact of distributed generation on protection and voltage regulation of distribution systems: A review," Renew. Sustain. Energy Rev., vol. 105, no. May 2018, pp. 157–167, 2019, doi: 10.1016/j.rser.2019.01.050.

[3] G. Courteau, E. Aurberson, P. Favre-Perrod, O. De Marignac, M. Bozorg, and M. Carpita, "STATCOM optimal placement method applied to a Swiss urban distribution network considering future photovoltaic integration scenarios," 2022 Int. Symp. Power Electron. Electr. Drives, Autom. Motion, SPEEDAM 2022, pp. 124–129, 2022, doi: 10.1109/SPEEDAM53979.2022.9842206.

[4] S. D. Veeraganti and A. Mohamed Imran, "OPTIMAL PLACEMENT and SIZING of DG and D-STATCOM in A DISTRIBUTION SYSTEM: A REVIEW," 2022 Int. Virtual Conf. Power Eng. Comput. Control Dev. Electr. Veh. Energy Sect. Sustain. Futur. PECCON 2022, pp. 1–13, 2022, doi: 10.1109/PECCON55017.2022.9851016.

[5] S. Sannigrahi and P. Acharjee, "Maximization of system benefits with the optimal placement of DG and DSTATCOM considering load variations," Procedia Comput. Sci., vol. 143, pp. 694–701, 2018, doi: 10.1016/j.procs.2018.10.446.

[6] D. K. Dhaked and D. Birla, "International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies RECENT DEVELOPMENTS OF DSTATCOM WITH OPTIMAL LOCATION & SIZE IDENTIFICATION IN ELECTRICAL 1 INTRODUCTION," Int. Trans. J. Eng. Manag. Appl. Sci. Technol., vol. 11, no. 16, pp. 1–17, 2020, doi: 10.14456/ITJEMAST.2020.313.

[7] B. Khan, K. Redae, E. Gidey, O. P. Mahela, I. B. M. Taha, and M. G. Hussien, "Optimal integration of DSTATCOM using improved bacterial search algorithm for distribution network optimization," Alexandria Eng. J., vol. 61, no. 7, pp. 5539–5555, 2022, doi: 10.1016/j.aej.2021.11.012.

[8] S. F. Mekhamer, R. H. Shehata, A. Y. Abdelaziz, and M. A. Al-Gabalawy, "Enhancing radial distribution system performance by optimal placement of DSTATCOM," Int. J. Electr. Comput. Eng., vol. 10, no. 3, pp. 2850–2860, 2020, doi: 10.11591/ijece.v10i3.pp2850-2860.

[9] D. K. Rukmani, Y. Thangaraj, and U. Subramaniam, "A New Approach to Optimal Location and Sizing of DSTATCOM in Radial Distribution Networks Using," 2020.

[10] A. Sunil and C. Venkaiah, "Multi-objective Adaptive Fuzzy Campus Placement based Optimization Algorithm for optimal integration of DERs and DSTATCOMs," J. Energy Storage, vol. 75, no. November 2023, p. 109682, 2024, doi: 10.1016/j.est.2023.109682.

[11] M. Kandasamy, R. Thangavel, T. Arumugam, S. Kumaravel, S. Aruchamy, W. W. Kim, and Z. W. Geem, "Strategic incorporation of DSTATCOM and distributed generations in balanced and unbalanced radial power distribution networks considering time varying loads," Energy Reports, vol. 9, pp. 4345–4359, 2023, doi: 10.1016/j.egyr.2023.03.076.

[12] K. D. Shinde and P. B. Mane, "Investigation of Effects of Solar Photovoltaic Penetration in an IEEE 13-bus Radial Low-Voltage Distribution Feeder System," 19th Int. Conf. Electr. Eng. Comput. Telecommun. Inf. Technol. ECTI-CON 2022, pp. 1–5, 2022, doi: 10.1109/ECTI-CON54298.2022.9795436.

[13] C. Udayakiran and S. H. Vali, "Design of battery energy storage system (BESS) support dynamic voltage restorer (DVR) to reduce the rating of voltage source converter (VSC) Applied to IEEE 11, 33 & 69 Bus Systems," Proc. - 7th IEEE Int. Adv. Comput. Conf. IACC 2017, pp. 477–481, 2017, doi: 10.1109/IACC.2017.0104.

[14] S. Sharma and G. Singh, "Design and Analysis of Novel Chaotic Pelican-Optimization Algorithm for Feature-Selection of Occupational Stress," Procedia Comput. Sci., vol. 218, pp. 1497–1505, 2022, doi: 10.1016/j.procs.2023.01.128.

[15] A. S. Hassan, Y. Sun, and Z. Wang, "Multi-objective for optimal placement and sizing DG units in reducing loss of power and enhancing voltage profile using BPSO-SLFA," Energy Reports, vol. 6, pp. 1581–1589, 2020, doi: 10.1016/j.egyr.2020.06.013.

[16] S. H. Dolatabadi, M. Ghorbanian, P. Siano, and N. D. Hatziargyriou, "An Enhanced IEEE 33 Bus Benchmark Test System for Distribution System Studies," IEEE Trans. Power Syst., vol. 36, no. 3, pp. 2565–2572, 2021, doi: 10.1109/TPWRS.2020.3038030.

[17] S. S. Halve, R. Arya, and A. Koshti, "Metaphor-less RAO-1 Optimization Based Algorithm To Determine Shunt Capacitor Capacity in Distribution System," Proc. - 2022 IEEE 11th Int. Conf. Commun. Syst. Netw. Technol. CSNT 2022, pp. 107–112, 2022, doi: 10.1109/CSNT54456.2022.9787589.

[18] L. M. Belmino, F. Soares, R. F. Sampaio, and R. Leao, "Placement and Sizing of Distributed Generation in Distribution System," 2019 IEEE PES Conf. Innov. Smart Grid Technol. ISGT Lat. Am. 2019, 2019, doi: 10.1109/ISGT-LA.2019.8894981.

[19] T. Ahmed, A. Waqar, R. M. Elavarasan, J. Imtiaz, M. Premkumar, and U. Subramaniam, "Analysis of Fractional Order Sliding Mode Control in a D-STATCOM Integrated Power Distribution System," IEEE Access, vol. 9, pp. 70337–70352, 2021, doi: 10.1109/ACCESS.2021.3078608.

[20] K. D. E. Kerrouche, E. Lodhi, M. B. Kerrouche, L. Wang, F. Zhu, and G. Xiong, "Modeling and design of the improved D-STATCOM control for power distribution grid," SN Appl. Sci., vol. 2, no. 9, pp. 1–11, 2020, doi: 10.1007/s42452-020-03315-8.

[21] M. M. Khaleel, M. R. Adzman, and S. M. Zali, "An integrated of hydrogen fuel cell to distribution network system: Challenging and opportunity for D-STATCOM," Energies, vol. 14, no. 21, 2021, doi: 10.3390/en14217073.

[22] A. Y. Hatata, E. O. Hasan, M. A. Alghassab, and B. E. Sedhom, "Centralized Control Method for Voltage Coordination Challenges With OLTC and D-STATCOM in Smart Distribution Networks Based IoT Communication Protocol," IEEE Access, vol. 11, no. January, pp. 11903–11922, 2023, doi: 10.1109/ACCESS.2023.3242236.

[23] A. R. Gidd, A. D. Gore, S. B. Jondhale, O. V. Kadekar, and M. P. Thakre, "Modelling, analysis and performance of a DSTATCOM for voltage sag mitigation in distribution network," Proc. Int. Conf. Trends Electron. Informatics, ICOEI 2019, vol. 2019-April, no. Icoei, pp. 366–371, 2019, doi: 10.1109/icoei.2019.8862554.

[24] A. Zeinalzadeh, A. Estebsari, and A. Bahmanyar, "Simultaneous optimal placement and sizing of DSTATCOM and parallel capacitors in distribution networks using multi-objective PSO," 2019 IEEE Milan PowerTech, PowerTech 2019, pp. 1–6, 2019, doi: 10.1109/PTC.2019.8810577.

[25] A. Amin, S. Kamel, A. Selim, and L. Nasrat, "Optimal Placement of Distribution Static Compensators in Radial Distribution Systems Using Hybrid Analytical-Coyote Optimization Technique," 2019 21st Int. Middle East Power Syst. Conf. MEPCON 2019 - Proc., pp. 982–987, 2019, doi: 10.1109/MEPCON47431.2019.9007924.

[26] A. Eid and S. Kamel, "Optimal allocation of shunt compensators in distribution systems using turbulent flow of waterbased optimization Algorithm," 2020 IEEE Electr. Power Energy Conf. EPEC 2020, vol. 3, 2020, doi: 10.1109/EPEC48502.2020.9320085.

[27] G. A. Setia, G. Hm Sianipar, K. Samudra, F. Haz, N. Winanti, and H. R. Iskandar, "Implementation of Backward-Forward Sweep Method on Load Model Variation of Distribution Systems," Proc. 2nd Int. Conf. High Volt. Eng. Power Syst. Towar. Sustain. Reliab. Power Deliv. ICHVEPS 2019, pp. 1–5, 2019, doi: 10.1109/ICHVEPS47643.2019.9011141.

[28] G. Gangil, S. K. Goyal, and M. Srivastava, "Optimal placement of dg for power losses minimization in radial distribution system using backward forward sweep algorithm," Proc. 2020 IEEE Int. Conf. Adv. Dev. Electr. Electron. Eng. ICADEE 2020, no. Icadee, 2020, doi: 10.1109/ICADEE51157.2020.9368941.

[29] A. D. Rana, J. B. Darji, M. Pandya, P. G. Student, E. E. Department, and A. ' Bad, "Backward / Forward Sweep Load Flow Algorithm for Radial Distribution System," IJSRD-International J. Sci. Res. Dev., vol. 2, no. 01, pp. 2321–0613, 2014, [Online]. Available: www.ijsrd.com.

[30] P. Trojovský and M. Dehghani, "Pelican Optimization Algorithm: A Novel Nature-Inspired Algorithm for Engineering Applications," Sensors, vol. 22, no. 3, 2022, doi: 10.3390/s22030855.