



OPTIMAL ENERGY-EFFICIENT INTEGRATION OF WIND DISTRIBUTED GENERATORS IN A HYBRID AC-DC NETWORK USING A TUNICATE SWARM ALGORITHM

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ABSTRACT

Due to improvements in wind energy technology, electrical distribution networks are becoming more capable of integrating large amounts of variable renewable generation. The wind distributed generators (WDGs) affect the medium-voltage (MV) electrical distribution network (EDN) by introducing variability, reverse power flows, power-quality issues, and higher fault levels. This paper applies a brand-new, reliable, and efficient algorithm, the tunicate swarm algorithm (TSA), to optimally link varying numbers of WDG units and allocate multiple WDG units in EDN. The main objective of this research is to propose an applied TSA algorithm for optimal energy-efficient integration of multiple WDG units in a hybrid medium-voltage AC-DC network and to test it in a modified IEEE 33-bus network based on the active power loss minimization. The proposed approach granted improved solution quality with enhanced convergence speed and adherence to EDN constraints. The applied TSA addresses the sensitivity to parameter settings like population size and iterations. The findings verify that, out of all the scenarios taken into consideration, three WDGs offer the best performance in terms of active loss minimization and improve the bus voltage profile.



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I. INTRODUCTION

Because of their many benefits, AC systems have been used in electrical distribution networks (EDNs) for over a century and are now widely used worldwide. However, clean, green, and ecologically friendly distributed energy resources (DERs), electric vehicles, energy storage systems, and diverse DC loads are swiftly revolutionizing the current world [1]. Many advancements in smart grid technology were brought about by the introduction of hybrid AC/DC distribution networks. To connect to current AC distribution systems, these DC-based smart energy technologies require converters, which are costly and incur power losses [2]. In order to directly connect AC and DC generation units and loads to the power system, the idea of medium-voltage (MV) electric distribution networks has recently been proposed. Higher transfer capacity, lower power losses, greater hosting capacity, voltage management, and an improved voltage profile are just a few other benefits of the hybrid AC/DC in EDN [3],[4]. Problems like increased power losses and voltage instability are brought about by the growing integration of wind energy into EDNs. The necessity for strong optimization techniques to guarantee effective and dependable wind distributed generators (WDG) allocation is the driving force behind this project. Electrical distribution grid-connected wind energy systems face persistent challenges in maintaining voltage stability, mitigating harmonics, and ensuring reliable power quality under fluctuating wind conditions and fault events. The intermittent nature of wind introduces significant variations in power flow, which, if not effectively managed, can lead to instability and degrade system performance. Power quality is a crucial aspect of modern electrical distribution grids, ensuring efficient, stable, and reliable power delivery while minimizing losses and disturbances.

With the growing integration of wind energy into grid-connected systems, Power quality issues have become more pronounced due to the inherent intermittency and variability of WDG. In recent years, many scholars have proposed numerous optimizations approaches to formulate the WDG planning problem in distribution systems. Numerous optimization approaches have been developed to address the efficient design of WDG units in EDN. The authors of [5] applied the equilibrium optimizer algorithm, the gorilla troops optimizer algorithm in [6], the lévy coyote optimization algorithm in [7], and used the manta-ray foraging optimization algorithm in [8] and modified the equilibrium algorithm in [9]. This paper introduces a novel bio-inspired optimization technique called the Tunicate Swarm Algorithm (TSA) [10]. This algorithm draws inspiration from the jet propulsion and collective foraging behaviors exhibited by tunicates, aiming to enhance navigation and foraging processes through innovative computational strategies. The TSA algorithm presents a straightforward framework, unique stabilizing characteristics, and remarkable efficiency [11]. The TSA algorithm surpasses competing methods in optimal solutions and highly effective for real-world optimization situations, and especially for power system problems: optimize the power system stabilizer parameters to prevent oscillations at low frequencies [12], used to address the dynamic economic emission dispatch issues [13],[14], the PID controller optimization for autonomous generation management in a hybrid power system [15], Optimal cost of a power system based on the design of a hybrid renewable system [16], and optimal renewable-based DG in electrical networks with electric load models [17]. Adaptive optimal control model-based optimal energy management strategy for a multi-microgrid at the tertiary level [18], optimizing battery energy storage systems and vehicle-to-grid operations in PV-powered EV charging systems [19], and optimal solutions searched for wind speed deterministic forecasting [20]. Recently, researchers applied the TSA algorithm for energy hub adjusting efficiency based on real-time load variations for optimal allocation [21]. The main objective of this research is to propose an applied TSA algorithm for optimal energy-efficient integration of multiple wind distributed generators in a hybrid medium-voltage AC-DC electric distribution network. The proposed approach ensures improved solution quality with enhanced convergence speed and adherence to EDN constraints. This, in turn, ultimately improves the stability, efficiency, and reliability of EDN. Through the balancing strategy between exploration and exploitation, TSA addresses the sensitivity to parameter settings like population size and iterations.

II. WIND DISTRIBUTED GENERATOR ALLOCATION PROBLEM

In EDN, computational solutions are crucial because of the intricate nature of real-time issues. This involves formulating the problem through mathematical equations, known as mathematical models, which are predicated on decision variables. These models precisely illustrate the system's response to variations in independent variables, guaranteeing relevance and accuracy in practical applications. Figure 1 represents the single-line diagram with DG placement in EDN.

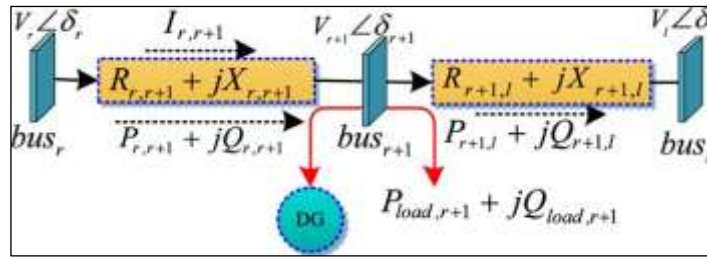


Figure 1: The single-line diagram with DG placement.

Source: [18-20].

II.1 OBJECTIVE FUNCTION

To achieve optimal integration of WDG units within the hybrid AC-DC EDN, the problem is formulated using a single objective function (OF), which aims to minimize the total active power losses (P_{Loss}), as expressed by the following equation:

$$OF = \sum_{i=1}^{N_{Bus}} \sum_{j=2}^{N_{Bus}} P_{Loss}(i, j) \quad (1)$$

The active power loss is calculated using the expression given in (2), as reported in [6],[22]:

$$P_{Loss}(i, j) = \alpha_{ij}(P_i P_j + Q_i Q_j) + \beta_{ij}(Q_i P_j + P_i Q_j) \quad (2)$$

And,

$$\alpha_{ij} = \frac{R_{ij}}{V_i V_j} \cos(\delta_i - \delta_j) \quad (3)$$

$$\beta_{ij} = \frac{R_{ij}}{V_i V_j} \sin(\delta_i - \delta_j) \quad (4)$$

Where R_{ij} denotes the resistance of the line connecting buses i and j . V_i and V_j are the voltage magnitudes. δ_i and δ_j represent the corresponding voltage angles. P_i , P_j and Q_i , Q_j refer to the power injections at buses i and j , respectively.

II.2 EQUALITY CONSTRAINTS

These constraints enforce active and reactive power balance in the system, where total generation (including WDG) equals load demand plus network losses, as defined in (5) and (6) [23],[34]:

$$P_G + P_{WDG} = P_{Load} + P_{Loss} \quad (5)$$

$$Q_G + Q_{WDG} = Q_{Load} + Q_{Loss} \quad (6)$$

Where P_G and Q_G denote the active and reactive power outputs of the generator, respectively. P_{WDG} and Q_{WDG} represent the total power supplied by the WDG unit. P_{Load} and Q_{Load} correspond to the total active and reactive load demands, while P_{Loss} and Q_{Loss} indicate the total active and reactive power losses, respectively.

II.3 DISTRIBUTION LINE CONSTRAINTS

These constraints ensure acceptable AC-DC distribution line operating conditions [23, 24]:

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

$$|1 - V_j| \leq \Delta V_{max} \quad (8)$$

$$|S_{ij}| \leq S_{max} \quad (9)$$

Where V_{max} , and V_{min} are the limit voltages; ΔV_{max} is the maximum drop of voltage. V_i is the sub-station voltage equal to 1.0 p.u. S_{max} is the maximum apparent power in line.

II.4 WDG CONSTRAINTS

These constraints specify the operational and placement limits associated with WDG units, as defined in [23],[24]:

$$P_{WDG}^{min} \leq P_{WDG} \leq P_{WDG}^{max} \quad (9)$$

$$Q_{WDG}^{min} \leq Q_{WDG} \leq Q_{WDG}^{max} \quad (10)$$

$$2 \leq WDG_{position} \leq N_{Bus} \quad (11)$$

$$N_{WDG} \leq N_{WDG.max} \quad (12)$$

$$n_{WDG}/Location \leq 1 \quad (13)$$

Where $WDG_{Position}$, N_{WDG} , and $N_{WDG.max}$ are the WDG position, number, and maximum units/location at the bus.

III. OVERVIEW OF APPLIED TUNICATE SWARM ALGORITHM

The TSA is predicated on tunicates' capacity to locate food sources in the ocean. Here, tunicates use two behaviours, such as swarm intelligence and jet propulsion actions, to locate food. Three requirements are considered for the implementation of jet propulsion behaviour: the search candidates must avoid conflicts with one another, approach the position of the best candidate, and exist close to the best candidate [10, 11]. The vector $\vec{\beta}$ is used to avoid conflicts among the tunicates, and the position of the new search candidate is calculated using this vector [25, 26]:

$$\vec{\beta} = \frac{\vec{g}}{\vec{m}} \quad (14)$$

$$\vec{g} = c_2 + c_3 - \vec{f} \quad (15)$$

$$\vec{f} = 2 \cdot c_1 \quad (16)$$

Here, \vec{f} indicates the water flow in the sea, \vec{m} indicates the force existing within search candidates, \vec{g} denotes the force of gravity, c_1, c_2, c_3 are the parameters distributed randomly between 0 and 1.

$$\vec{m} = [p_{min} + c_1 \cdot p_{max} - p_{max}] \quad (17)$$

Here, p_{min}, p_{max} values are given by 1 and 4, respectively and indicate the interaction speeds of search candidates. The tunicates move to the best neighbor search candidate after avoiding conflicts, and this is given by the next equation [24]:

$$\vec{d} = |\vec{f}_s - r \cdot \vec{p}(t)| \quad (18)$$

Where, \vec{p} indicates the location of the search candidate for the current location, t indicates the value of the current iteration, \vec{d} represents the distance between the tunicate and the food location, \vec{f}_s denotes the position of food, and r ranges between 0 and 1. The location of the search candidate has to be adjacent to the best search candidate, which is given by,

$$\vec{p}(t) = \begin{cases} \vec{f}_s + \beta \cdot \vec{d}, & r \geq 0.5 \\ \vec{f}_s - \beta \cdot \vec{d}, & r < 0.5 \end{cases} \quad (19)$$

Here, in accordance with \vec{f}_s , the updating of the search candidate's position is given by $\vec{p}(t)$. The position updating is achieved by the swarm intelligence behaviour of the search candidates and is,

$$\vec{p}(t+1) = \frac{\vec{p}(t) + \vec{p}(t+1)}{2 + c_1} \quad (20)$$

The solution of the first two best candidates is given by $\vec{p}(t)$ and $\vec{p}(t+1)$. Considering the position of the best candidate, the other candidate's solution can be updated by preserving these solutions. Figure 2 shows how search agents can update their positions according to the position of $\vec{p}(t)$. The final position would be in a random place, within a cylindrical or cone-shaped, which is defined by the position of tunicate [25].

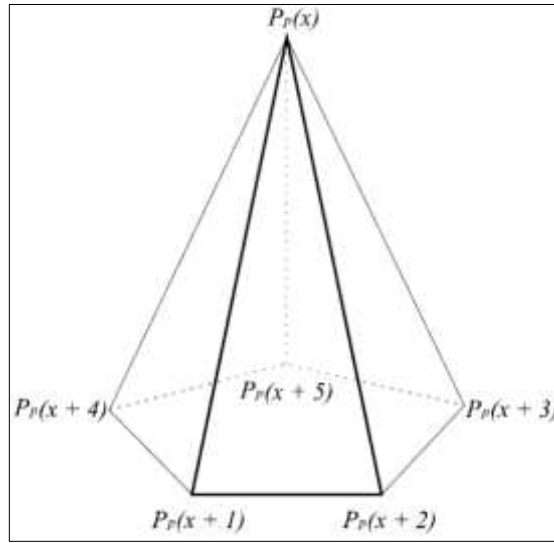


Figure 2: Presentation of the 3D position vectors of the tunicate. Source: [25].

The parameters, positions and velocities are continuously updated till the convergence criteria are met. At each iteration, update the global best solution based on the fitness evaluations [26]. Consequently, preserve the solutions of the first two best candidates and use them to update other candidates' solutions while maintaining swarm intelligence behavior.

Table 1: Parameters of Applied TSA.

Parameters	Values
c_1	0.5
c_2	0.3
c_3	0.7
p_{min}	1
p_{max}	4
Population size	50
Maximum iterations	200

Source: Authors, (2026).

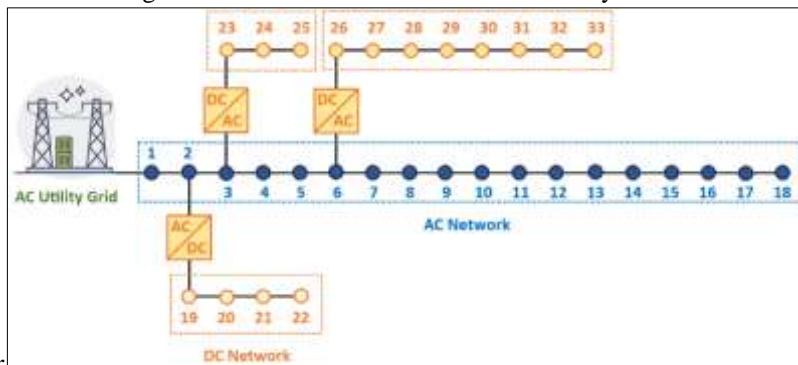
IV. RESULTS AND DISCUSSIONS

In this section, an applied optimization TSA technique for the optimum location of multiple WDG units is utilized to lessen power loss. The proposed controller is executed on MATLAB software. The performance of the proposed system is analyzed with a modified IEEE 33-bus system represented in Figure 3, which was adopted for the validation of the proposed model. The illustration demonstrates the one-line representation of the modified IEEE 33 bus distribution system, designed as a hybrid AC-DC network. It emphasizes the incorporation of DC sub-networks into a traditional radial AC feeder using power electronic interfaces. The AC utility grid provides power to the system via the substation at Bus 1, preserving the radial configuration of the 33-bus feeder. Buses 1 through 18 constitute the AC distribution network, illustrated in blue.

In addition to providing traditional AC loads, this portion acts as the framework for linking DC subsystems. Practical MV distribution systems are reflected in the radial structure. The AC system is linked to two DC networks (illustrated in orange). DC loads and DC-based distributed resources, including wind distributed generation, energy storage systems, DC microgrids, and DC consumption, are represented by these DC sections. This one-line diagram serves as the test system architecture for evaluating voltage profiles, power flow, and the impact of WDG penetration in a hybrid network. It provides the structural basis for the voltage performance results observed in the different case studies (cases 1 to 4). The four configurations for case studies in this paper:

- Case 1: Hybrid EDN without WDG (basic case),
- Case 2: Hybrid EDN with one WDG,
- Case 3: Hybrid EDN with two WDGs,
- Case 4: Hybrid EDN with three WDGs.

Figure 3: One-line diagram of the tested modified IEEE 33-bus hybrid AC-DC network.



Source: Author s, (2026).

Figure 4 represents the bus voltage of a hybrid AC-DC network without WDG units (case 1).

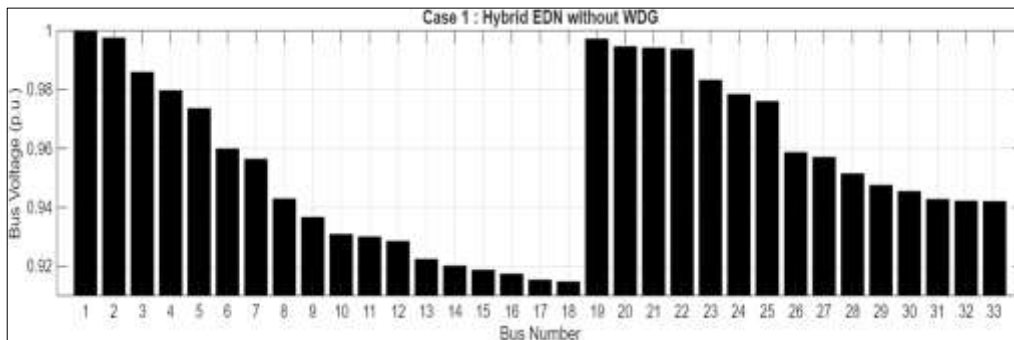


Figure 4: The bus voltage of a hybrid AC-DC network without WDG units (Case 1).
Source: Authors, (2026).

As observed in Figure 4, because the feeder is radial, the bus voltage magnitude gradually drops from the substation (Bus 1) to the end buses. Some buses suffer from severe undervoltage, with values falling below 0.95 p.u., especially in the downstream AC network (around buses 9–18). Voltages in the DC network (buses 19–33) likewise progressively drop, suggesting greater vulnerability to loading and inadequate voltage support. From the standpoint of power quality, this instance is crucial since the voltage profile. Figure 5 represents the branch active power loss of a hybrid AC-DC network without WDG units (case 1).

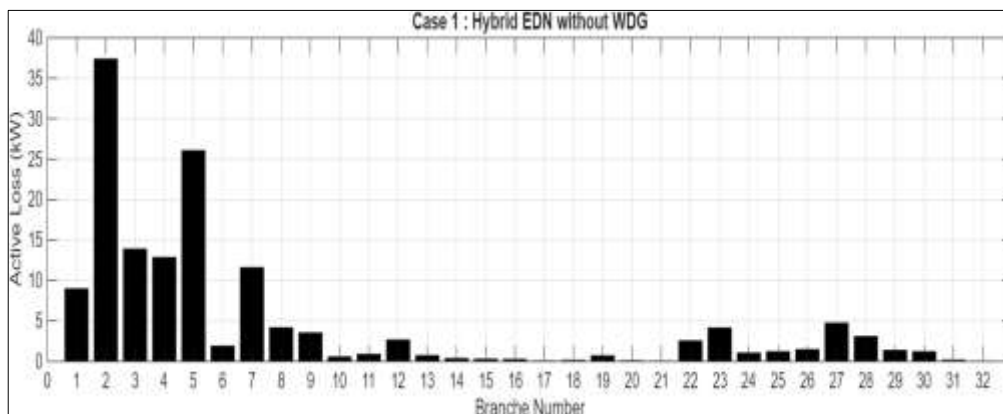


Figure 5: The branch active power loss of a hybrid AC-DC network without WDG units (Case 1).
Source: Authors, (2026).

As demonstrated by Figure 5, the upstream branches, particularly those near the substation (e.g., branches 2–6), have a significant concentration of active power losses. This is because there is no local production to balance the electricity demand, and the entire downstream load is supplied by a high current flow. Even while losses in downstream branches are very minor, they nevertheless add to the overall inefficiency of the system. As a result, the overall active power loss is comparatively large. The branch reactive power loss of a hybrid AC-DC network without WDG units (case 1) is shown in Figure 6.

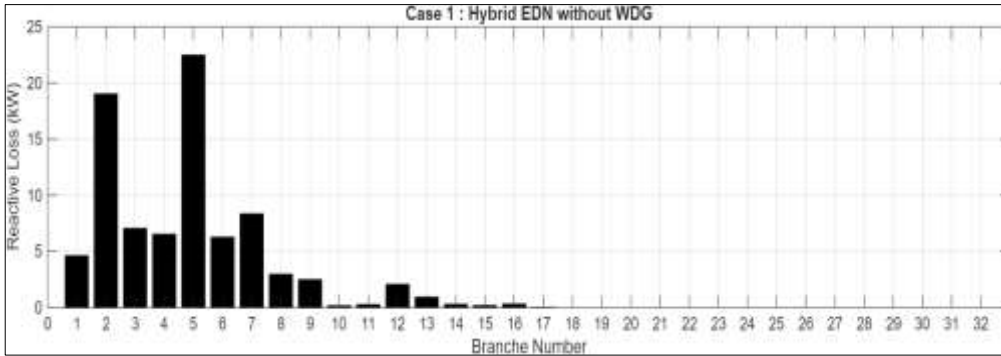


Figure 6: The branch reactive power loss of a hybrid AC-DC network without WDG units (Case 1).
Source: Authors, (2026).

As shown in Figure 6, with peak losses in the first feeder branches, reactive power losses exhibit a similar pattern to active losses. Large reactive power demands from loads are indicated by high reactive losses, which worsen voltage drops along the feeder. The system has very little reactive support, which exacerbates voltage deterioration. The convergence characteristics of the proposed TSA algorithm after integrating one, two, and three WDG units in EDN are presented in Figure 7.

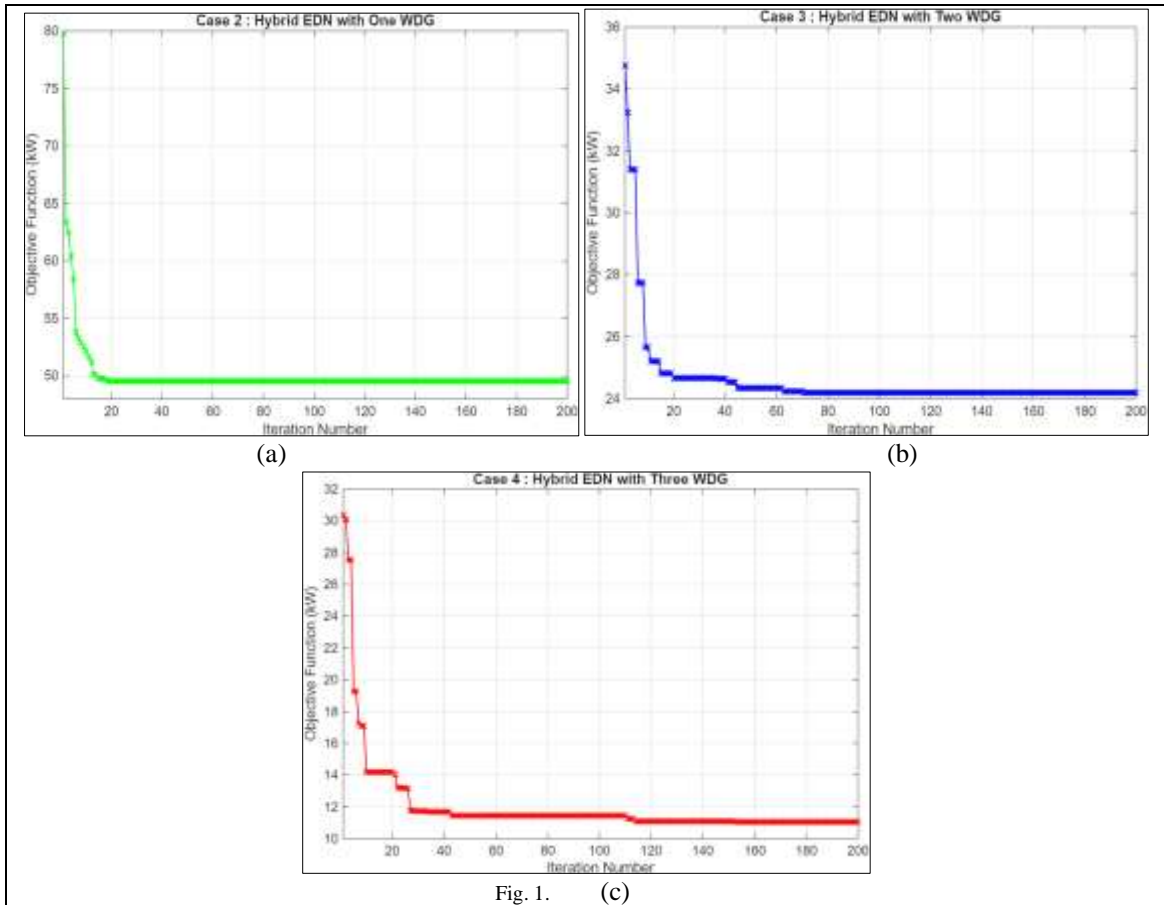


Figure 7: The convergence curves of the TSA approach for all case studies:
a). Case 1: One WDG, b). Case 2: Two WDGs, c). Case 3: Three WDGs.
Source: Authors, (2026).

The proposed approach ensures improved solution quality with enhanced convergence speed and adherence to EDN constraints. This, in turn, ultimately improves the stability, efficiency, and reliability of the test system. At each iteration, update the best global solution based on the objective function. Through the balancing strategy between exploration and exploitation, TSA addresses the sensitivity to parameter settings like population size and iterations for the three case studies. Tables 2, 3, and 4 summarize the optimal parameters after installing one, two, and three WDG units and technical parameters for the hybrid AC-DC test system.

Table 2: Optimal Planning of One WDG unit (Case 2).

Parameters		Values
WDG Unit	<i>Bus Location</i>	6
	P_{WDG} (MW)	2.5234
	Q_{WDG} (MVar)	0.6507
Hybrid AC-DC Network	ΣP_{Loss} (MW)	49.5134
	ΔP_{Loss} (%)	66.5456
	ΣQ_{Loss} (MVar)	24.9955
	ΔQ_{Loss} (%)	70.3752
	V_{min} (p.u.)	0.9578
	V_{max} (p.u.)	1.0009
	ΣVD (p.u.)	0.4876

Source: Authors, (2026).

Table 3: Optimal Planning of Two WDG Units (Case 3).

Parameters		Values
WDG Units	<i>Bus Location</i>	13 – 30
	P_{WDG} (MW)	0.8424 – 1.1210
	Q_{WDG} (MVar)	0.3734 – 0.1058
Hybrid AC-DC Network	ΣP_{Loss} (MW)	24.1855
	ΔP_{Loss} (%)	83.6587
	ΣQ_{Loss} (MVar)	7.6940
	ΔQ_{Loss} (%)	90.8810
	V_{min} (p.u.)	0.9847
	V_{max} (p.u.)	1.0001
	ΣVD (p.u.)	0.1778

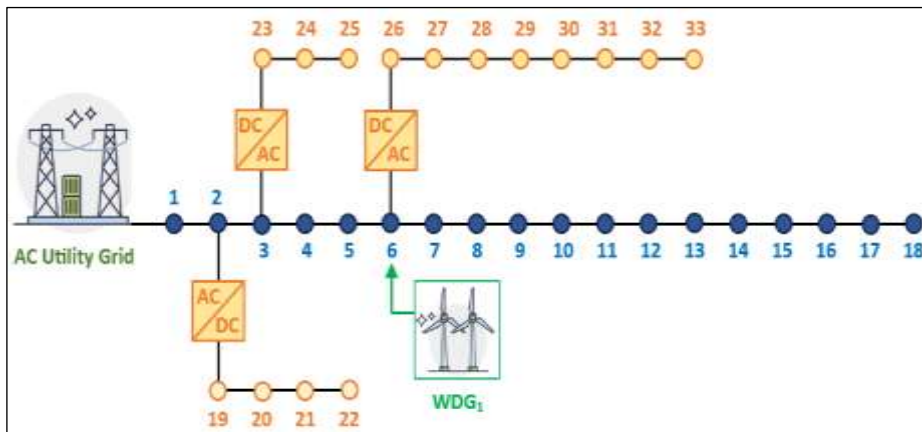
Source: Authors, (2026).

Table 4: Optimal Planning of Three WDG Units (Case 4).

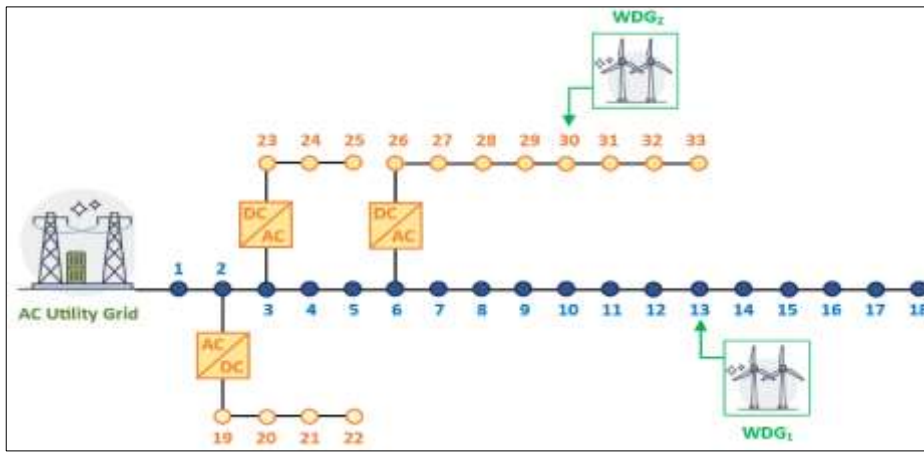
Parameters		Values
WDG Units	<i>Bus Location</i>	14 – 24 – 30
	P_{WDG} (MW)	0.8059 – 1.1683 – 0.9941
	Q_{WDG} (MVar)	0.3671 – 0.1955 – 0.1118
Hybrid AC-DC Network	ΣP_{Loss} (MW)	11.0467
	ΔP_{Loss} (%)	92.5361
	ΣQ_{Loss} (MVar)	4.6155
	ΔQ_{Loss} (%)	94.5297
	V_{min} (p.u.)	0.9929
	V_{max} (p.u.)	1.0034
	ΣVD (p.u.)	0.0803

Source: Authors, (2026).

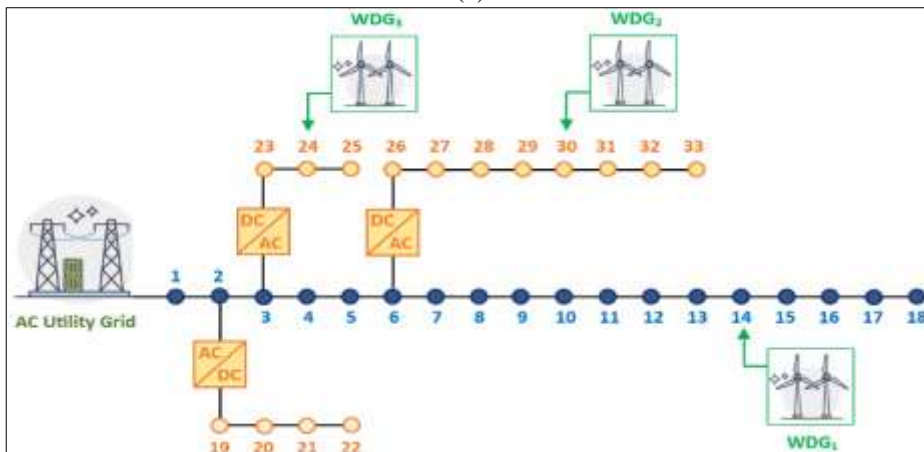
Tables 1, 2, and 3 demonstrate the benefits of installing WDG units, particularly in terms of reduced power losses and voltage deviation. Furthermore, compared to other situations, the integration of the three WDG produces a good performance. The configuration for the hybrid AC-DC systems with the three case studies, with location one, two, and three WDG units, is presented in Figure 7.



(a)



(b)



(c)

Figure 8: Optimal configuration of WDG integration for various case studies:
 a). Case 1: One WDG, b). Case 2: Two WDGs, c). Case 3: Three WDGs.
 Source: Authors, (2026).

Figure 9 compares bus voltage magnitudes (p.u.) across the hybrid AC-DC network for different case studies with increasing numbers of WDG units.

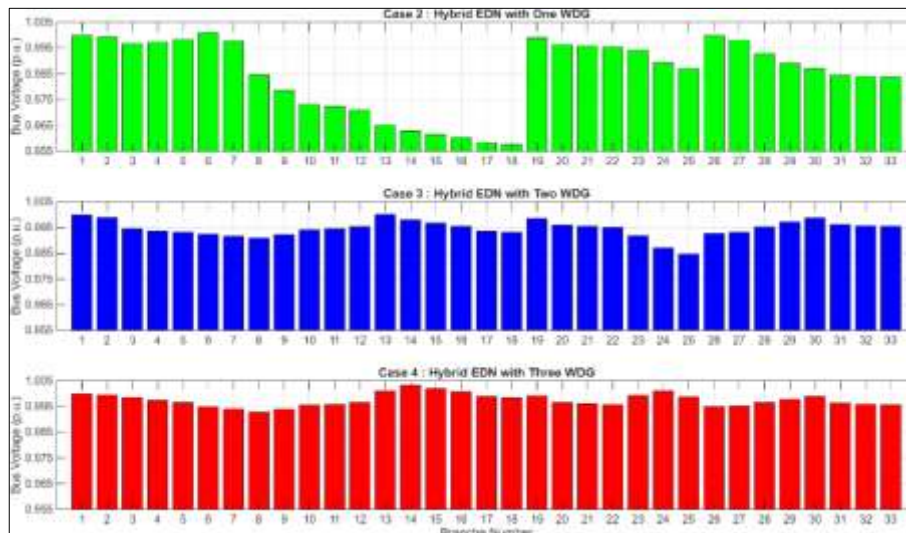


Figure 9: The Bus voltage of a hybrid AC-DC network with WDG units for various case studies.
 Source: Authors, (2026).

After analyzing Figure 9. In case 2, the hybrid EDN with one WDG (green color): The voltage profile shows larger variations along the feeder. Several downstream buses (roughly buses 9–18) experience noticeable voltage drops, approaching the lower acceptable

limit (~0.955–0.965 p.u.). This indicates that a single WDG provides limited voltage support, especially in buses far from the source or in load-intensive sections. Voltage regulation is weaker and more location-dependent.

For Case 3, the hybrid EDN with two WDG units (blue color), the voltage profile becomes significantly flatter than in Case 2. Most bus voltages lie within a narrower band (~0.985–1.0 p.u.). Localized voltage dips are reduced, showing that additional WDG improves reactive power support and reduces line voltage drops. Overall voltage regulation and uniformity are improved. Finally, in Case 4, the hybrid EDN with three WDG units (red color): This case exhibits the best voltage profile among all scenarios. Bus voltages are very close to the nominal value (~1.0 p.u.) across the entire network. Voltage deviations are minimal, and no critical undervoltage buses are observed. The results highlight that higher WDG penetration enhances voltage stability and reduces losses in the hybrid AC–DC network. In conclusion, the figure clearly demonstrates the positive impact of coordinated WDG integration on bus voltage performance in a hybrid AC-DC distribution system. The branch active power loss (kW) over the hybrid AC-DC network for several case studies with an increase in WDG units is compared in Figure 10.

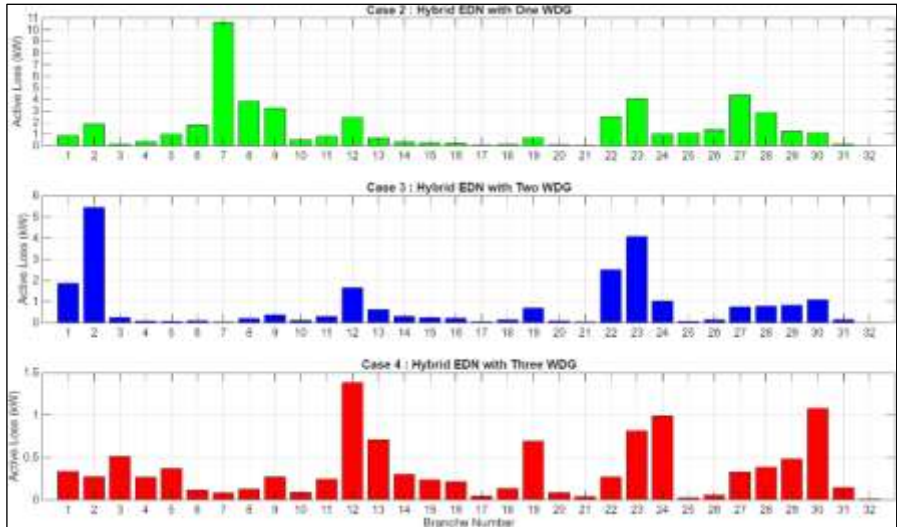


Figure 10: The branch active loss of a hybrid AC-DC network with WDG units for various case studies. Source: Authors, (2026).

Out of all the possibilities, case 2 shows the greatest branch losses. Some branches have extremely large loss peaks, particularly those near branches 6–8 and 12. Higher power flow from the main grid and increased current in several branches result from the single WDG's restricted local power support. In the hybrid network, one WDG is not enough to considerably reduce branch losses. When comparing Case 3 to Case 2, a significant decrease in branch losses is seen. Peak losses are distributed more uniformly among branches and are substantially lower. In Case 4, the arrangement of three WDGs exhibits the lowest branch losses of any branch. Loss values are uniformly distributed and quite modest. This shows that the hybrid AC-DC network is making the best use of distributed generation. Near-optimal loss minimization and the best-balanced network functioning are achieved by three WDG units. Figure 11 illustrates the branch reactive power losses in the hybrid AC–DC distribution network for different case studies with an increasing number of WDG units.

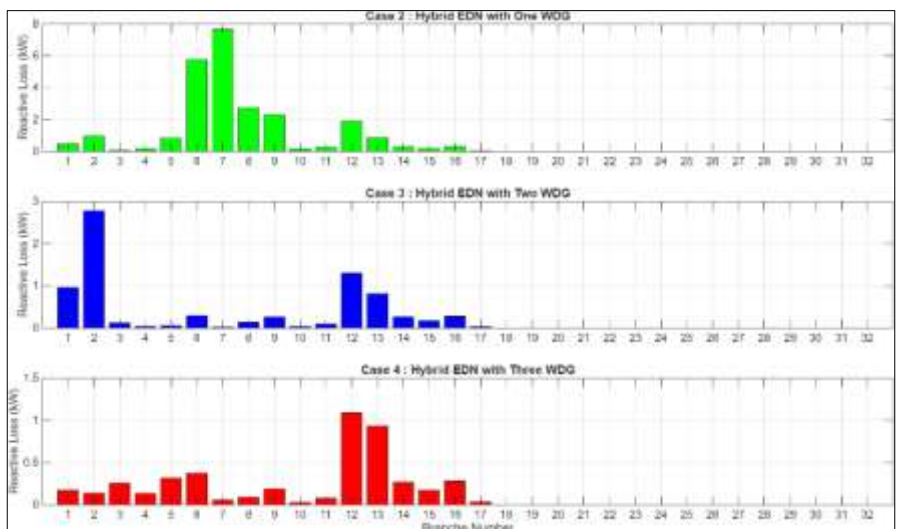


Figure 11: The Branch reactive loss of a hybrid AC-DC network with WDG units for various case studies. Source: Authors, (2026).

Out of all cases, Case 2 has the largest reactive power losses. There are noticeable loss peaks in several branches, especially in the mid-feeder and upstream parts (around branches 6–8 and 12). The losses are more uniformly distributed, and the peak loss magnitudes

are significantly smaller in Case 3. Better local reactive power adjustment is provided by the extra WDG. However, some branches continue to exhibit moderate losses, indicating partial but incomplete optimization.

Out of all the branches, Case 4 has the lowest reactive power losses. There are no sharp peaks in the loss numbers, which are minor and evenly dispersed. Increased WDG penetration improves both overall reactive current flow reduction and local reactive power support. Figure 12 represents the total active and reactive power losses in a hybrid AC-DC network with increasing WDG penetration.

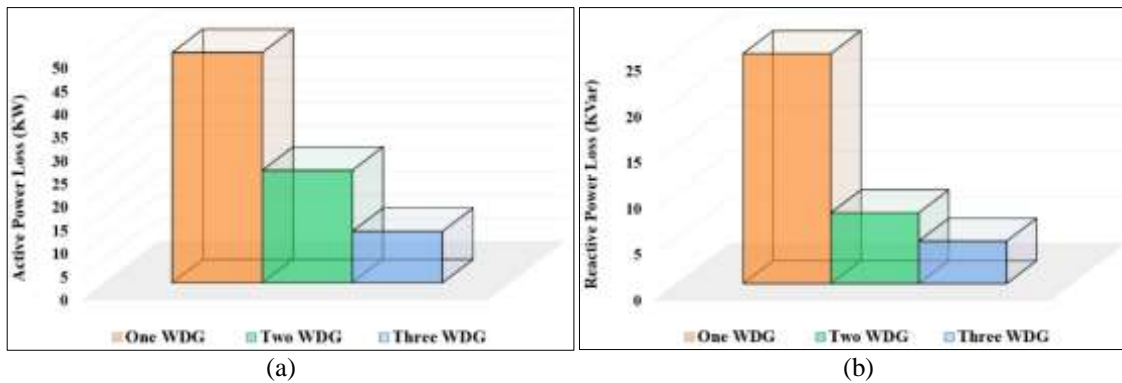


Figure 12: The total losses in the hybrid AC-DC network for various WDG units: a). Active power loss, b). Reactive power loss. Source: Authors, (2026).

Below is a clear technical analysis of Figures 12 (a) and (b) showing the total losses in a hybrid AC-DC network with increasing WDG penetration. The active power loss achieves its lowest value when three WDGs are integrated into EDN, as shown in Figure 12.a, indicating the most successful loss minimization of the situations under study. Increasing the number of WDG devices lowers line currents by improving local power supply and voltage support. As WDG penetration rises, the graph unmistakably demonstrates a monotonic decline in active power losses. More WDG units raise the overall power factor, decrease needless reactive power circulation, and increase local reactive power support. Reactive losses are significantly reduced as a result, which is essential for voltage stability. The findings verify that, out of all the scenarios taken into consideration, three WDGs offer the best performance in terms of loss minimization.

V. CONCLUSIONS

This paper studies the minimization of active power losses by the optimal allocation of multiple WDG units based on applying the TSA algorithm and tested on the modified IEEE 33-bus with a hybrid AC-DC distribution network. In conclusion, the figure clearly demonstrates the positive impact of coordinated WDG integration on bus voltage performance in EDN. The optimal results clearly demonstrate that higher WDG penetration significantly improves power loss performance in the hybrid AC-DC distribution network. The configuration with three WDG units provides the most efficient and stable operation, validating the effectiveness of WDG in reducing reactive losses and enhancing overall network efficiency. These simulation results clearly demonstrate that strategic integration of multiple WDG units in a hybrid AC-DC EDN leads to substantial loss reduction and improved power flow performance, validating the effectiveness of distributed renewable generation in modern EDN. Increasing the number of WDG units leads to a progressive reduction in branch power losses. The hybrid AC-DC network benefits substantially from distributed active and reactive power support, especially when WDGs are optimally integrated.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: Mohamed Zellagui, Samir Settoul and Claude Ziad El-Bayeh.

Methodology: Samir Settoul.

Investigation: Mohamed Zellagui and Samir Settoul.

Discussion of results: Mohamed Zellagui and Samir Settoul.

Writing – Original Draft: Mohamed Zellagui and Samir Settoul.

Writing – Review and Editing: Mohamed Zellagui, Samir Settoul and Claude Ziad El-Bayeh.

Resources: Mohamed Zellagui, Samir Settoul and Claude Ziad El-Bayeh.

Supervision: Mohamed Zellagui.

Approval of the final text: Mohamed Zellagui, Samir Settoul and Claude Ziad El-Bayeh.

VII. REFERENCES

- [1] S. J. U. Hassan, A. Mehdi, Z. Haider, J. S. Song, A. D. Abraham, G. S. Shin, and C. H. Kim, "Towards medium voltage hybrid AC/DC distribution Systems: architectural topologies, planning and operation", *International Journal of Electrical Power & Energy Systems*, vol. 159, 110003, 2024. <https://doi.org/10.1016/j.ijepes.2024.110003>.
- [2] S. Charadi, Y. Chaibi, A. Redouane, A. Allouhi, A. El Hasnaoui, and H. Mahmoudi, "Efficiency and energy-loss analysis for hybrid AC/DC distribution systems and microgrids: A review", *International Transactions on Electrical Energy Systems*, vol. 31, e13203, 2021. <https://doi.org/10.1002/2050-7038.13203>.
- [3] Y. Chen, Q. Lu, K. Zeng, Y. Yang, and P. Xie, "Flexibility-oriented AC/DC hybrid grid optimization using distributionally robust chance-constrained method", *Energies*, vol. 17, no. 19, 4902, 2024. <https://doi.org/10.3390/en17194902>.
- [4] M. Zellagui, N. Belbachir, A. Lasmari, R. J. J. Molu, and S. Kamel, "Enhancing PV distributed generator planning in medium-voltage DC distribution networks: a multi-design techno-economic analysis with load demand response", *IET Generation, Transmission & Distribution*, vol. 18, no. 1, pp. 173–189, 2024. <https://doi.org/10.1049/gtd2.13080>.

- [5] M. Zellagui, S. Settoul, and A. Lasmari, "Applied equilibrium optimizer algorithm for optimal planning multiple photovoltaic distributed generators in hybrid AC-DC distribution networks, Brazilian Journal of Technology, vol. 7, no. 4, e76100, 2024. <https://doi.org/10.38152/bjtv7n4-042>.
- [6] N. Belbachir, M. Zellagui, S. Settoul, and A. Benali, "Optimal design of wind energy generation in electricity distribution network based technical-economic parameters using metaheuristic optimization algorithms", Engineering Review, vol. 43, no. 3, pp. 115–128, 2023. <https://doi.org/10.30765/er.2281>.
- [7] E. Kaymaz, S. Duman, and U. Guvenc, "Optimal power flow solution with stochastic wind power using the Lévy coyote optimization algorithm", Neural Computing and Applications, vol. 33, no. 12, pp. 6775–6804, 2021. <https://doi.org/10.1007/s00521-020-05455-9>.
- [8] A. K. Khamees, A. Y. Abdelaziz, M. R. Eskaros, H. H. Alhelou, and M. A. Attia, "Stochastic modeling for wind energy and multi-objective optimal power flow by novel meta-heuristic method", IEEE Access, vol. 9, pp. 158353–158366, 2021. <https://doi.org/10.1109/access.2021.3127940>.
- [9] M. Q. Duong, T. Nguyen, and T. T. Nguyen, "Optimal placement of wind power plants in transmission power networks by applying an effectively proposed metaheuristic algorithm", Mathematical Problems in Engineering, vol. 2021, e1015367, 2021. <https://doi.org/10.1155/2021/1015367>.
- [10] S. Kaur, L. K. Awasthi, A. Sangal, and G. Dhiman, "A new bio-inspired based metaheuristic paradigm for global optimization", Engineering Applications of Artificial Intelligence, vol. 90, 103541, 2020. <https://doi.org/10.1016/j.engappai.2020.103541>.
- [11] H. Jumakhan, S. Abouelnour, A. Al-Redhaei, S. N. Makhadmeh, and M. A. Al-Betar, "Recent versions and applications of tunicate swarm algorithm", Archives of Computational Methods in Engineering, vol. 32, pp. 4857–4886, 2025. <https://doi.org/10.1007/s11831-025-10287-8>.
- [12] M. R. Islam, M. S. Azam, M. S. Hossen, M. S. Islam, M. Y. Worku, M. S. Shahriar, and M. Shafullah, "Power system stability enhancement through optimal PSS design", E-Prime - Advances in Electrical Engineering, Electronics and Energy, vol. 9, 100735, 2024. <https://doi.org/10.1016/j.prime.2024.100735>.
- [13] L. L. Li, Z. F. Liu, M. L. Tseng, S. J. Zheng, and M. K. Lim, "Improved tunicate swarm algorithm: solving the dynamic economic emission dispatch problems", Applied Soft Computing, vol. 108, 107504, 2021. <https://doi.org/10.1016/j.asoc.2021.107504>.
- [14] R. M. Rizk-Allah, E. A. Hagag, and A. A. El-Fergany, "Chaos-enhanced multi-objective tunicate swarm algorithm for economic-emission load dispatch problem", Soft Computing, vol. 27, pp. 5721–5739, 2023. <https://doi.org/10.1007/s00500-022-07794-2>.
- [15] A. S. Memon, J. Laghari, M. A. Bhayo, S. Khokhar, S. Chandio, and M. S. Memon, "Tunicate swarm algorithm based optimized PID controller for automatic generation control of two area hybrid power system", Journal of Intelligent & Fuzzy Systems, vol. 45, no. 2, pp. 2565–2578, 2023. <https://doi.org/10.3233/JIFS-223227>.
- [16] R. Krishnakumar, and C. Ravichandran, "Reliability and cost minimization of renewable power system with tunicate swarm optimization approach based on the design of PV/Wind/FC system", Renewable Energy Focus, vol. 42, pp. 266–276, 2022. <https://doi.org/10.1016/j.ref.2022.07.003>.
- [17] H. S. Madupu, P. R. Chinda, and S. Kotni, "A novel tunicate swarm algorithm for optimal integration of renewable distribution generation in electrical distribution networks considering extreme load growth", Journal of Electrical Engineering & Technology, vol. 18, pp. 2709–2722, 2023. <https://doi.org/10.1007/s42835-023-01388-0>.
- [18] R. Rashidi, A. Hatami, M. Moradi, and X. Liang, "Optimal multi-microgrids energy management through information gap decision theory and tunicate swarm algorithm", IEEE Access, vol. 12, pp. 114795–114808, 2024. <https://doi.org/10.1109/access.2024.3443471>.
- [19] P. Hemachandu, S. Premalatha, K. P. Arunachalam, and P. V. H. Prasad, "Energy management in photovoltaic-based electric vehicle charging systems with battery storage and vehicle-to-grid support", Energy Storage, vol. 7, no. 5, e70236, 2025. <https://doi.org/10.1002/est2.70236>.
- [20] J. Wang, S. Wang, and Z. Li, "Wind speed deterministic forecasting and probabilistic interval forecasting approach based on deep learning, modified tunicate swarm algorithm, and quantile regression", Renewable Energy, vol. 179, pp. 1246–1261, 2021. <https://doi.org/10.1016/j.renene.2021.07.113>.
- [21] Q. Su, Z. Gao, and Z. Zhong, "Dynamic energy hub-based planning and operation for optimal integration of variable energy conversion efficiency in community-level energy systems", Energy, vol. 332, 137143, 2025. <https://doi.org/10.1016/j.energy.2025.137143>.
- [22] H. A. El-Sattar, S. Kamel, and M. A. Elseify, "A modified white shark optimizer for optimizing photovoltaic, wind turbines, biomass, and hydrogen storage hybrid systems", Journal of Energy Storage vol. 113, 115655, 2025. <https://doi.org/10.1016/j.est.2025.115655>.
- [23] S. Settoul, M. Zellagui, and R. Chenni, "A new optimization algorithm for optimal wind turbine location problem in Constantine city electric distribution network based active power loss reduction", Journal of Optimization in Industrial Engineering, vol. 14, no. 2, pp. 13–22, 2021. <https://doi.org/10.22094/joie.2020.1892184.1725>.
- [24] N. Belbachir, M. Zellagui, and S. Kamel, "Multi-dimensional energy management based on an optimal allocation of hybrid wind turbine distributed generation and battery energy storage system in a flexible interconnected distribution network considering seasonal uncertainties", Engineering Proceedings, vol. 56, no. 1, 246, 2023. <https://doi.org/10.3390/ASEC2023-16292>.
- [25] O. Akdağ, "A modified tunicate swarm algorithm for engineering optimization problems", Arabian Journal for Science and Engineering, vol. 48, no. 11, pp. 14745–14771, 2023. <https://doi.org/10.1007/s13369-023-07803-y>.
- [26] R. Zheng, A. G. Hussien, A. Bouaouda, R. Zhong, G. Hu, "A comprehensive review of the tunicate swarm algorithm: variations, applications, and results", Archives of Computational Methods in Engineering, vol. 32, pp. 2917–2986, 2025. <https://doi.org/10.1007/s11831-025-10228-5>.