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A Metaheuristic Approach for the Optimal Allocation of Distributed Energy Resources in a Distribution System

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ABSTRACT

In this paper, a variant of the Chimp optimisation algorithm, namely, Chimp Particle Swarm Optimisation Algorithm (ChPSO), a metaheuristic optimisation technique, is recommended to optimise the placement of Distributed Energy Resources (DER) in electric power distribution systems. By integrating the Chimp Optimization Algorithm with Particle Swarm Optimization, ChPSO enhances the efficiency and reliability of power distribution networks. The algorithm's effectiveness is evaluated using the IEEE-33 bus distribution system, a well-established benchmark in power system research. The primary goal is to strategically position DERs to minimize real power losses, and reduce voltage deviations across all nodes. Results indicate significant improvements in these performance metrics, showcasing ChPSO's capability to tackle complex optimization challenges. Specifically, the implementation of three optimally placed DERs achieved a remarkable 92.20% reduction in real power loss, while positioning four DERs resulted in an even greater reduction of 92.90%. Additionally, reactive power losses decreased by 90.55% and 91.59% for three and four DERs, respectively. These findings highlight the potential of the ChPSO algorithm as a decent solution for optimized DER placement, significantly enhancing the operational efficiency and reliability of modern distribution systems and emphasizing the need for innovative optimization strategies in sustainable energy solutions.

1. Introduction

The integration of distributed energy resources (DERs) is playing a pivotal role in the evolving electricity market, bringing both benefits and challenges [1, 2]. DERs provide consumers with greater flexibility and self-consumption capabilities, while also supporting decarbonization efforts by replacing fossil fuel generation with renewable sources. DER integration can increase market competitiveness and reduce price volatility. However, the existing grid infrastructure often lacks the flexibility to seamlessly accommodate DERs, leading to technical issues like voltage problems and grid stability concerns. Addressing these challenges requires modernizing the grid, deploying advanced control systems, and implementing market reforms to enable effective DER participation. Overcoming the barriers to large-scale DER integration will be crucial for harnessing the full potential of these distributed resources in the future electricity system and realizing the associated benefits for consumers, the environment, and the overall market.

Integrating distributed energy resources (DERs) like solar, wind, and energy storage into the electrical grid presents several key technical and operational challenges. Power quality issues like voltage disturbances and transients [3] can arise from the variable and intermittent nature of renewable energy sources. Maintaining grid stability and reliability is critical as the system evolves from large, centralized power plants to smaller, decentralized DER sources. Interconnection and control challenges require advanced inverters, updated grid control software, and compatibility with interconnection standards. Additionally, there are economic and regulatory hurdles, as the traditional grid was not designed for DER integration, requiring new business models, investments, and policy changes [4, 5]. Overcoming these challenges through innovative hardware, control algorithms, and a collaborative approach between utilities, customers, and DER providers will be essential for the successful large-scale integration of distributed energy resources into the modern electricity grid. Several researchers in the literature consider different objectives such as power loss reduction, voltage profile improvement, enhancing the system's reliability and efficiency, etc. The process involves both identifying the best location (bus/node) for DER installation and recommending the size/capacity. This can be done either by analytical approaches or by applying optimization algorithm approaches. Analytical Approaches evaluate each bus in the system to determine where DER provides the greatest benefit, such as maximum loss reduction or voltage improvement. Analytical techniques are more practical for smaller systems. As the size of the system increases, the computational complexity increases, and it becomes difficult to obtain the best solution over time. Optimization algorithms generally work as a black box approach where they take the requirements as input parameters and generate the solution in the best possible time. The operational constraints and system parameters can be provided as input, and it generates the optimal location and size of DER to meet the required objectives. Further, these can be single-objective or multi-objective.

The optimal placement of distributed energy resources (DERs) within a distribution system is a necessity for enhancing the overall performance and efficiency of the grid. Strategically locating DERs can help minimize power losses [6, 7] improve voltage profiles [8], increase system capacity, and enhance reliability - all while facilitating the integration of renewable energy sources. There are several approaches, like the Evolutionary Programming Algorithm, to reduce the generation operating costs [9]. However, proper DER placement can also defer costly grid upgrades, leading to significant cost savings for utilities and consumers. Furthermore, optimal DER integration is often mandated by regulatory policies, making it a critical consideration for grid operators. By carefully planning the placement of distributed resources [10], utilities can unlock the full technical, economic, and environmental benefits that DERs can provide, ultimately creating a more resilient, sustainable, and cost-effective electricity distribution system.

The state-of-the-art approaches for the optimal placement of distributed energy resources (DERs) encompass a variety of methodologies that aim to maximize the benefits of DERs while minimizing potential drawbacks. Cooperative game theory-based approaches have been proposed to determine optimal locations and sizes of DERs by considering locational marginal costs and the Shapley value, which have been shown to reduce the total cost of generation in case studies [11]. Comprehensive literature reviews have classified and compared uncertainty modeling methods and optimization techniques, providing valuable insights into current research achievements and future directions [12].

However, it is important to note that unplanned placement of DERs can lead to issues such as voltage instability and increased power losses. Therefore, optimization techniques like enhanced particle swarm optimization and genetic algorithms have been applied to address these issues, focusing on power loss reduction and voltage profile enhancement [13, 14]. As the sizing of DERs plays a vital role in the efficient placement [15], various optimization techniques have been reviewed for optimal placement and sizing of DERs, considering single and multiple objectives and taking into account various constraints [16]. Multi-objective optimization has also been explored, with methods like the Memetic evolutionary algorithm and NSGA-II genetic algorithm being proposed to balance trade-offs between investment costs, energy not supplied, and greenhouse gas emissions [17]. Probabilistic techniques have been used to address uncertainties in DER penetration scenarios [18], multi-objective planning methods have been developed to consider technical, environmental, and economic impacts of DER integration [19]. Lastly, the network reconfiguration problem has been expanded to include random generation sources from renewable energy, with algorithms like the biased random-key evolution framework (BRKGA) being developed to address this combinatorial optimization problem [20]. On the other hand, the application of meta-heuristic algorithms for electrical/energy engineering research is also increasing [21-26] which further recommends implementing these algorithms and benefiting from solving real-time research problems.

In summary, the state-of-the-art approaches for optimal placement of DERs are diverse and multi-faceted, incorporating game theory, comprehensive literature reviews, optimization algorithms, multiobjective and probabilistic methods, and network reconfiguration techniques. These methods aim to optimize the integration of DERs in terms of cost, reliability, environmental impact, and network stability, while addressing the challenges posed by the inherent uncertainties and complexities of power systems.

The manuscript contributions are summarized as follows:

- The Chimp Particle Swarm Optimization Algorithm (ChPSO) is introduced as a novel hybrid meta-heuristic approach to address the optimal integration of Distributed Energy Resources (DER) in distribution systems. The algorithm aims to minimize annual energy losses and node voltage deviations while considering these objectives simultaneously.
- The effectiveness of the proposed methods is validated by solving the designed dispatchable DER integration problems on the well-known IEEE-33 bus distribution system. The performance of the ChPSO algorithm is compared to existing optimization techniques to demonstrate its superiority.
- The simulation results are compared with similar methods reported in the literature, showcasing the proposed technique's ability to provide the most balanced and compromising solutions for the optimal placement and sizing of DERs in distribution networks.

The listed contributions are explained in this manuscript as follows: the proposed hybrid algorithm is explained in section 2, section 3 explains the distribution system mathematical equations, and different objective functions are applied to derive optimal solutions. Finally, Section 4 provides a detailed analysis of the test system considered, where final conclusions are summarized in Section 5.

2. Chimp Optimization Algorithm (ChOA)

Meta-heuristics are high-level strategies for exploring search spaces that balance intensification (exploiting known good areas) and diversification (exploring new areas). This balance helps quickly find high-quality solutions while avoiding wasted effort in already explored or unpromising regions. Chimp Optimization Algorithm (ChOA) algorithm [27] is inspired by the complex social structure and cooperative foraging of chimpanzees, which have been celebrated for their social interactions and teamwork. In real hunting, there appear to be different roles in the wild, with each contributing in a unique way to the success of the unit. This leads ChOA to the categorization of chimps into four roles: Attacker, Barrier, Chaser, and Driver.

Here, the Attacker will lead the group towards the likely prey while the Barrier will support the Attacker by controlling the group dynamics. The Chaser will pursue the prey from the back and ensure that the hunt is focused and efficient. Lastly, the Driver maintains the cohesion of the group and directs paths towards all possible routes. These roles are indicative of a high degree of cooperation and communication that is witnessed among chimps and which ChOA exploits to further the optimization process.

As such, through the years, ChOA has built a reputation for effectively navigating complex solution landscapes by simulating social interactions and hunting phases. The algorithm's design leans toward fostering cooperation and strategic moves to explore different areas of the search space, without falling into local optima. The behavioral inspirations drawn from the chimpanzee are unique while at the same time enriching the framework of the algorithm and making it perform better on a variety of optimization challenges, thus rendering it a very powerful tool to solve real-world complex problems.

2.1. Hybrid Chimp Particle Swarm Optimization Algorithm (ChPSO):

Combining the ChOA with Particle Swarm Optimization (PSO) offers an effective strategy for optimization tasks, leveraging the unique strengths of both algorithms to develop a more powerful and adaptable optimization method [28]. By integrating ChOA's exploratory prowess with PSO's exploitation strengths through the velocity function of the particle swarm optimization (PSO) [29, 30] the hybrid ChPSO algorithm achieves a balanced exploration-exploitation trade-off, leading to enhanced solution quality and convergence speed. This integration not only enhances the speed of the optimization process but also allows for seamless adaptation to a diverse range of problem characteristics, thereby ensuring flexibility. The hybrid algorithm, known as ChPSO, excels in traversing intricate and challenging optimization landscapes, making it a versatile and formidable tool applicable across numerous fields. By combining the strengths of ChOA and PSO, ChPSO promises improved performance and reliability, surpassing the capabilities of each individual algorithm when used in isolation. This synergy enables it to tackle complex problems more effectively, offering users a reliable solution that can be tailored to meet specific needs across various domains. Equations (1) and (2) illustrate the act of pursuing and chasing a target or prey.

$$d = |c.x_{prey}(n) - mx_{chimp}(n)| \tag{1}$$

$$x_{chimp}(n+1) = x_{prey}(n) - a.d \tag{2}$$

The coefficient vectors c, m, and a are determined by equations (3) to (4), where n represents the total number of iterations.:

$$x = 2.k.r_1 - k \tag{3}$$

$$c = 2r_2 \tag{4}$$

$$m = chaotic\ value \tag{5}$$

The values r_1 and r_2 are constrained within the range of 0 to 1, while *m* denotes the chaotic vector. Meanwhile, *k* progressively decreases from 2.5 to 0 throughout the iterations. In this context, the roles of attacker, driver, barrier, and chaser assume that the target is located at the position of the current initial solution. The iterative process involves maintaining four optimal solutions and encouraging other chimpanzees to adjust their positions based on the locations of the superior chimps. This approach is mathematically represented by equations (6) to (9).

$$d_{attacker} = |c_1 x_{attacker}(n) - m_1 x(n)| \tag{6}$$

$$d_{barrier} = |c_2 x_{barrier}(n) - m_2 x(n)| \tag{7}$$

$$d_{chaser} = |c_3 x_{chaser}(n) - m_3 x(n)| \tag{8}$$

$$d_{driver} = |c_4 x_{driver}(n) - m_4 x(n)| \tag{9}$$

When the random vectors are within the range of [-1, 1], a chimp's next position may be located anywhere between its current location and the position of the target or prey:

$$x_1(n+1) = x_{attacker}(n) - a_1 d_{attacker} \tag{10}$$

$$x_2(n+1) = x_{barrier}(n) - a_2 d_{barrier} \tag{11}$$

$$x_3(n+1) = x_{chaser}(n) - a_3 d_{chaser} \tag{12}$$

$$x_4(n+1) = x_{driver}(n) - a_4 d_{driver} \tag{13}$$

Based on the aforementioned equations, the chimps' positions in the search process are updated according to the mathematical equation (14).:

$$x_{chimp}(n+1) = \frac{x_1 + x_2 + x_3 + x_4}{4} \tag{14}$$

To adjust the chimps' positions within the search domain during the search process, the mathematical equation (15) was employed.

$$x_{chimp}(n+1) = \begin{cases} x_{prey}(n) - xd\,, & if\ \emptyset < 0.5 \\ chaotic_{value} & if\ \emptyset > 0.5 \end{cases} \tag{15}$$

The proposed ChPSO algorithm employs a velocity function to update the chimp's position. Hence, the update function of the ChOA algorithm in (14) is altered for the ChPSO algorithm as in (16).

$$\left.\begin{array}{c} v_{t+1} = \omega * \big(v + c_1 * r_1 * (x_{attacker} - x_{chimp}) + \\ c_2 * r_2 * (x_{barrier} - x_{chimp}) + \\ c_3 * r_3 * (x_{chaser} - x_{chimp}) + \\ c_4 * r_4 * (x_{driver} - x_{chimp})\big) \\ x_{chimp}(n+1) = x_{chimp} + v_{t+1} \end{array}\right\} \tag{16}$$

3. Problem Formulation

Power systems that are vertically integrated—where a single utility owns the generation, transmission, and distribution functions—often experience significant power losses in their distribution networks as electricity is delivered to end consumers. These losses stem from factors such as line resistance, inefficiencies in transformers, and the technical limitations of the distribution infrastructure itself. A considerable amount of energy is lost during transmission, leading to not only less efficient power delivery from sources to various locations but also substantial financial losses for utilities due to unpaid bills from customers who do not receive the electricity they are owed. Consequently, addressing power losses serves as a strong motivation for utility companies to enhance their efficiency. This emphasis on minimizing losses is crucial for ensuring a sustainable energy supply and for utilities to fulfill their financial obligations while providing satisfactory service to their customers, where it is expressed as:

$$f_{1,minimize} = \sum_{x=1}^{N}\sum_{y=1}^{N}\alpha_{xy}\left(P_xP_y + Q_xQ_y\right) + \beta_{xy}\left(Q_xP_y - P_xQ_y\right) \quad (17)$$

Here the factors will be calculated using, $\alpha_{xy} = r_{xy}\cos(\delta_x - \delta_y)/V_xV_y$ and $\beta_{xy} = r_{xy}\sin(\delta_x - \delta_y)/V_xV_y$. Where, N, P_x, Q_x, r_{xy}, V_x , and δ_x represent the total number of nodes in the system, real and reactive power injections at the x^{th} node, resistance of branch between nodes x and y, voltage magnitude, and the angle of the x^{th} node, respectively.

The increasing focus of power consumers on the quality of voltage supplied constitutes a considerable portion of the present energy landscape. The voltage variation sensed is the deviation in voltage levels at different nodes, and hence important to assess voltage quality. Thus, the deviation of node voltages shall become one of the more important yardsticks in the evaluation of voltage quality experienced. In this way, the utility companies have major responsibility for the regulation of node voltage. The regulated voltages at the nodes are kept in good condition. Utility companies try their utmost to ensure that a stable and uniform voltage profile is maintained throughout the system, guaranteeing a reliable supply to consumers. Node voltage regulation is considered an important objective function in the optimization model for the integration of DER. In integrating DER systems, the regulation prioritizes voltages within the acceptable range for utility and consumer standards and thus ensures improved performance of the DER system.

$$f_{2,minimize} = \sum_{x=1}^{N}(V_x - 1)^2 \quad (18)$$

Equation 19 summarizes the main operational constraints of the electrical network. It ensures load balance across the system and assumes that all reactive loads are supplied by node 1. Additionally, it enforces voltage limits at all nodes to maintain reliable operation and restricts the power flow through each branch to remain within thermal limits, thereby preventing line overloads. The constraints for different objectives are considered as follows:

$$\begin{aligned} P_x &= V_x\sum_{y=1}^{N}V_yY_{xy}\,cos\left(\theta_{xy} + \delta_y - \delta_x\right) \quad \forall x \\ Q_x &= -V_x\sum_{y=1}^{N}V_yY_{xy}\,sin\left(\theta_{xy} + \delta_y - \delta_x\right) \quad \forall x \\ V_{min} &\le V_x \le V_{max} \quad \forall x \\ S_{DER_x} &\le S_{DER}^{max} \quad \forall x \end{aligned} \quad (19)$$

Equation (19) outlines the constraints related to active and reactive nodal power balances, establishes limits on node voltages, and specifies the maximum installation size for a single DER on the line connecting nodes x and y. In these equations, Y_{xy}, θ_{xy} represent the Y-bus element, impedance angle, of the line between nodes x and y.

4. Simulation results and discussion: Case Studies

The proposed algorithm has been implemented on the standard IEEE-33 bus distribution system to optimize different factors explained in section 3 by allocating DER units optimally. The IEEE 33 Bus System serves as a widely recognized test case in power system studies, especially for evaluating and improving distribution networks. This network features 33 nodes (buses) connected by 37 lines (branches), with a few tie lines incorporated to enable changes in network configuration. Operating at a standard substation voltage of either 12.66 kV or 13.8 kV, it is equipped with a 3 MW transformer at the main bus. The system's total load is distributed throughout the network, amounting to approximately 3.72 MW of real power and 2.30 MVar of reactive power. The IEEE 33-bus system is a radial distribution system, meaning it is supplied by a single source (in this case, bus 1) and has a single path to each load. The single-line diagram of the IEEE-33 bus system is shown in Fig. 1.

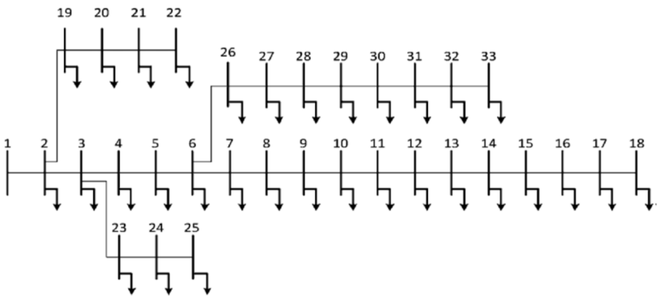

Fig. 1 Single line diagram of IEEE-33 bus system.

In this simulation study, the optimal placement of different numbers of DERs with appropriate sizing under different operating conditions is considered. Here, the number of DERs is considered as 3 and 4 for the two cases of unity power factor (UPF) and 0.85 pf lagging conditions. The study has been done in a MATLAB environment with version R2024a.

Case Study 1: Three DERs are optimally placed

The proposed hybrid ChPSO algorithm and ChOA algorithms have been employed to identify the optimal location of DER units for the considered test system. The resulting optimal solutions for low power factor (LPF) and UPF conditions with different objective functions are given in Table 1. The limits are considered to be 0 to 2000 W for DER sizing, and bus numbers 1 to 33 are considered for optimal location. The optimal values within the given limits ensure the satisfactory operation of the proposed algorithm.

The voltage magnitudes at each bus are identified in different conditions are tabulated in Table 2. Where different conditions are, with different power factor values, while applying different objective functions using the individual ChOA algorithm and the proposed hybrid algorithm.

The bus voltage at different buses with the optimally placed DERs minimized the voltage deviation, and the maximum and minimum values are close to unity. The complete profile under different conditions is depicted in Fig. 2. From the results, it can be observed that without DER placement, the voltage profiles at Buses 6 to 18 and 26 to 33 exhibit significant voltage deviations exceeding 5% (or 0.05 p.u.). After DER installation, the voltage profiles improved drastically, with deviations reduced to within the permissible limit of 5%—in fact, the deviations are now within 2%. The active and reactive power losses under different case studies are presented in Tables 3 and 4, respectively.

Table 1 Optimized 3 DER location and ratings under objective function 1 (eq. 17) and objective function 2 (eq. 18) with different power factors.

Algorithm	Objective function & PF	Optimal DER location			DER Sizing (Respectively)			Optimized value
ChOA [28]	Obj1 & 0.85LPF	13	30	24	917	1327	656	0.018246
	Obj1 & UPF	24	31	14	1316	928	832	0.073155
	Obj2 & 0.85LPF	24	32	12	937	1271	1223	0.000586
	Obj2 & UPF	23	13	30	1744	1035	1867	0.000339
ChPSO	Obj1 & 0.85LPF	24	30	15	1043	1377	869	0.015801
	Obj1 & UPF	24	29	12	1219	1044	882	0.073157
	Obj2 & 0.85LPF	24	16	29	1535	703	1780	0.000436
	Obj2 & UPF	29	23	11	1957	1438	1316	0.000533

Table 2 Voltage profile at different buses with 3 DERs.

Bus	Without DG	ChOA				ChPSO			
		UPF		0.85 LPF		UPF		0.85 LPF	
		Obj1	Obj2	Obj1	Obj2	Obj1	Obj2	Obj1	Obj2
1	1	1	1	1	1	1	1	1	1
2	0.997032325	0.99915	1.000153	0.99904	0.999379	0.999194	1.000188	0.999292	0.999756
3	0.982938399	0.996373	1.002736	0.995674	0.997823	0.996653	1.00296	0.997273	1.000219
4	0.975457068	0.993856	1.003126	0.994412	0.99718	0.994558	1.004267	0.996014	0.999555
5	0.968060134	0.99162	1.003915	0.993482	0.996894	0.992762	1.006009	0.995088	0.999246
6	0.949659703	0.986177	1.006052	0.991314	0.996338	0.988421	1.010538	0.992929	0.998633
7	0.946174256	0.985445	1.005935	0.990841	0.996781	0.987837	1.011249	0.992308	0.997517
8	0.941330244	0.984713	1.006118	0.990497	0.99781	0.987328	1.012675	0.991743	0.996206
9	0.935061411	0.985492	1.008444	0.991938	1.001621	0.988489	1.017146	0.992795	0.995956
10	0.929246681	0.986764	1.011267	0.993875	1.005945	0.990146	1.022129	0.99434	0.996185
11	0.928386708	0.987018	1.011764	0.994234	1.006679	0.99046	1.022966	0.994637	0.996274
12	0.926887185	0.987632	1.012838	0.995045	1.008204	0.991188	1.021608	0.995331	0.996571
13	0.92077434	0.991679	1.019083	1.000042	1.002595	0.985481	1.016074	0.999757	0.999081
14	0.918507679	0.993951	1.017037	0.997957	1.000515	0.983364	1.014022	1.002196	1.000658
15	0.917095425	0.992647	1.015763	0.996658	0.99922	0.982046	1.012744	1.005113	1.002771
16	0.915727562	0.991384	1.014529	0.9954	0.997965	0.980769	1.011506	1.003865	1.005545
17	0.913700436	0.989512	1.0127	0.993536	0.996106	0.978877	1.009672	1.002017	1.0037
18	0.913093395	0.988952	1.012152	0.992978	0.995549	0.978311	1.009122	1.001464	1.003148
19	0.996503962	0.998623	0.999626	0.998513	0.998852	0.998667	0.999662	0.998765	0.999229
20	0.992926369	0.995053	0.99606	0.994942	0.995282	0.995097	0.996095	0.995195	0.995662
21	0.992221866	0.99435	0.995358	0.994239	0.99458	0.994394	0.995393	0.994492	0.994959
22	0.991584447	0.993714	0.994722	0.993603	0.993944	0.993758	0.994758	0.993856	0.994323
23	0.979352696	0.997365	1.005153	0.99441	0.997524	0.997316	1.004341	0.997336	1.001946
24	0.972681584	1.000212	0.998656	0.992562	0.997684	0.999476	0.997839	0.998248	1.006319
25	0.969356618	0.996979	0.995418	0.989304	0.994442	0.996241	0.994599	0.995009	1.003106
26	0.947730506	0.985699	1.00689	0.991408	0.996344	0.988105	1.011495	0.993094	0.999355
27	0.945166855	0.98516	1.008192	0.99167	0.996483	0.987795	1.012962	0.993454	1.000497
28	0.933727697	0.98261	1.013707	0.992629	0.996901	0.986248	1.019205	0.994845	1.00531
29	0.925509904	0.981097	1.018286	0.993767	0.997628	0.985491	1.024331	0.996309	1.00936
30	0.921952622	0.981105	1.021549	0.995195	0.998832	0.982153	1.021121	0.997911	1.006101
31	0.917791611	0.985079	1.017798	0.991343	1.005547	0.978249	1.017368	0.99407	1.002292
32	0.916876225	0.984226	1.016972	0.990496	1.008289	0.97739	1.016542	0.993225	1.001454
33	0.916592592	0.983962	1.016717	0.990234	1.008031	0.977124	1.016286	0.992963	1.001194
Min	**0.913093395**	**0.981097**	**0.994722**	**0.989304**	**0.993944**	**0.977124**	**0.994599**	**0.991743**	**0.994323**
Max	**1**	**1.000212**	**1.021549**	**1.000042**	**1.008289**	**1**	**1.024331**	**1.005113**	**1.00936**

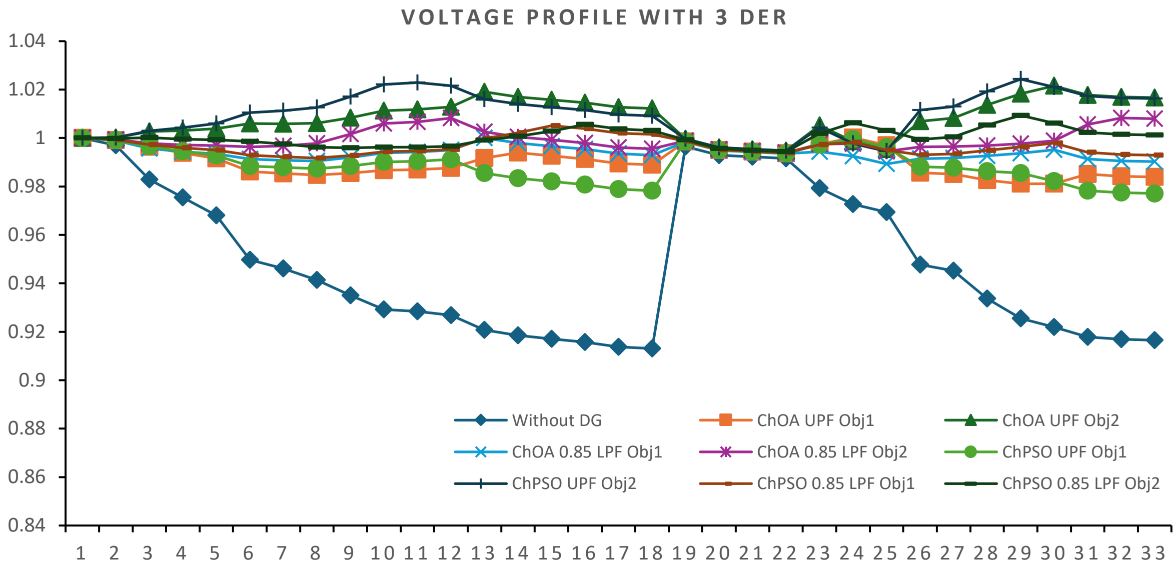

Fig. 2. Bus voltage profile with 3 optimally placed DERs.

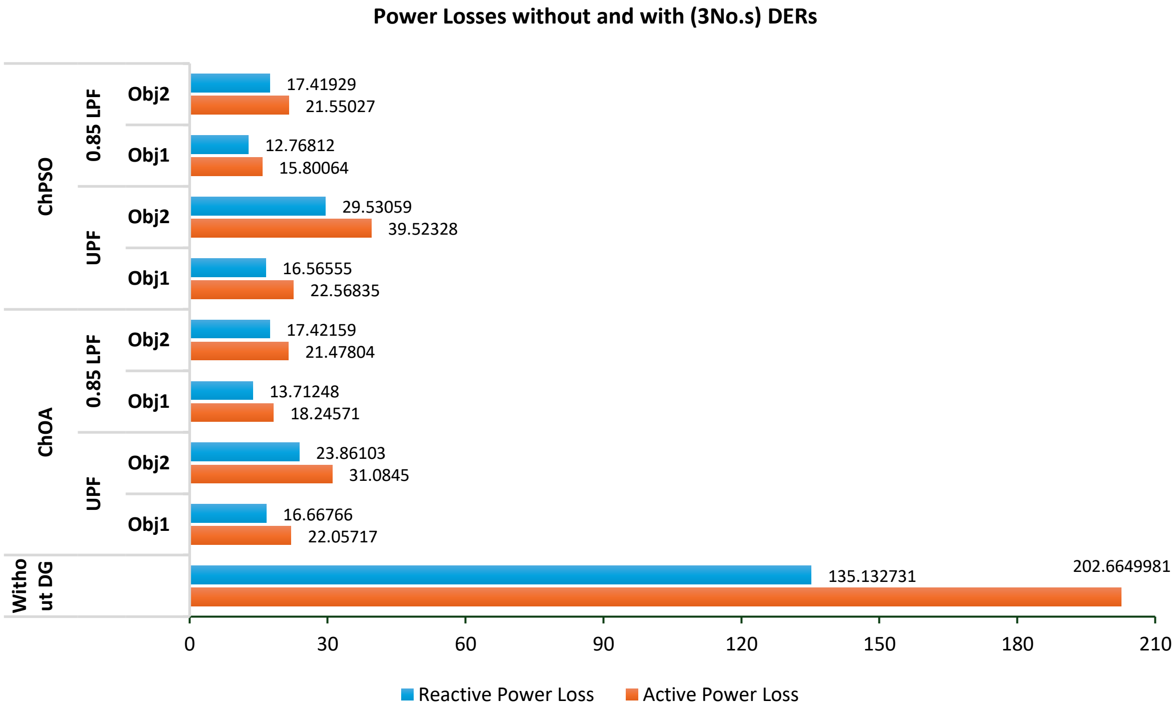

Fig 3. Active and Reactive power losses with 3 DERs optimally placed.

From the results, it is observed that the proposed methods relatively reduced the real and reactive power losses compared to the base case. Further, the cumulative power losses in the test system presented in Tables 3 and 4 with 3 DERS are represented in Fig. 3. From Fig. 3, it can be observed that the active power loss in the test system without DER can be brought down to as low as 12.76812 W from the actual value of 202.6649981 W, which is a 92.20 % reduction. Similarly, a reduction in the reactive power loss can be observed from 135.132731 VAR to 12.76812 VAR, which is a 90.55% reduction.

Case Study 2: Four DERs are optimally placed

The proposed hybrid ChPSO algorithm and ChOA algorithms have been employed to identify the optimal location of DER units for the considered test system. The resulting optimal solution is given in Table 5, where limits are considered the same as in case study 1. In this second case study, the obtained optimal values are also within the applied limits.

Table 3 Power losses (Active) at each bus with 3 DERs.

Bus	Without DG	ChOA				ChPSO			
		UPF		0.85 LPF		UPF		0.85 LPF	
		Obj1	Obj2	Obj1	Obj2	Obj1	Obj2	Obj1	Obj2
1	12.23988013	1.003667	0.032493	1.280705	0.536568	0.902094	0.049219	0.696705	0.082564
2	51.78865621	2.037779	1.721766	2.982683	0.652393	1.709451	1.982733	1.086535	0.061556
3	0.160953905	0.160267	0.159944	0.160303	0.160194	0.160253	0.159932	0.160222	0.160072
4	19.89919814	2.357634	0.114743	0.663661	0.23461	1.664165	0.635852	0.659767	0.244023
5	3.181587088	0.263565	1.431208	0.430299	0.056566	0.133847	0.484301	0.03307	0.742299
6	18.69769488	1.810888	0.259134	0.386003	0.106627	1.203198	1.046501	0.383522	0.111039
7	38.24603134	3.337113	0.782192	0.613425	0.179512	2.145361	2.717227	0.609409	0.183169
8	1.914395503	0.172208	0.047911	0.108033	0.021534	0.133257	0.036704	0.141657	0.295009
9	2.600710789	0.30563	0.535411	0.136949	0.13557	0.214723	0.663533	0.144587	0.429108
10	4.837636216	0.136612	0.074549	0.066883	0.340244	0.088555	0.567641	0.098213	0.359466
11	4.18023073	0.110132	0.587389	0.254154	1.51248	0.182122	2.068336	0.15794	0.063451
12	3.56064787	0.195714	0.833236	0.40889	1.92303	0.307699	2.54633	0.271578	0.042516
13	0.553659818	0.062764	0.211198	0.115387	0.444988	0.091115	0.573241	0.082047	0.0138
14	0.88106658	0.182661	0.511814	0.303449	1.004977	0.248645	0.722732	0.227416	0.055413
15	2.666026291	1.109642	2.630271	1.685624	2.245514	2.324825	2.185877	1.324395	0.438227
16	0.72910386	0.587187	0.594085	0.617133	0.613965	0.635677	0.59764	0.68026	0.275717
17	0.356945113	0.304467	0.290709	0.302011	0.300457	0.311106	0.292452	1.292376	0.676157
18	0.28144362	0.240013	0.229153	0.238074	0.236848	0.245253	0.230529	0.234063	1.0781
19	0.251613284	0.214526	0.204808	0.212791	0.211694	0.219216	0.206039	0.209202	0.2085
20	0.053131457	0.045297	0.043244	0.04493	0.044698	0.046287	0.043504	0.044172	0.044024
21	0.832175154	0.828619	0.826942	0.828803	0.828236	0.828545	0.826883	0.828381	0.827604
22	0.100757877	0.100327	0.100124	0.100349	0.100281	0.100318	0.100117	0.100298	0.100204
23	0.043634413	0.043448	0.04336	0.043457	0.043428	0.043444	0.043357	0.043435	0.043394
24	5.143606689	0.909388	4.878714	0.47498	0.05959	0.539407	4.886734	0.135505	2.108358
25	1.287434678	1.217099	1.220918	1.236057	1.223316	1.218903	1.222931	1.221923	1.202276
26	3.328752078	0.363495	0.896336	0.220404	0.204196	0.262913	1.093861	0.242429	0.730209
27	11.30002204	1.172177	3.941198	0.985065	0.87094	0.896593	4.744175	1.109125	3.258711
28	7.832766624	0.816229	3.484079	0.925276	0.79913	0.679025	4.141409	1.049718	2.921035
29	3.895375825	0.434596	2.91808	0.860319	0.724163	3.43065	3.172738	0.981631	3.268584
30	1.593513811	1.337585	1.295507	1.365656	3.865804	1.402504	1.296603	1.358167	1.33595
31	0.213178485	0.185011	0.173287	0.182676	1.785599	0.187608	0.173434	0.181674	0.1787
32	0.013167584	0.011427	0.010703	0.011283	0.010888	0.011588	0.010712	0.011221	0.011037
Total	**202.6649981**	**22.05717**	**31.0845**	**18.24571**	**21.47804**	**22.56835**	**39.52328**	**15.80064**	**21.55027**

The voltage magnitudes at each bus are identified in different conditions are tabulated in Table 6. Where different conditions are, with different power factor values, while applying different objective functions using the individual ChOA algorithm and the proposed hybrid algorithm.

The bus voltage at different bus with the optimally placed DERs minimized the voltage deviation and maximum and minimum values are close to unity. The complete profile under different conditions are depicted in fig. 4. From the results, it can be observed that without DER placement, the voltage profiles at Buses 6 to 18 and 26 to 33 exhibit significant voltage deviations exceeding 5% (or 0.05 p.u.). After DER installation, the voltage profiles improved drastically, with deviations reduced to within the permissible limit of 5%—in fact, the deviations are now within 2%. The active and reactive power losses under different case studies are presented in Tables 7 and 8, respectively.

From the results, it is observed that the proposed methods relatively reduced the real and reactive power losses compared to the base case. The DER placed with LPF resulted in lesser reactive power losses. Further, the cumulative power losses in the test system presented in Tables 7 and 8 with 4 DERS are represented in Fig. 5. From Fig. 5, it can be observed that the active power loss in the test system without DER can be brought down to as low as 14.38053 W from the actual value of 202.6649981 W, which is a 92.90 % reduction. Similarly, a reduction in the reactive power loss can be observed from 135.132731 VAR to 11.37142 VAR, which is a 91.59% reduction.

Though the considered algorithms resulted in efficient outcomes, the metaheuristic approaches inherently have a tendency to be susceptible to the local optima in a large search space. By the use of the velocity function in the ChPSO algorithm, the probability of this limitation can be minimized, but cannot be avoided completely.

Table 4 Power Losses (Reactive) at each bus with 3 DERs.

Bus	Without DG	ChOA				ChPSO			
		UPF		0.85 LPF		UPF		0.85 LPF	
		Obj1	Obj2	Obj1	Obj2	Obj1	Obj2	Obj1	Obj2
1	6.239418285	0.51163	0.016564	0.652854	0.273522	0.459853	0.02509	0.355153	0.042088
2	26.37754883	1.037903	0.876948	1.519172	0.332284	0.870676	1.009867	0.553406	0.031352
3	0.153593208	0.152938	0.152629	0.152972	0.152868	0.152925	0.152618	0.152894	0.152751
4	10.13445501	1.200719	0.058437	0.337996	0.119485	0.847542	0.323833	0.336012	0.124278
5	2.173943482	0.180091	0.977929	0.294018	0.038651	0.091456	0.330918	0.022596	0.507205
6	9.523019091	0.922313	0.131981	0.196597	0.054307	0.612807	0.532999	0.195334	0.056554
7	33.01580483	2.880755	0.675225	0.529538	0.154964	1.851979	2.345641	0.526071	0.15812
8	6.328140692	0.569244	0.158371	0.357109	0.071183	0.440489	0.121327	0.468256	0.97517
9	1.324697023	0.155676	0.272717	0.069757	0.069054	0.109371	0.337977	0.073647	0.21857
10	1.598718406	0.045147	0.024637	0.022103	0.112442	0.029265	0.187591	0.032457	0.118795
11	3.003272563	0.079124	0.422007	0.182596	1.086636	0.130845	1.485989	0.113472	0.045586
12	2.523830865	0.138724	0.590608	0.289826	1.363067	0.218101	1.80487	0.192498	0.030136
13	0.183051313	0.020751	0.069826	0.038149	0.147122	0.030124	0.189525	0.027126	0.004562
14	0.291335584	0.060399	0.169238	0.100339	0.332308	0.082218	0.23898	0.075198	0.018323
15	2.097588805	0.873049	2.069457	1.326223	1.766736	1.829137	1.719815	1.042014	0.34479
16	0.959708534	0.772906	0.781986	0.812323	0.808153	0.836732	0.786665	0.895416	0.362923
17	0.31768719	0.270981	0.258736	0.268795	0.267412	0.27689	0.260287	1.150236	0.601791
18	0.205529644	0.175274	0.167344	0.173858	0.172963	0.179101	0.168348	0.170929	0.787303
19	0.335939847	0.286423	0.273448	0.284107	0.282641	0.292685	0.275092	0.279314	0.278378
20	0.041663192	0.035519	0.03391	0.035232	0.03505	0.036296	0.034114	0.034637	0.034521
21	0.749853878	0.746649	0.745138	0.746815	0.746304	0.746582	0.745085	0.746435	0.745735
22	0.11771079	0.117207	0.11697	0.117233	0.117153	0.117197	0.116962	0.117174	0.117064
23	0.057692955	0.057446	0.05733	0.057459	0.057419	0.057441	0.057326	0.05743	0.057376
24	4.061616373	0.718092	3.852446	0.375065	0.047055	0.425939	3.858779	0.107001	1.664852
25	1.007388898	0.952353	0.955341	0.967187	0.957217	0.953765	0.956916	0.956128	0.940754
26	1.694829084	0.185073	0.456368	0.112218	0.103966	0.133862	0.556938	0.123432	0.371785
27	9.963012825	1.033486	3.474879	0.868513	0.767891	0.790509	4.182848	0.977894	2.873143
28	6.823720837	0.71108	3.035247	0.806078	0.696183	0.591551	3.607897	0.914489	2.544736
29	1.984147095	0.221366	1.486352	0.438212	0.368859	1.747434	1.616065	0.500003	1.664885
30	1.574870484	1.321936	1.280351	1.349679	3.820576	1.386096	1.281433	1.342277	1.32032
31	0.248467934	0.215638	0.201973	0.212916	2.081187	0.218665	0.202144	0.211748	0.208282
32	0.020473469	0.017767	0.016641	0.017543	0.016929	0.018017	0.016655	0.017447	0.017161
Total	**135.132731**	**16.66766**	**23.86103**	**13.71248**	**17.42159**	**16.56555**	**29.53059**	**12.76812**	**17.41929**

Table 5 Optimized 4 DER location and ratings under objective function 1 (eq. 17) and objective function 2 (eq. 18) with different power factors.

Algorithm	Objective function & PF	Optimal DER location				DER Sizing (Respectively)				Optimized value
ChOA [28]	Obj1 & 0.85LPF	6	25	31	14	1546	1304	816	526	0.015373
	Obj1 & UPF	24	10	30	26	1143	848	743	463	0.070554
	Obj2 & 0.85LPF	17	26	23	30	453	1726	1427	807	0.000442
	Obj2 & UPF	16	8	23	30	719	916	1053	1723	0.000373
ChPSO	Obj1 & 0.85LPF	7	13	24	30	1177	338	1415	1132	0.014381
	Obj1 & UPF	16	31	6	25	358	647	1503	508	0.069556
	Obj2 & 0.85LPF	24	13	28	29	1319	839	1315	523	0.000323
	Obj2 & UPF	13	24	20	31	1245	1492	659	1615	0.000332

Table 6 Voltage profile at different buses with 4 DERs.

Bus	Without DG	ChOA				ChPSO			
		UPF		0.85 LPF		UPF		0.85 LPF	
		Obj1	Obj2	Obj1	Obj2	Obj1	Obj2	Obj1	Obj2
1	1	1	1	1	1	1	1	1	1
2	0.997032325	0.999229	1.000003	0.999873	1.00001	0.999114	1.000386	0.999791	0.999744
3	0.982938399	0.996875	1.001787	1.000959	1.00183	0.996142	1.00195	1.000436	1.000139
4	0.975457068	0.995113	1.00334	1.001351	1.002458	0.995551	1.002213	1.000211	0.999971
5	0.968060134	0.993662	1.005339	1.002141	1.003494	0.995319	1.002868	1.000358	1.000178
6	0.949659703	0.990188	1.010512	1.004285	1.006252	0.9949	1.004671	1.000893	1.00086
7	0.946174256	0.989499	1.012196	1.002645	1.004391	0.992725	1.005165	1.002229	1.00016
8	0.941330244	0.988831	1.015082	1.000544	1.001957	0.989823	1.006268	0.999256	0.99947
9	0.935061411	0.989713	1.01496	0.998914	0.999745	0.986825	1.010191	0.996114	1.000293
10	0.929246681	0.991087	1.015308	0.997747	0.997992	0.984284	1.014624	0.993423	1.001602
11	0.928386708	0.990282	1.015415	0.997616	0.997768	0.983937	1.015375	0.993052	1.001861
12	0.926887185	0.988878	1.015745	0.997495	0.997471	0.983406	1.016932	0.992474	1.002482
13	0.92077434	0.983156	1.018387	0.997975	0.997097	0.981918	1.02551	0.990749	1.006549
14	0.918507679	0.981035	1.020016	0.998639	0.997377	0.981704	1.023477	0.988644	1.004478
15	0.917095425	0.979714	1.022165	0.997341	0.998283	0.982159	1.022211	0.987333	1.003187
16	0.915727562	0.978434	1.024977	0.996084	0.999631	0.982979	1.020984	0.986063	1.001938
17	0.913700436	0.976537	1.023167	0.994221	1.003425	0.981092	1.019167	0.984181	1.000086
18	0.913093395	0.975969	1.022625	0.993663	1.002873	0.980526	1.018623	0.983617	0.999531
19	0.996503962	0.998702	0.999477	0.999346	0.999484	0.998587	1.000771	0.999264	0.999217
20	0.992926369	0.995132	0.99591	0.995779	0.995917	0.995016	1.005387	0.995696	0.995649
21	0.992221866	0.994429	0.995207	0.995076	0.995214	0.994313	1.004691	0.994993	0.994946
22	0.991584447	0.993793	0.994572	0.994441	0.994579	0.993677	1.004062	0.994358	0.994311
23	0.979352696	0.997279	1.001863	1.001895	1.003176	0.994374	1.003529	1.001758	1.001138
24	0.972681584	0.998901	0.995344	1.00462	0.996666	0.991476	1.007594	1.005289	1.003995
25	0.969356618	0.995664	0.992096	1.010536	0.993422	0.991841	1.004385	1.002073	1.000774
26	0.947730506	0.990106	1.01115	1.003656	1.008038	0.994022	1.005152	1.000711	1.001664
27	0.945166855	0.989195	1.012171	1.002906	1.007272	0.992923	1.005954	1.000587	1.002917
28	0.933727697	0.985013	1.01646	0.99943	1.003726	0.987918	1.009279	0.999853	1.008222
29	0.925509904	0.982263	1.020109	0.997209	1.001449	0.984544	1.012201	0.999707	1.004074
30	0.921952622	0.981603	1.02287	0.996822	1.001029	0.983546	1.014577	1.000437	1.000799
31	0.917791611	0.977698	1.019124	0.999805	0.9972	0.985144	1.02399	0.996606	0.996969
32	0.916876225	0.976838	1.018299	0.998965	0.996358	0.984291	1.023169	0.995763	0.996126
33	0.916592592	0.976572	1.018044	0.998704	0.996097	0.984027	1.022915	0.995502	0.995865
Minimum	**0.913093395**	**0.975969**	**0.992096**	**0.993663**	**0.993422**	**0.980526**	**1**	**0.983617**	**0.994311**
Maximum	**1**	**1**	**1.024977**	**1.010536**	**1.008038**	**1**	**1.02551**	**1.005289**	**1.008222**

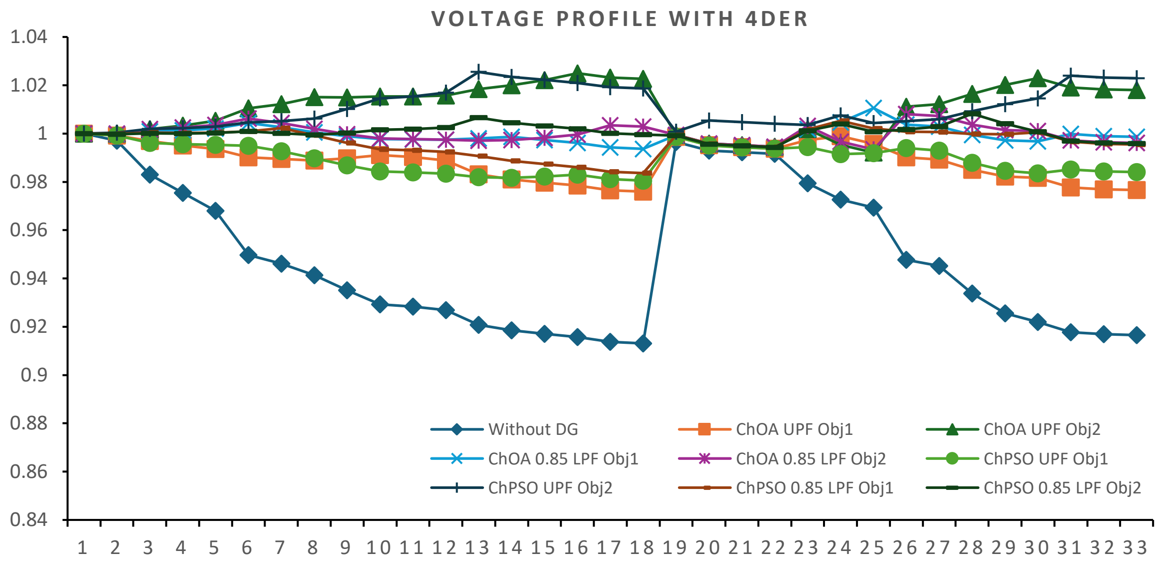

Fig. 4 Bus voltage profile with 4 optimally placed DERs.

Table 7 Power losses (Active) at each bus with 4 DERs.

Bus	Without DG	ChOA				ChPSO			
		UPF		0.85 LPF		UPF		0.85 LPF	
		Obj1	Obj2	Obj1	Obj2	Obj1	Obj2	Obj1	Obj2
1	12.23988013	0.825531	1.76E-05	0.022411	0.000146	1.091372	0.206907	0.060973	0.091307
2	51.78865621	1.470291	0.821544	0.307412	0.855287	2.329878	0.632292	0.112311	0.047011
3	0.160953905	0.160242	0.159992	0.160034	0.15999	0.160279	0.075643	0.160061	0.160076
4	19.89919814	1.206467	0.875352	0.114756	0.193239	0.210845	0.090193	0.094519	0.086082
5	3.181587088	0.068987	0.032705	0.23713	0.46094	0.805316	0.625102	0.446179	0.26643
6	18.69769488	0.816569	1.362099	0.259784	0.404565	0.095633	0.199395	0.073348	0.079821
7	38.24603134	1.404267	3.461253	0.784473	1.158147	0.169836	0.620119	0.219442	0.248676
8	1.914395503	0.159795	0.247457	0.525366	0.643415	0.836169	0.022716	0.143819	0.161464
9	2.600710789	0.144825	0.357655	0.412118	2.059199	0.664954	0.256981	0.162957	0.502079
10	4.837636216	0.120457	1.995315	0.897148	1.203882	1.714854	0.376361	1.801351	0.124672
11	4.18023073	0.126251	0.055178	0.345173	0.580906	1.013716	1.599696	1.104286	0.115338
12	3.56064787	0.222191	0.047272	0.187726	0.367812	0.722643	2.019418	0.802693	0.204098
13	0.553659818	0.485379	0.016801	0.014639	0.037422	0.088644	0.464466	0.101306	0.06463
14	0.88106658	0.772226	0.063923	0.012635	0.037375	0.109382	1.043938	0.12906	0.186112
15	2.666026291	2.33592	0.482886	0.046831	0.04988	0.205568	4.966391	0.25901	1.120433
16	0.72910386	0.638715	0.295113	0.049049	0.015542	0.027151	0.586597	0.628873	0.609107
17	0.356945113	0.312596	0.699506	0.301596	0.12861	0.041256	0.287037	0.307769	0.298075
18	0.28144362	0.246429	1.107168	0.237746	0.257423	0.099094	0.226256	0.242619	0.234967
19	0.251613284	0.220269	0.200637	0.212498	0.695918	0.218227	0.202215	0.216858	0.210011
20	0.053131457	0.04651	0.042363	0.044868	0.044048	0.046078	0.042696	0.045789	0.044343
21	0.832175154	0.828486	0.827191	0.827409	0.82718	0.828679	1.259245	0.827547	0.827625
22	0.100757877	0.100311	0.100154	0.10018	0.100153	0.100334	0.098271	0.100197	0.100207
23	0.043634413	0.043441	0.043373	0.043384	0.043372	0.043451	0.042557	0.043391	0.043396
24	5.143606689	0.322594	4.911343	0.835777	4.898284	1.049769	1.824326	1.382486	0.915648
25	1.287434678	1.220317	1.22911	3.892245	1.225831	0.026764	1.199215	1.204757	1.207885
26	3.328752078	0.624494	0.61506	0.489519	0.499792	0.802382	0.449808	0.212204	0.844931
27	11.30002204	1.98421	2.772149	1.553711	1.586082	2.567207	2.066656	0.787298	3.732615
28	7.832766624	1.314937	2.508826	1.039463	1.05923	1.698609	1.909164	0.652558	2.287027
29	3.895375825	0.580635	2.179069	0.47967	0.485016	0.738125	1.710315	0.513707	3.303462
30	1.593513811	1.404089	1.292135	0.748008	1.349644	0.212303	7.639859	1.351256	1.35027
31	0.213178485	0.187821	0.172836	0.179592	0.180533	0.184987	0.171194	0.180749	0.180617
32	0.013167584	0.011601	0.010675	0.011092	0.01115	0.011426	0.010573	0.011164	0.011155
Total	**202.6649981**	**20.40685**	**28.98616**	**15.37344**	**21.62001**	**18.91493**	**32.9256**	**14.38053**	**19.65957**

Table 8 Power Losses (Reactive) at each bus with 4 DERs.

Bus	Without DG	ChOA				ChPSO			
		UPF		0.85 LPF		UPF		0.85 LPF	
		Obj1	Obj2	Obj1	Obj2	Obj1	Obj2	Obj1	Obj2
1	6.239418285	0.420824	8.97E-06	0.011424	7.44E-05	0.556339	0.105473	0.031082	0.046545
2	26.37754883	0.748864	0.418438	0.156575	0.435624	1.186678	0.322046	0.057203	0.023944
3	0.153593208	0.152914	0.152675	0.152715	0.152673	0.152949	0.072184	0.152741	0.152755
4	10.13445501	0.614441	0.445808	0.058444	0.098415	0.107381	0.045935	0.048138	0.043841
5	2.173943482	0.047138	0.022347	0.162028	0.314956	0.550264	0.427125	0.304869	0.182049
6	9.523019091	0.415891	0.693738	0.132312	0.206051	0.048708	0.101555	0.037357	0.040654
7	33.01580483	1.21223	2.987919	0.677194	0.999768	0.146611	0.535316	0.189433	0.214669
8	6.328140692	0.528211	0.817983	1.736626	2.126846	2.764004	0.075087	0.475402	0.533727
9	1.324697023	0.073768	0.182175	0.209916	1.048873	0.338701	0.130896	0.083004	0.255739
10	1.598718406	0.039808	0.659402	0.296485	0.397853	0.566717	0.124378	0.595302	0.041201
11	3.003272563	0.090705	0.039642	0.247988	0.41735	0.728301	1.149296	0.793371	0.082864
12	2.523830865	0.157492	0.033507	0.133062	0.260709	0.512218	1.431388	0.568959	0.144667
13	0.183051313	0.160476	0.005555	0.00484	0.012373	0.029308	0.153562	0.033494	0.021368
14	0.291335584	0.255346	0.021137	0.004178	0.012359	0.036169	0.345191	0.042675	0.06154
15	2.097588805	1.837866	0.379927	0.036846	0.039245	0.161738	3.907481	0.203785	0.881539
16	0.959708534	0.84073	0.388453	0.064562	0.020457	0.035739	0.772129	0.827776	0.801759
17	0.31768719	0.278216	0.622572	0.268425	0.114465	0.036718	0.255468	0.273919	0.265292
18	0.205529644	0.179959	0.808531	0.173619	0.187988	0.072365	0.165228	0.177177	0.171589
19	0.335939847	0.29409	0.267879	0.283715	0.929151	0.291365	0.269986	0.289537	0.280395
20	0.041663192	0.036471	0.033219	0.035183	0.03454	0.036132	0.03348	0.035906	0.034771
21	0.749853878	0.74653	0.745363	0.745559	0.745353	0.746704	1.134677	0.745684	0.745754
22	0.11771079	0.117189	0.117005	0.117036	0.117004	0.117216	0.114805	0.117056	0.117067

Table 8 Power Losses (Reactive) at each bus with 4 DERs. (cont.)

Bus	Without DG	ChOA				ChPSO			
		UPF		0.85 LPF		UPF		0.85 LPF	
		Obj1	Obj2	Obj1	Obj2	Obj1	Obj2	Obj1	Obj2
23	0.057692955	0.057437	0.057347	0.057362	0.057346	0.05745	0.056268	0.057372	0.057377
24	4.061616373	0.254734	3.878211	0.659966	3.867899	0.828943	1.440567	1.091671	0.723036
25	1.007388898	0.954871	0.961751	3.045595	0.959185	0.020942	0.938359	0.942695	0.945143
26	1.694829084	0.31796	0.313157	0.249238	0.254468	0.408532	0.229019	0.108043	0.430195
27	9.963012825	1.74944	2.444151	1.369877	1.398418	2.263457	1.822131	0.694145	3.290975
28	6.823720837	1.145542	2.185629	0.905555	0.922776	1.479788	1.663219	0.568493	1.992403
29	1.984147095	0.295752	1.10993	0.244325	0.247048	0.375971	0.871166	0.261662	1.68265
30	1.574870484	1.387662	1.277018	0.739256	1.333853	0.209819	7.550477	1.335447	1.334473
31	0.248467934	0.218912	0.201447	0.209321	0.210418	0.21561	0.199533	0.21067	0.210516
32	0.020473469	0.018037	0.016597	0.017247	0.017337	0.017765	0.01644	0.017358	0.017345
Total	**135.132731**	**15.64951**	**22.28852**	**13.20648**	**17.94087**	**15.1006**	**26.45986**	**11.37142**	**15.82784**

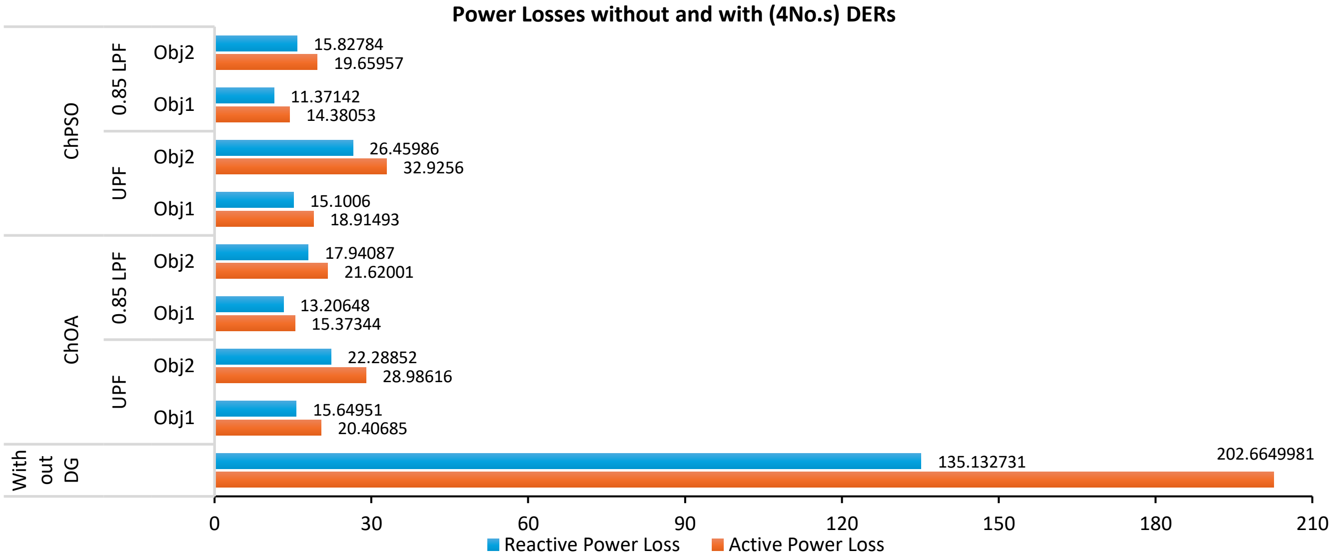

Fig 5. Active and Reactive power losses with 4 DERs optimally placed.

5. Conclusion

The paper introduces a novel hybrid optimization method, ChPSO, which significantly improves the optimization of the formulated optimal DG allocation problem. The proposed modifications aim to address the inherent limitations of the existing approaches. By employing the ChPSO method, this research successfully identifies the optimal sites for DG installations and introduces an innovative analytical framework for accurately determining DG capacities. The application of this approach to the IEEE-33 bus distribution system highlights its significant advantages over existing literature in terms of performance. Furthermore, the study underscores the effectiveness of combining the ChOA with PSO, particularly in achieving substantial reductions in power losses within the 33-bus system. This demonstrates the inherent potential of the proposed method to effectively tackle a variety of challenges faced in industry practices, offering a robust solution that enhances both efficiency and reliability in power distribution systems. The results obtained with the proposed algorithm are impressive, and implementing it in a real-time or complex system is highly recommended as a future direction for this work. Additionally, analyzing the system with the incorporation of an energy storage system would further strengthen the case for implementing the proposed algorithm in future research.

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