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Hybrid Siting and Sizing of Distributed Generators and Shunt Capacitors with System Reconfiguration using Wild Horse Optimizer

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ABSTRACT

Injection of Distributed generators (DG_S) and Shunt capacitors (SC_S) simultaneously with system reconfiguration significantly promotes smart grid performance. In addition, system reconfiguration increases the injected distributed generation capacity in the system. This work proposes a wild horse optimizer (WHO) for the optimal siting and sizing of DG_S and SC_S in parallel with network reconfiguration. The proposed method aims to attain single and multi-objectives: minimizing active power loss, maximizing voltage stability index (VSI), and minimizing voltage deviation index (VDI). Five operational cases are introduced to elucidate the superior performance of the proposed method. The five cases are executed on IEEE 33-bus standard radial distribution test system. The single-objective function results are compared with other optimization algorithms. The simulation results belay that the proposed WHO optimizer has the best results for unfixed DG_S and SC_S locations.

1. Introduction

In electrical power distribution networks, the main objective is to supply power continuously to the consumer within reasonable limits of individual parameters considering the unforetold nature of consumer demand [1]. Some of the main system constraints are overcurrent protective device coordination, interconnected radial configuration, and voltage drop limit. The traditional centralized generation stations have been changed because of the high r/x ratio of the distributed network, resulting in high power loss, high voltage drop, low voltage stability, decreased reliability, increased generation cost, and increased carbon emissions. The electrical power traditional system has been sophisticated to be more masterful, it is named by smart grid technology (SGT) [2]. The SGT is an intelligent two-way power flow (bidirectional power flow) and communication system, leading to better reliability, security, robustness, flexibility, and efficiency of the system. The two-way power

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flow is applied by installing distrusted generators (DG_S) and shunt capacitors (SC_S), which are electrical power sources added close to the consumption point to improve the voltage profile, reduce overall system losses, and boost the network load. In addition, network reconfiguration plays an essential role in system reliability and security by supplying consumers during fault currents, planning maintenance outages, enhancing the voltage profile, and reducing power loss [3]. Network reconfiguration is changing the structure of the feeders by the opened (tie switch) or closed (sectionalize switch) status of line switches. The reconfiguration process must guarantee that there are no isolated loads and that the radial structure of the system is conserved.

1.1 Literature Survey

The traditional methods have been used in distribution networks for improving the overall system parameters are network reconfiguration, distributed generators placement, and capacitors placement. Moreover, few of research have been presented system reconfiguration with DGs placement, system reconfiguration with SC_S placement, and hybrid siting and sizing of DGs and SC_S simultaneously with network reconfiguration as the proposed work. Siting and sizing of injected DGs and SCs in the distribution system, which is specified using single or multiple indices, might not be the optimal solution for all systems configurations; therefore, system reconfiguration, DGs, and SCs integration need to be implemented simultaneously to find the optimal solution for minimizing losses and improving network parameters.

1.1.1 Reconfiguration with DG_S siting and sizing

Simultaneous reconfiguration with DG_S siting and sizing are studied using some algorithms. A Sensitivity analysis and meta heuristic Harmony Search Algorithm (HSA) is presented to minimize the real power loss and improve voltage profile in the distribution network [1]. Fireworks Algorithm (FWA) is illustrated to minimize power loss and enhance voltage stability [4]. A combination of fuzzy-ant colony (ACO) algorithm is introduced to reduce losses, improve the voltage profile, and increase the load balancing of the feeder [5]. Moreover, A meta heuristic cuckoo search algorithm (CSA) is used to reduce the real power loss and enhance voltage stability [6]. Grey Wolf Optimizer (GWO), Particle Swarm Optimizer (PSO), and the hybrid GWO-PSO are presented to minimize power losses [7]. A mixed-integer linear programming (MILP) solver is illustrated to maintain system reliability, minimize active power losses, and meet the consumer energy demand [8]. A heuristic method based on uniform voltage distribution based constructive reconfiguration algorithm (UVDA) is introduced to maximize system loss reduction [9]. The particle swarm optimization (PSO) is introduced to minimize the bus voltage deviation and the total active power cost [10].

1.1.2 Reconfiguration with SC_S siting and sizing

Simultaneous reconfiguration with SC_S siting and sizing are studied using some algorithms. A Binary Gravitational Search Algorithm (BGSA) is used to minimize the cost considering the improvement of the system performance [11]. The Hybrid Shuffled Frog Leaping Algorithm (HSFLA) is illustrated to minimize the total real power losses, bus voltage violation, and load balancing on the feeders [12]. Furthermore, Genetic Algorithm (GA) is introduced to maintain the voltage profile and reduce power losses [13]. Sensitivity analysis and a meta heuristic Harmony Search Algorithm (HSA) are presented to minimize real power loss and improve voltage profile [1]. A hybrid heuristic search algorithm called Moth Swarm Algorithm (MSA) is used to minimize power loss and enhance the system performance [14]. A mixed integer non-linear programming (MINLP) is implemented in General Algebraic Modelling System (GAMS) to maximize the DG owner's profit and minimize the distribution company's (DisCo's) costs [15].

1.1.3 Reconfiguration with DG$_S$ and SC$_S$ siting and sizing

Simultaneous reconfiguration with SC$_S$ siting and sizing are studied using few algorithms. Genetic algorithm (GA) is presented to minimize total power loss, improve the voltage profile, and minimize branch currents [16]. A combination of a fuzzy multi-objective approach and bacterial foraging optimization (BFO) as a metaheuristic algorithm is used to improve power loss reduction, load balancing of feeders, and network voltage profile [17]. Binary particle swarm optimization (BPSO) is used for minimizing power loss [18]. Success History Based Adaptive Differential Evolution Algorithm (SHADE) is utilized to maximize the hosting capacity (HC) of the DGS, reduce power losses, and improve the voltage profile [19]. to minimize the real power loss. Finally, A successful alternative adaptation for the selection of control parameters of the linear population size reduction technique of SHADE (LSHADE-EpSin) is illustrated to minimize the real power loss [20].

1.2 Paper Organization

The rest of the paper is organized as follows: the problem formulation for the system's objective functions, equality constraints, and inequality constraints are given in Section 2. The proposed WHO optimizer is described in Section 3. The five proposed case studies are illustrated in Section 4. Section 5 illustrates the results of five case studies on the standard IEEE 33-radial bus system to boost the performance of the proposed technique for network reconfiguration process simultaneously with optimal siting and sizing of DG$_S$ and SC$_S$. The conclusion of this paper based on the illustrated results is listed in Section 6.

2. Problem Formulation

The problem formulation includes a multi-objective function solved by the WHO optimizer based on the simultaneous system reconfiguration with optimal siting and sizing of DG$_S$ and SC$_S$ while considering the equality and inequality constraints.

2.1 Objective Functions

Minimizing the network real power loss (objec$_1$) that can be expressed as follows

$$\mathrm{objec}_1 = \min \sum_{y=1}^{\mathrm{Tnbr}} \left|\mathrm{I}_y\right|^2 * \mathrm{R}_y \tag{1}$$

Where $\mathrm{I_y}$ is the yth branch flow current magnitude, $\mathrm{R_y}$ is the ith branch resistance, and Tnbr is the total number of network branches.

Minimizing the voltage deviation index (VDI) minimization is one of the operative formulas to track the quality of the bus voltage. Minimizing VDI (objec2) can be derived as follows [21]:

$$\mathrm{objec}_2 = \min(\mathrm{VDI}) = \min \sum_{x=1}^{\mathrm{Tnb}} (\mathrm{V_x} - 1)^2 \tag{2}$$

where $\mathrm{V_x}$ is the xth bus voltage magnitude and Tnb is the total number of network buses.

Maximizing the voltage stability index (VSI) is a formula to preserve the voltage profile to acceptable limits. Maximize VSI (objec3) can be calculated as follows [22]:

$$\mathrm{objec}_3 = \max(\mathrm{VSI}) \tag{3}$$

$$\mathrm{VSI(x)} = \{|V_x|^4 - 4\left(P_{x+1}X_{x,x+1} - Q_{x+1}R_{x,x+1}\right)^2 - 4\left(P_{x+1}R_{x,x+1} - Q_{x+1}X_{x,x+1}\right)^2|V_x|^2\} \tag{4}$$

Where V_x is the voltage magnitude at the xth node, P_{x+1} and Q_{x+1} are the active and reactive power of the load at $x + 1$ node, respectively, and $R_{x,x+1}$ and $X_{x,x+1}$ are the resistance and reactance of the branch between nodes x and $x + 1$, respectively. In addition, the distribution network stability with ‘x’ number of nodes illustrates the function as $\mathrm{VSI(x)} \geq 0$, for x = 2, 3, . . ., x.

2.2 Constraints

The equality and inequality constraints are illustrated as follows [23]:

2.2.1 Equality constrains

Power balance equation is determined as the sum of incoming power equivalent to the sum of outgoing power as follows:

$$P_{SL} + \sum_{x=1}^{TN_{DG}} P_{DGx} = \sum_{y=1}^{Tnbr} P_{Ly} + \sum_{x=1}^{Tnb} P_{DEx} \tag{5}$$

$$Q_{SL} + \sum_{x=1}^{TN_{DG}} Q_{DGx} + \sum_{x=1}^{N_{SC}} Q_{SCx} = \sum_{y=1}^{Tnbr} Q_{Ly} + \sum_{x=1}^{Tnb} Q_{DEx} \tag{6}$$

Where P_{SL} and $Q_{SL}$are the slack bus of active and reactive powers, respectively. P_{DGx} and Q_{DGx} are active and reactive capacity of DG at xth bus, respectively. P_{Ly} and Q_{Ly} are the active and reactive power losses of the yth branch, respectively. P_{DEx} and Q_{DEx} are the active and reactive power demands at the xth bus, respectively. TN_{DG} and TN_{sc} are the gross number of DGs and SCs, respectively.

2.2.2 Inequality constrains

Distributed Generator operating constraints [21,23]:

$$P_{DGx}^{\min} \leq P_{DGx} \leq P_{DGx}^{\max}, \tag{7}$$

$$Q_{DGx}^{\min} \leq Q_{DGx} \leq Q_{DGx}^{\max} \tag{8}$$

where $P_{DGx}^{\min}$ and $P_{DGx}^{\max}$ are the real DG minimum and maximum power at the xth bus, respectively. Moreover, $Q_{DGx}^{\min}$ and $Q_{DGx}^{\max}$ are the reactive DG minimum and maximum power at the xth bus, respectively.

SCs reactive power capacity constraints:

$$Q_{SCx}^{\min} \leq Q_{SCx} \leq Q_{SCx}^{\max} \tag{9}$$

DGs active power capacity constraints:

$$\sum_{x=1}^{TN_{DG}} P_{DGx} \leq \sum_{x=1}^{Tnb} P_{DEx} \tag{10}$$

Reactive power source constraints:

$$\sum_{x=1}^{N_{DG}} Q_{DGx} + \sum_{x=1}^{N_{CB}} Q_{SCi} \leq \sum_{x=1}^{Tnb} Q_{DEx} \tag{11}$$

Bus voltage constraints:

$$0.95 \leq V_x \leq 1.05 \qquad x = 1,2,3 \ldots, nbus \tag{12}$$

3. Proposed Wild Horse Optimizer

Wild horse optimizer (WHO) is a new metaheuristic technique motivated by the social life behaviour of wild horses' life. The hierarchy group behaviours, including leadership, grazing, domination, and mating represent the numerous difficulties of this optimization. Horses' social life can be divided into two group categories, territorial and non-territorial. The WHO optimizer illustrates non-territorial horse groups. These groups contain many mares, offspring, and a stallion, which is the leader. In addition, adult stallions make single family groups, they converse with mares, and the foals start grazing nearby until their maturity. Then, they leave their first family group and join other groups to have new families. In order to prevent mating neither between brothers and sisters nor fathers with daughters, Male and female foals of one group get involved in two different groups. The five main significant steps of the proposed algorithm are assuming the initial population and horse groups with their leaders, grazing and mating of horses, leadership of the stallion, leadership selection and update, and execute and save the best solution [24].

3.1 Initial Population for the Problem

In this step, the parameters are initialized to implement the initial random solutions. The most comparable and best solutions are chosen and updated according to the algorithm procedures. Foals and stallions are chosen from the initial population and form different groups. The number of horses in these groups is derived as follows [24]:

$$G = [N \times PS] \tag{13}$$

Where G is the horse group number, N is the population size, and PS is the percentage of stallion percentage in the total population size.

3.2 Horses Grazing Behaviour

In this phase, foals graze around the centred stallion. The new positions of the group members can be calculated as follows:

$$X_{x,G}^{y} = 2Z\cos(2\pi RZ) * \left(Stallion^{y} - X_{x,G}^{y}\right) + Stallion^{y} \tag{14}$$

Where X is the current location of the (mare or foal) group member, $\mathrm{Stallion}^{y}$ represents the stallion position, a stochastic uniform number (R) is within the range [−2,2], as horses graze at 360◦ angles, $\pi = 3.14$, and Z is the adaptive mechanism calculated as follows [24]:

$$P = \overrightarrow{R_1} < TDR; IDX = (P == 0); Z = R_2 \Theta IDX + \overrightarrow{R_3} \Theta (\sim IDX) \tag{15}$$

$$TDR = 1 - iter * \left(\frac{1}{Maxiter}\right) \tag{16}$$

Where P is a vector composed of 0 and 1, $\overrightarrow{R_1}$ and $\overrightarrow{R_3}$ are two random uniformly distributed vectors within a range, [0,1], R2 is a uniformly distributed random number within the range [0,1]. IDX indexes for vector $\overrightarrow{R_1}$ return the redeem condition (P==0). TDR is a parameter that begins with 1 and decreases until it becomes 0 at the end implementation of this algorithm. Iter and Maxiter are the existing iteration and the maximum iteration number, respectively.

3.3 Horse Mating Behaviour

The departure and mating nature behaviour of the foals is shown in Figure 1. This behaviour is like the crossover operator. It can be calculated as shown [24]:

$$X^{p}_{G,k} = \mathrm{Crossover}\left(X^{q}_{G,x}, X^{Z}_{G,y}\right) \quad x \neq y \neq k, p = q = end, \tag{17}$$
$$crossover = mean$$

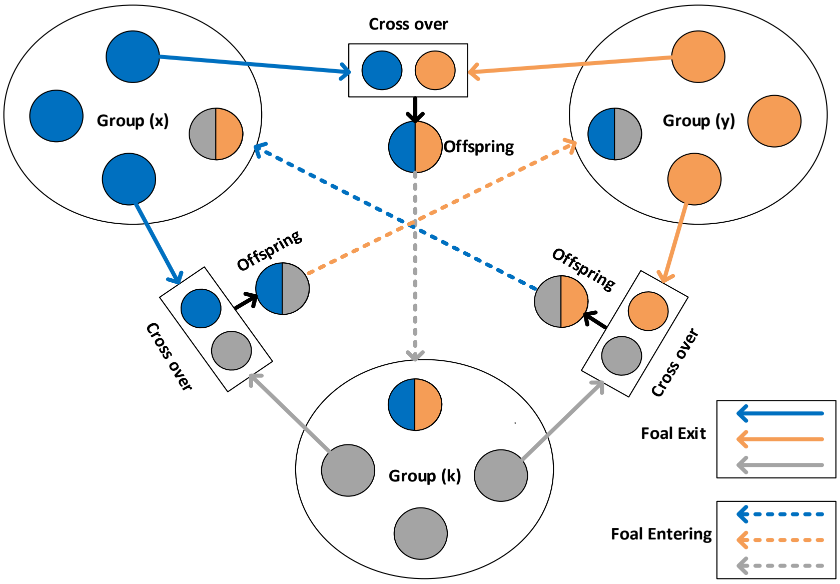

Fig. 1. Behaviour of foals while leaving their main family and joining a new group

Where $X^{p}_{G,k}$ is the position of horse p in group k and it leaves this group. Another horse takes the place of horse P. $X^{q}_{G,x}$is the position foal q, which is in group x mated with the foal z, which left group y with the position $X^{Z}_{G,y}$.

3.4 Groups Leadership

In this step, the stallion of the group guides the rest of the group to the water hole area for feeding. On the other side, the stallions fight with each other to have the waterhole. This behaviour can be derived by [24]:

$$\mathrm{Stallion}_{Gi}` = \begin{Bmatrix} 2Z\cos(2\pi RZ)*(WH-\mathrm{Stallion}_{Gx})+WH & \text{if } R_3 > 0.5 \\ 2Z\cos(2\pi RZ)*(WH-\mathrm{Stallion}_{Gx})-WH & \text{if } R_3 \leq 0.5 \end{Bmatrix} \quad (18)$$

Where $\mathrm{Stallion}_{Gx}`$ is the group x stallion next position, WH is the water hole position, and $\mathrm{Stallion}_{Gx}$ is the stallion's current position.

3.5 Exchanging and Selecting Leaders

First, the leaders are chosen randomly. In this phase, stallions and other group members are chosen and updated according to the ones with the best fitness value. The new positions of the stallion and the corresponding members are calculated by the following equation [24]:

$$\mathrm{Stallion}_{Gx} = \begin{Bmatrix} X_{G,x} & \text{if } \cos t(X_{G,x}) < \cos t(\mathrm{Stallion}_{Gx}) \\ \mathrm{Stallion}_{Gx} & \text{if } \cos t(X_{G,x}) > \cos t(\mathrm{Stallion}_{Gx}) \end{Bmatrix} \quad (19)$$

Furthermore, the flowchart of the main steps of the proposed WHO is shown in Figure 2.

3.6 The WHO Optimizer Implementation for Network Reconfiguration and DG_S / SC_S Allocation

Network reconfiguration, DG_S, SC_S units' siting in proper places reduce the distribution line current, reduce overall system losses, and improve all system parameters. The Fitness function control variables are the network reconfiguration, siting of DG_S and SC_S, and sizing of DG_S and SC_S capacities. The complexity of solving this problem lies in the fact of finding those many variables simultaneously using the proposed technique. Most of the articles use two or three techniques to find the optimal reconfiguration, DG_S and SC_S locations, and DG_S and SC_S sizes separately.

4. Case Study

The proposed WHO optimizer is applied to a standard IEEE 33-bus radial distribution test system to study its effectiveness. Load flow and simulation study calculations are implemented using MATPOWER open-source tool and MATLAB. In this study, five operational cases are carried out to demonstrate the superior performance of the WHO optimizer. Furthermore, the optimal configuration simultaneously with the optimal siting and sizing of DG_S and SC_S are introduced, and they cannot be located at the slack bus.

i. Case 1: Minimizing active power loss by simultaneous system reconfiguration with optimal siting and sizing of three P-type DG_S.
ii. Case 2: Minimizing active power loss by simultaneous system reconfiguration with optimal siting and sizing of three PQ^+-type DG_S.
iii. Case 3: Minimizing active power loss by simultaneous system reconfiguration with optimal siting and sizing of three SC_S and three P-type DG_S.

iv. Case 4: Minimizing active power loss by simultaneous system reconfiguration with optimal siting and sizing of three SC_S and three PQ^+-type DG_S.
v. Case 5: Solving multi-objective function by simultaneous system reconfiguration with optimal siting and sizing of three SC_S and three PQ^+-type DG_S.

The multi-objective function can be calculated as follows:

$$\text{Multiobjec} = \min\left(\text{objec}_1+\text{objec}_2-\text{objec}_3\right) \tag{20}$$

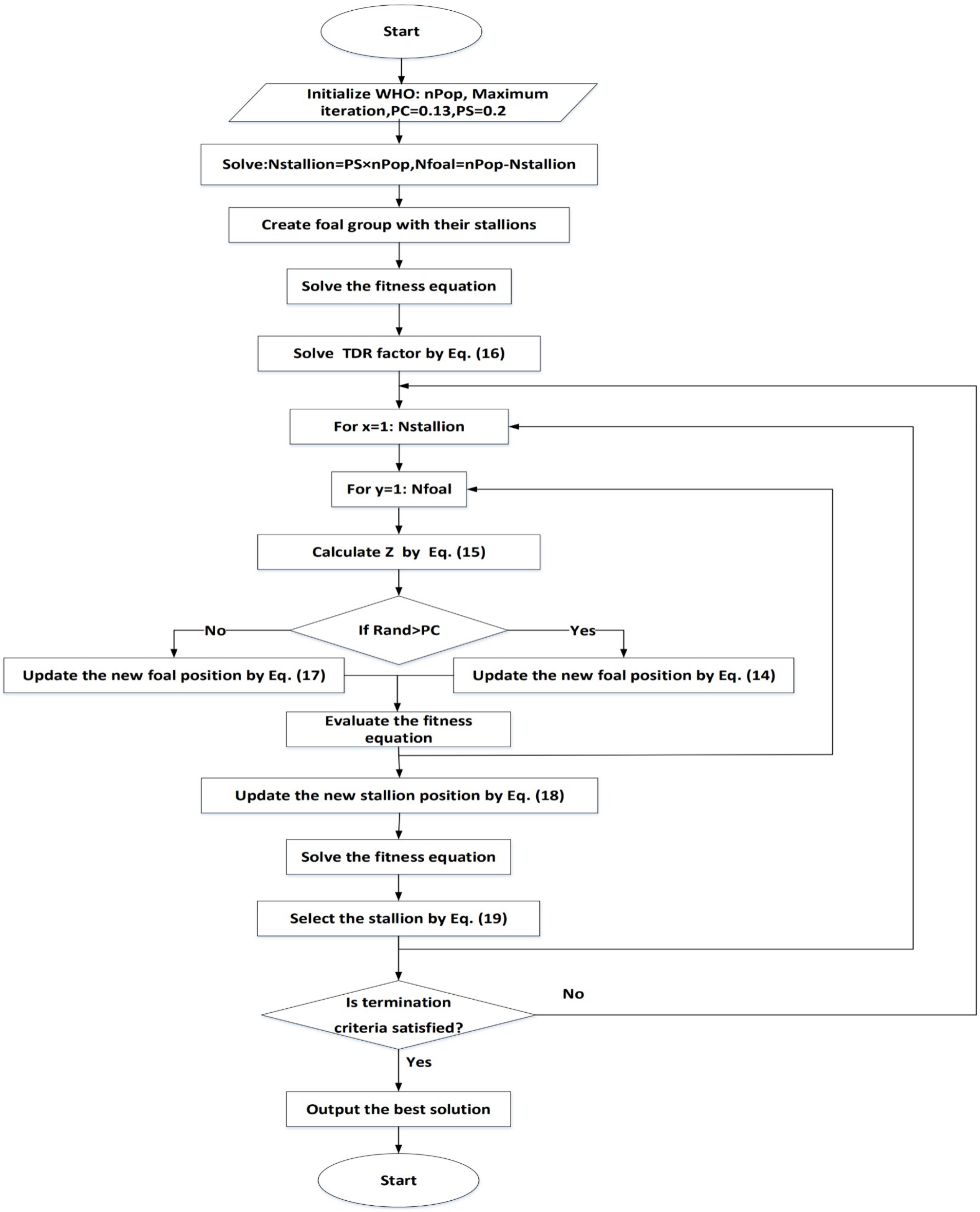

Fig. 2. The proposed WHO optimizer flowchart

5. Results and Discussions

The following tables and figures present the results of the five cases applied to the standard IEEE 33-bus radial distribution test system. Reconfiguration of the system with the installation of DG_S and SC_S reduces the current flow. This leads to an improvement in the overall system parameters.

5.1 IEEE 33-Bus Radial System

The standard IEEE 33-bus radial distribution test system is composed of 33 buses and 32 distribution branches. Net real and reactive power loads are 3.715 MW and 2.3 MVAR, respectively. The system voltage base value is 12.66 KV, and the capacity base value is 100 MVA. The base system configuration has normally opened tie switches from 33-37 and normally closed sectionalized switches from 1 to 32. In addition, this system has five loops formed by tie switches. Tie switches are reconfigured during system faults to improve the performance, reliability, and security of the system.

5.1.1 Case 1

In this case, the proposed WHO optimizer size of population is 50, and the iterations maximum number is 200, with an elapsed time of 116.0277 seconds for minimizing the real power loss.

Table 1 shows the simulation results of WHO compared with other optimization methods to show the performance of the proposed WHO technique. The WHO optimally reconfigures the tie switches to 28, 33, 11, 34, and 30. The optimal locations of the three DGs (P-type) are 18, 7, and 25 buses with sizes 0.8725, 0.9623, and 1.1249 MW, respectively. The minimum bus voltage magnitude of the system is improved from 0.913 (p.u.) at bus 18 to 0.96838 (p.u.) at bus 31. The active power loss is 202.67 KW, which decreases to 50.8236 KW. The VDI is improved from 0.117 to 0.010307 (p.u.). Moreover, the minimum VSI is increased from 0.6933 to 0.87752 (p.u.).

Table 1
Case 1 of the 33-Bus radial test system with network reconfiguration and P-type DG_S

Methods	Base Case	PSO [7]	GWO [7]	Hybrid GWO-PSO [7]	Proposed WHO
Objectives	Minimize real power loss				
Real power loss (KW)	202.67	50.8905	51.3088	50.7175	50.8236
Switches opened	33,34,35,36,37	11, 28, 30, 33, 34	11, 28, 31, 33, 34	11, 28, 30, 33, 34	28,33,11,34,30
DG_s Size (MW) (Position)	-	0.9581 (7), 1.1257 (25), 0.8546 (33)	0.8141 (8), 0.7540 (17), 1.3085 (25)	0.9569 (7), 0.7529 (17), 1.2795 (25)	0.8725 (18), 0.9623 (7), 1.1249 (25)
Min. Bus Voltage (p.u.) (Position)	0.913 (18)	0.9734 (32)	0.9699 (31)	0.9734 (32)	0.96838 (31)
VDI (p.u.)	0.117	-	-	-	0.010307
VSI (p.u.)	0.6933	-	-	-	0.87752
Population size	-	50	50	50	50
Iterations	-	6000	6000	2000	200
Elapsed time (sec)	-	10560.81	6121.91	7014.11	116.0277

5.1.2 Case 2

In this case, the size of population is 50, and the iterations maximum number is 200, with an elapsed time of 114.18 seconds to minimize the real power loss. Figure 3 shows the conversion curve of the proposed WHO technique compared with Hybrid GWO-PSO, GWO, and PSO to observe its best performance.

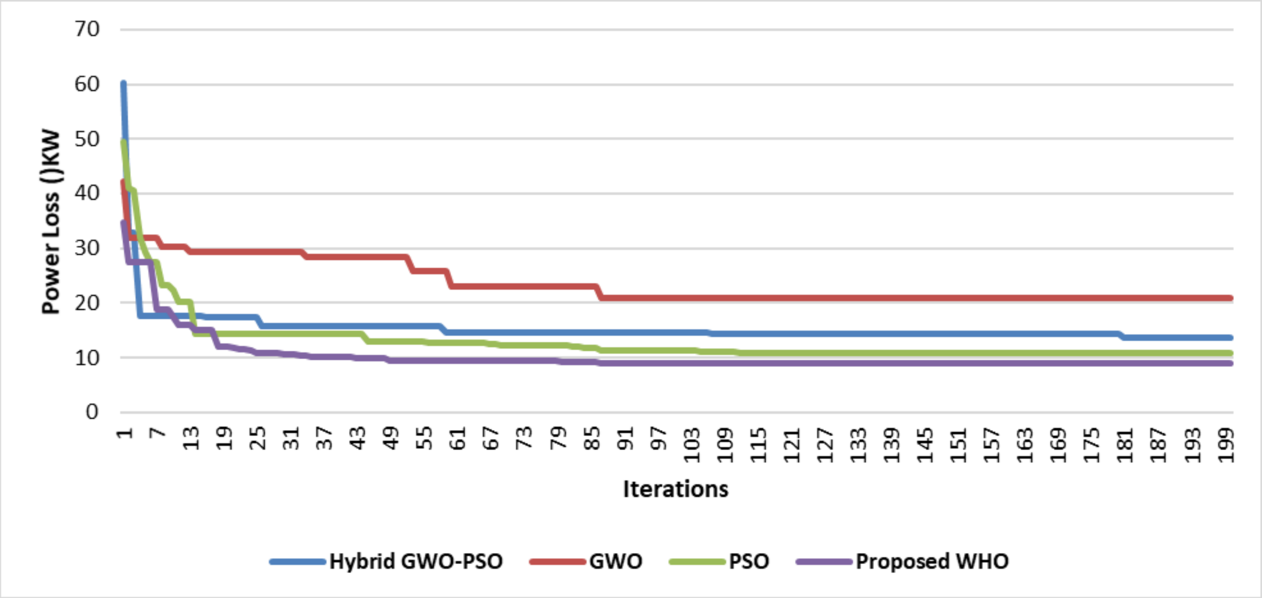

Fig. 3. Power loss conversion curve of case 2 for four different techniques

Table 2 shows the simulation results of WHO compared with other optimization methods. The WHO optimally reconfigures the tie switches to 23, 5, 11, 13, and 15. The optimal locations of the three DGs (PQ$^+$-type) are 25, 32, and 8 buses with a sizing of 1.1523, 0.7491, and 1.09747 MW for active power injection and 0.8046, 0.5620, and 0.5593 for reactive power injection, respectively. The minimum bus voltage magnitude of the system is improved to 0.96509 p.u at bus 13. The active power loss is improved to 8.9162 KW. The VDI is improved to 0.00033764 p.u. Additionally, the VSI is increased to 0.96509 p.u.

Table 2
Case 2 of the 33-Bus radial test system with network reconfiguration and PQ$^+$-type DG$_S$

Methods	Base Case	PSO [7]	GWO [7]	Hybrid GWO-PSO [7]	Proposed WHO
Objectives	Minimize real power loss				
Real power loss (KW)	202.6	10.8466	8.9540	8.9162	8.9162
Switches opened	33,34,35, 36,37	25,7,21,34,16	26,5,11,13 ,15	23,5,11,13,15	23,5,11,13,15
DG$_S$ Size (MVA) (Position)	-	0.9533+j 0.4627(24), 0.7826+j 0.3752(12), 1.1959+j 1.0738(30)	1.1327+j 0.8311(25), 1.0818+j 0.5138(8), 0.7528+j 0.5720(32)	1.0974+j 0.5593(8) 0.7491+j 0.5620(32) 1.1523+j 0.8047(25)	1.1523+j 0.8046(25), 0.7491+j 0.5620(32), 1.09747+j 0.5593(8)

Min. Bus Voltage (p.u.) (Position)	0.913 (18)	0.99208(17)	0.9915(13)	0.9916(13)	0.96509(13)
VDI (p.u.)	0.117	-	-	-	0.00033764
VSI (p.u.)	0.693	-	-	-	0.96509
Population size	-	50	50	50	50
Iterations	-	8000	8000	3000	200
Elapsed time (sec)	-	9906.67	9629.51	9751.61	114.18

5.1.3 Case 3

In this case, the size of population is 50, and the iterations maximum number is 200, with an elapsed time of 109.53 seconds for minimizing the real power loss.

Table 3 below shows the best result of WHO compared with other optimization methods. The WHO optimizer reconfigures the tie switches to 26, 4, 11, 13, and 15. The optimal locations of the three DGs (P-type) at 8, 25, and 32 buses with sizing 1.1419, 1.1176, and 0.7525 MW, respectively. Additionally, the optimal locations of the three SCs are 25, 8, and 30 buses with sizing 0.4456, 0.5436, and 0.9494 MVAR, respectively. The minimum bus voltage magnitude of the system is improved to 0.9915 (p.u.) at bus 13. The active power loss is improved to 7.9269 KW. The VDI is improved to 0.00042621 p.u. Finally, the minimum VSI is increased to 0.96476 (p.u.).

Table 3
Case 3 of the 33-Bus radial test system with network reconfiguration, P-type DG$_S$, and SC$_S$

Methods	Base Case	GA [16]	Fuzzy-BFO [17]	BPSO [18]	SHADE [19]	SHADE-EpSin [20]	Proposed WHO
Objectives	Minimize real power loss						
Power loss (KW)	202.6	50.149	45.65	15.47	12.70	15.63	7.9269
Switches opened	33,34,35,36,37	7,9,15,27, 34	9, 14, 27, 33, 36	7,35,10,36,26	11,25,33,34,35	7, 11, 12, 17, 26	26,4,11,13,15
DG$_s$ Size (MW) (Position)	-	0.25 (16), 0.25 (22), 0.5 (30)	0.758 (14), 0.1045 (24), 0.987 (30)	0.70 (15), 0.60 (31), 0.70 (25)	1.532 (29), 0.721 (8), 0.641 (16)	0.557 (15), 0.813 (25), 0.630 (32)	1.1419 (8), 1.1176 (25), 0.7525 (32)
SC$_s$ Size (MVAR) (Position)	-	0.3 (15), 0.3 (18), 0.3(29), 0.6 (30), 0.3(31)	0.150 (8), 0.150 (18), 0.300 (30)	0.382 (14), 1.013 (30), 0.419 (24)	1.260 (30), 0.236 (14), 0.197 (2)	0.703 (3), 0.399 (9), 0.1198 (30)	0.4456 (25), 0.5436 (8), 0.9494 (30)
Min. Bus Voltage (p.u.) (Position)	0.913 (18)	0.981	-	0.9887	0.9936	0.9863 (8)	0.9915 (13)
VDI (p.u.)	0.117	-	-	-	-	-	0.00042621
VSI (p.u.)	0.693	-	-	-	-	-	0.96476

Population size	-	-	-	-	-	150	50
Iterations	-	-	-	-	-	50000	200
Elapsed time (sec)	-	-	-	-	-	-	109.53

5.1.4 Case 4

In this case, the population size is 50, and the maximum number of iterations is 200, with an elapsed time of 125.03 seconds for minimizing the real power loss. Table 4 shows the optimal reconfiguration of the tie switches; 26, 5, 11, 13, and 15. The optimal locations of the three DGs (PQ+-type) are 25, 8, and 32 buses with sizing 1.12768, 1.08156, and 0.753378 MW for active power injection and 0.388751, 0.449226, and 0.275447 MVAR for reactive power injection, respectively. Besides, the optimal locations of the three SCs are 3, 12, and 30 buses with sizing 0.292198, 0.114578, and 0.674815 MVAR, respectively. The minimum voltage magnitude of the system is improved to 0.99316 (p.u.) at bus 14.

Table 4
Case 4 of 33-Bus radial system with network reconfiguration PQ$^+$-type DG$_S$ and SC$_S$

Methods	Base Case	Proposed WHO
Objectives	Minimize real power loss	
Power loss (KW)	202.6	6.7891
Switches opened	33,34,35,36,37	26,5,11,13,15
DG$_s$ Size (MVA) (Position)	-	1.12768+j 0.388751 (25), 1.08156+j 0.449226 (8), 0.753378+j 0.275447(32)
SC$_s$ Size (MVAR) (Position)	-	0.292198 (3), 0.114578 (12), 0.674815 (30)
Min. Bus Voltage (p.u.) (Position)	0.913 (18)	0.99316 (14)
VDI (p.u.)	0.117	0.00027295
VSI (p.u.)	0.693	0.97099
Population size	-	50
Iterations	-	200
Elapsed time (sec)	-	125.03

The active power loss is improved to 6.7891 KW. Moreover, the voltage deviation index is improved to 0.00027295 (p.u.). The minimum voltage stability index is increased to 0.97099 (p.u.). The single-line diagram of the optimal reconfigured lines with the allocation of DGs and SCs is shown below in Figure 4.

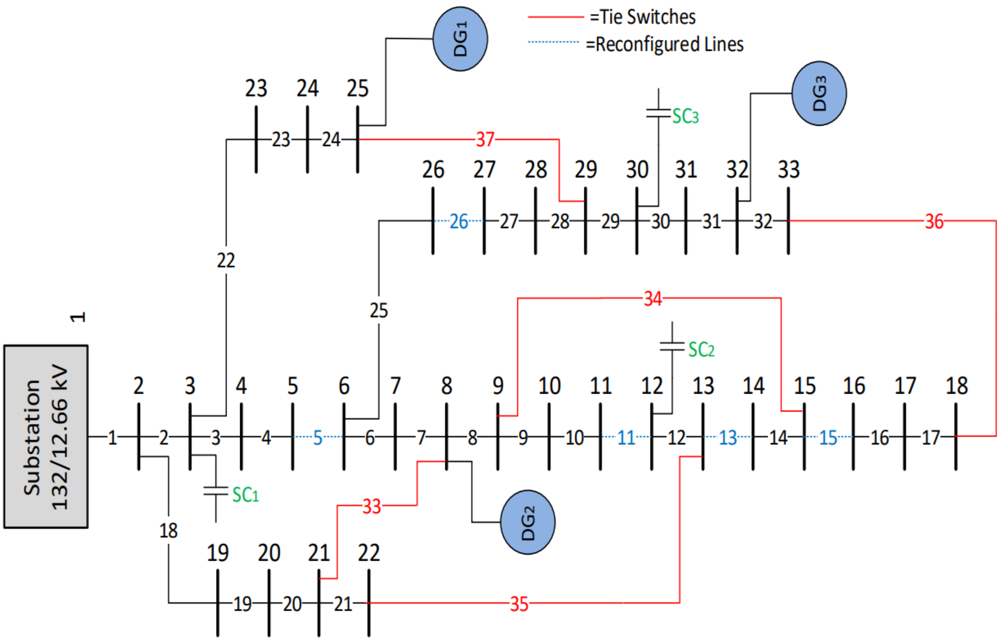

Fig. 4. The single line diagram of the 33-bus radial system for Case 4

5.1.5 Case 5

In this case, the size of population is 50, and the iterations maximum number is 200, with an elapsed time of 156.125 seconds for the above-mentioned multi-function. Table 5 shows the optimal reconfiguration of the tie switches; 27, 33, 35, 13, and 15. The optimal locations of the three DGs (PQ^+-type) are 25, 8, and 32 buses with sizing 1.1, 1.09707, and 0.59112 MW for active power injection and 0.335926, 0.44788, and 0.422017 MVAR for reactive power injection, respectively. Additionally, the optimal locations of the three SCs are 30, 18, and 2 buses with sizing 0.485267, 0, and 0.0217901 MVAR, respectively. The minimum bus voltage magnitude of the system is enhanced to 0.99079 (p.u.) at bus 14. The active power loss is improved to 9.4338 KW. Furthermore, the VDI is improved to 0.00098886 (p.u.). The minimum VSI is increased to 0.96176 (p.u.).

Table 5
Case 5 of the 33-Bus radial test system with network reconfiguration, PQ^+-type DG_s, and SC_s

Methods	Base Case	Proposed WHO
Objectives	Minimize real power loss + Minimize VDI + Maximize VSI	
Power loss (KW)	202.6	9.4338
Opened switches	33,34,35,36,37	27,33,35,13,15
DG_s Size (MVA) (Position)	-	1.1+j0.335926 (25), 1.09707+j0.44788 (8), 0.59112+j0.422017 (32)
SC_s Size (MVAR) (Position)	-	0.485267 (30), 0 (18), 0.0217901 (2)
Min. Bus Voltage (p.u.) (Position)	0.913 (18)	0.99079 (14)
VDI (p.u.)	0.117	0.00098886
VSI (p.u.)	0.693	0.96176
Population size	-	50
Iterations	-	200

Elapsed time (sec)	-	156.125

5.2 Comparative Analysis

Comparative analysis of the voltage profiles and voltage stability index for all cases are shown in Figure 5 and Figure 6, respectively. Figure 7 shows that the proposed WHO optimizer has reached the optimal solution compared to the other techniques. In addition, the real power loss, voltage deviation index, and voltage stability index comparative analysis for cases 1 to 5 are shown below in Figure 8, Figure 9, and Figure 10, respectively. Voltage profile, active power loss, voltage deviation index, and voltage stability index are improved in all scenarios after the simultaneous system reconfiguration with the optimal sizing and siting of DG_s and SC_s.

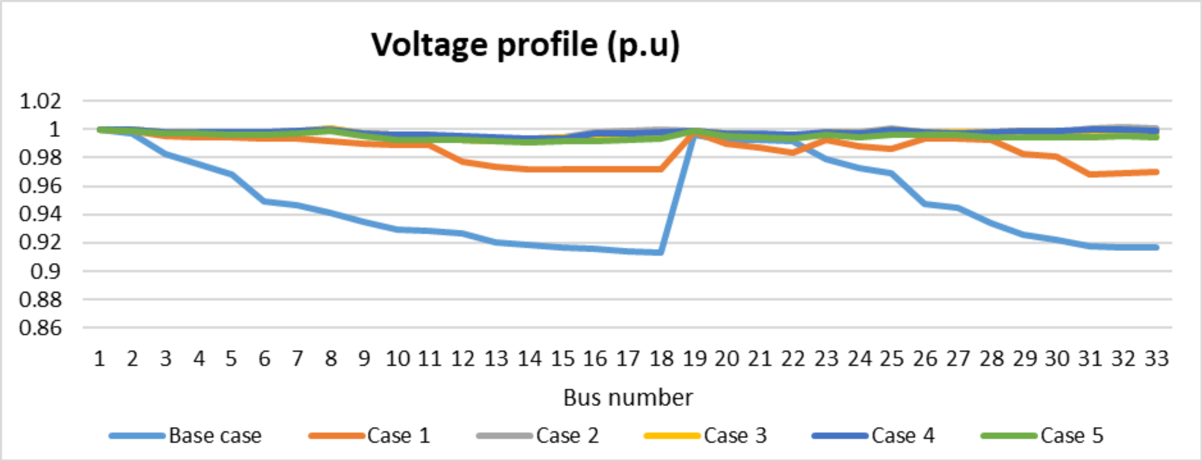

Fig. 5. Voltage profiles of the five cases for a 33-bus radial test system

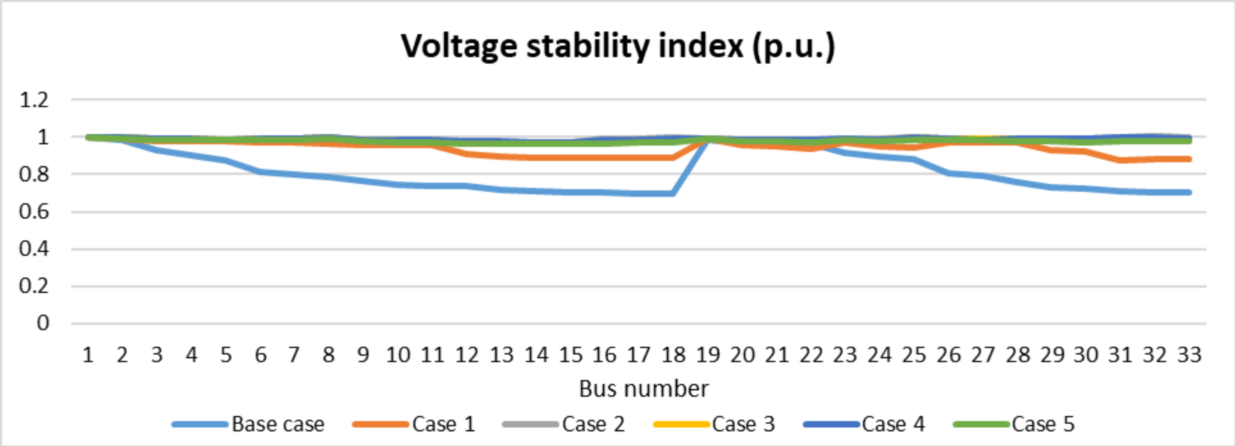

Fig. 6. Voltage stability index of the five cases for a 33-bus radial test system

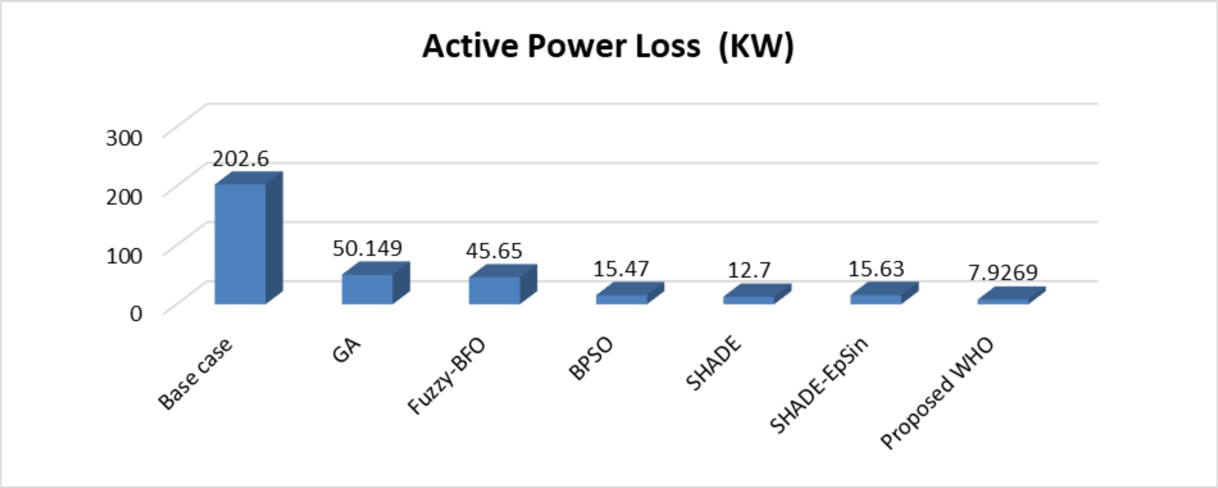

Fig. 7. Active power loss comparative study for case 3 using different techniques

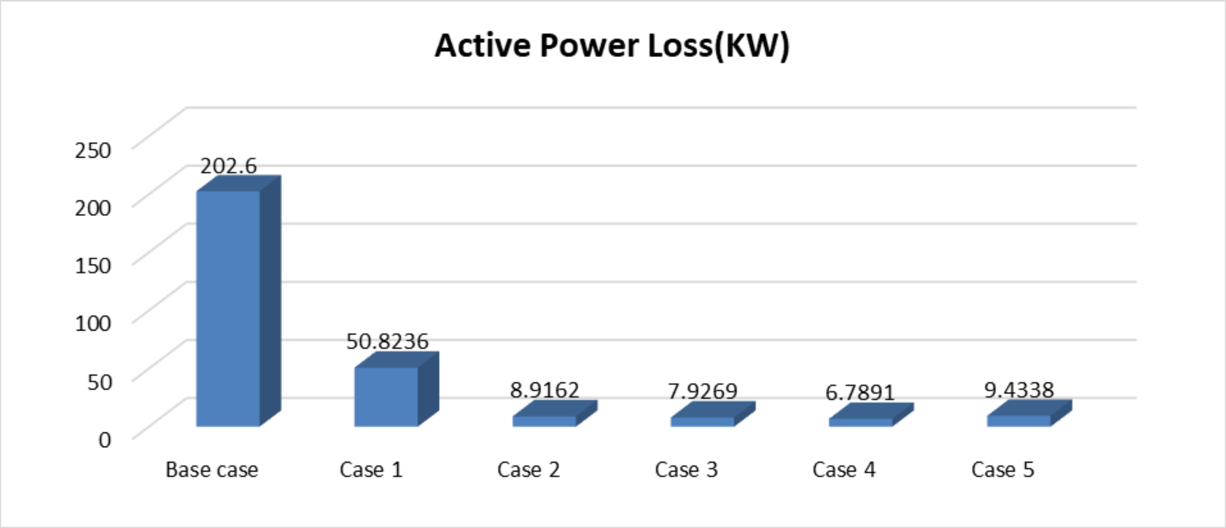

Fig. 8. Active power loss of different cases for the 33-bus radial test system

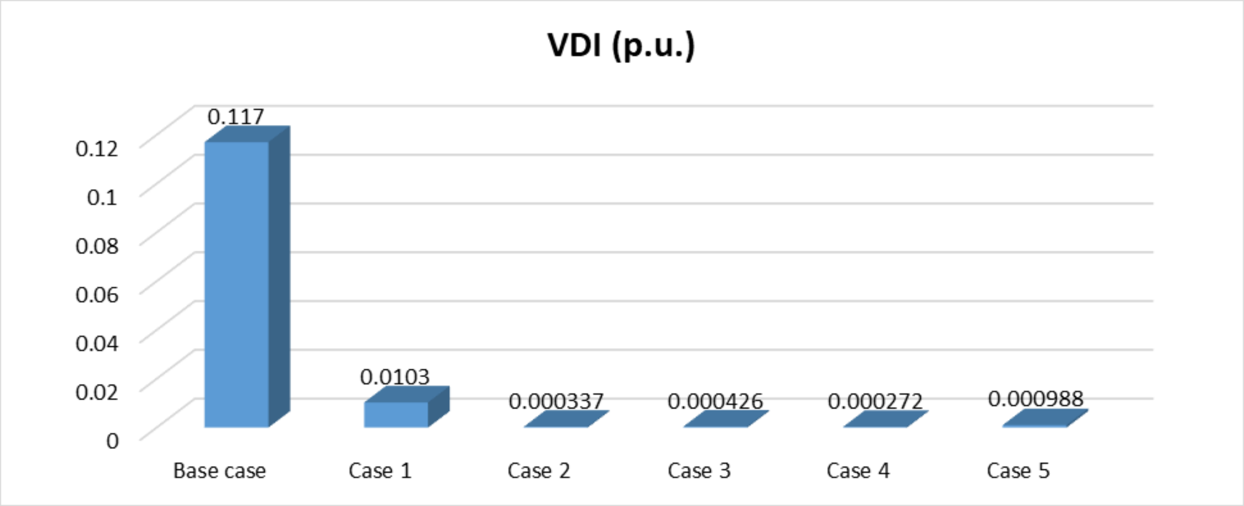

Fig. 9. Voltage deviation index of different cases for the 33-bus radial test system

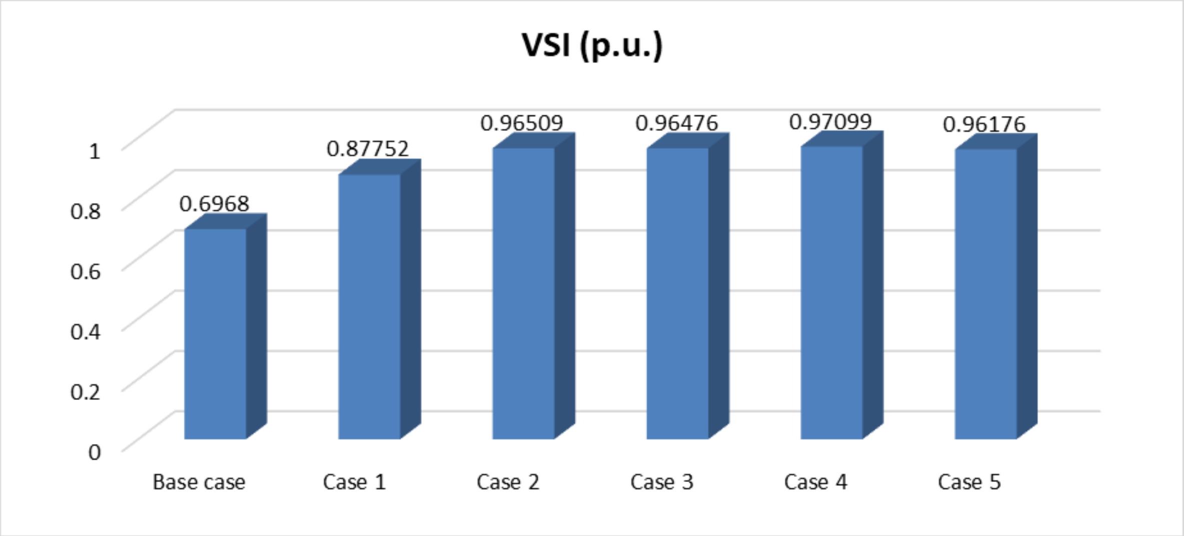

Fig. 10. Minimum voltage stability index of different cases for a 33-bus radial test system

6. Conclusions

The wild horse optimizer has been used for single and multi-objective frameworks for hybrid siting and sizing of DGs and SCs in parallel with system reconfiguration in the distribution network. It is implemented to the IEEE 33-bus radial standard system to show its superior performance compared to other techniques. Five different cases of simultaneous system reconfiguration with hybrid siting and sizing of DGs and SCs have been utilized. The remarkable results of the proposed method's simulation can be summarised as follows:

i. Excellent conversion characteristics have been observed for WHO.
ii. The active power loss is improved by 74.9%, 95.59%, 96.08%, 96.64%, and 95.34% from case 1 to case 5
iii. The voltage deviation index is improved by 91.19%, 99.71%, 99.63%, 99.76%, and 99.15% from case 1 to case 5.
iv. The minimum voltage stability index is improved by 20.59%, 27.79%, 27.77%, 28.23% , and 27.54% from case 1 to case 5.

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References

[1] Rao, R. Srinivasa, Kumudhini Ravindra, K. Satish, and S. V. L. Narasimham. "Power loss minimization in distribution system using network reconfiguration in the presence of distributed generation." *IEEE transactions on power systems* 28, no. 1 (2012): 317-325. https://doi.org/10.1109/TPWRS.2012.2197227

[2] Tuballa, Maria Lorena, and Michael Lochinvar Abundo. "A review of the development of Smart Grid technologies." *Renewable and Sustainable Energy Reviews* 59 (2016): 710-725. https://doi.org/10.1016/j.rser.2016.01.011

[3] Su, Ching-Tzong, and Chu-Sheng Lee. "Network reconfiguration of distribution systems using improved mixed-integer hybrid differential evolution." *IEEE Transactions on power delivery* 18, no. 3 (2003): 1022-1027. https://doi.org/10.1109/TPWRD.2003.813641

[4] Imran, A. Mohamed, M. Kowsalya, and D. P. Kothari. "A novel integration technique for optimal network reconfiguration and distributed generation placement in power distribution networks." *International Journal of Electrical Power & Energy Systems* 63 (2014): 461-472. https://doi.org/10.1016/j.ijepes.2014.06.011

[5] Tolabi, Hajar Bagheri, Mohd Hasan Ali, and M. Rizwan. "Simultaneous reconfiguration, optimal placement of DSTATCOM, and photovoltaic array in a distribution system based on fuzzy-ACO approach." *IEEE Transactions on sustainable Energy* 6, no. 1 (2014): 210-218. https://doi.org/10.1109/TSTE.2014.2364230

[6] Nguyen, Thuan Thanh, Anh Viet Truong, and Tuan Anh Phung. "A novel method based on adaptive cuckoo search for optimal network reconfiguration and distributed generation allocation in distribution network." *International Journal of Electrical Power & Energy Systems* 78 (2016): 801-815. https://doi.org/10.1016/j.ijepes.2015.12.030

[7] Abd El-salam, Mirna Fouad, Eman Beshr, and Magdy B. Eteiba. "A new hybrid technique for minimizing power losses in a distribution system by optimal sizing and siting of distributed generators with network reconfiguration." *Energies* 11, no. 12 (2018): 3351. https://doi.org/10.3390/en11123351

[8] Franco, John F., Marcos J. Rider, Marina Lavorato, and Rubén Romero. "A mixed-integer LP model for the reconfiguration of radial electric distribution systems considering distributed generation." *Electric Power Systems Research* 97 (2013): 51-60. https://doi.org/10.1016/j.epsr.2012.12.005

[9] Bayat, Akbar, A. Bagheri, and R. Noroozian. "Optimal siting and sizing of distributed generation accompanied by reconfiguration of distribution networks for maximum loss reduction by using a new UVDA-based heuristic method." *International Journal of Electrical Power & Energy Systems* 77 (2016): 360-371. https://doi.org/10.1016/j.ijepes.2015.11.039

[10] Olamaei, J., Taker Niknam, and G. Gharehpetian. "Application of particle swarm optimization for distribution feeder reconfiguration considering distributed generators." *Applied Mathematics and computation* 201, no. 1-2 (2008): 575-586. https://doi.org/10.1016/j.amc.2007.12.053

[11] Esmaeilian, Hamid Reza, and Roohollah Fadaeinedjad. "Distribution system efficiency improvement using network reconfiguration and capacitor allocation." *International Journal of Electrical Power & Energy Systems* 64 (2015): 457-468. https://doi.org/10.1016/j.ijepes.2014.06.051

[12] Sedighizadeh, Mostafa, and Mahdi Mahmoodi. "Optimal reconfiguration and capacitor allocation in radial distribution systems using the hybrid shuffled frog leaping algorithm in the fuzzy framework." *Journal of Operation and Automation in Power Engineering* 3, no. 1 (2015): 56-70.

[13] Priyadarshini, Radhika, R. Prakash, and C. B. Shankaralingappa. "Joint optimization for capacitor placement and network reconfiguration for loss reduction in distribution system." In *2014 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, pp. 1-6. IEEE, 2014. https://doi.org/10.1109/PEDES.2014.7041962

[14] Mohamed, Emad, Al-Attar Ali Mohamed, and Yasunori Mitani. "MSA for optimal reconfiguration and capacitor allocation in radial/ring distribution networks." (2018). https://doi.org/10.9781/ijimai.2018.05.002

[15] Nikkhah, Saman, and Abbas Rabiee. "Multi-objective stochastic model for joint optimal allocation of DG units and network reconfiguration from DG owner's and DisCo's perspectives." *Renewable energy* 132 (2019): 471-485. https://doi.org/10.1016/j.renene.2018.08.032

[16] Saonerkar, A. K., and B. Y. Bagde. "Optimized DG placement in radial distribution system with reconfiguration and capacitor placement using genetic algorithm." In *2014 IEEE international conference on advanced communications, control and computing technologies*, pp. 1077-1083. IEEE, 2014. https://doi.org/10.1109/ICACCCT.2014.7019263

[17] Mohammadi, M., A. Mohammadi Rozbahani, and S. Bahmanyar. "Power loss reduction of distribution systems using BFO based optimal reconfiguration along with DG and shunt capacitor placement simultaneously in fuzzy framework." *Journal of Central South University* 24 (2017): 90-103. https://doi.org/10.1007/s11771-017-3412-1

[18] Essa, Mohammed B., Lubna A. Alnabi, and Abbas K. Dhaher. "Distribution power loss minimization via optimal sizing and placement of shunt capacitor and distributed generator with network reconfiguration." *TELKOMNIKA (Telecommunication Computing Electronics and Control)* 19, no. 3 (2021): 1039-1049. https://doi.org/10.12928/telkomnika.v19i3.15223

[19] Sayed, Mahmoud M., Mohamed Y. Mahdy, Shady HE Abdel Aleem, Hosam KM Youssef, and Tarek A. Boghdady. "Simultaneous Distribution Network Reconfiguration and Optimal Allocation of Renewable-Based Distributed Generators and Shunt Capacitors under Uncertain Conditions." *Energies* 15, no. 6 (2022): 2299. https://doi.org/10.3390/en15062299

[20] Biswas, Partha P., Ponnuthurai N. Suganthan, and Gehan AJ Amaratunga. "Distribution network reconfiguration together with distributed generator and shunt capacitor allocation for loss minimization." In *2018 IEEE congress on evolutionary computation (CEC)*, pp. 1-7. IEEE, 2018. https://doi.org/10.1109/CEC.2018.8477894

[21] Venkatesan, Chandrasekaran, Raju Kannadasan, Dhanasekar Ravikumar, Vijayaraja Loganathan, Mohammed H. Alsharif, Daeyong Choi, Junhee Hong, and Zong Woo Geem. "Re-allocation of distributed generations using available renewable potential based multi-criterion-multi-objective hybrid technique." *Sustainability* 13, no. 24 (2021): 13709. https://doi.org/10.3390/su132413709

[22] Kalaivani, R., and V. Kamaraj. "Application of hybrid PSOGA for optimal location of SVC To improve voltage stability of power system." *International Journal of Electrical and Electronics Engineering* 1, no. 4 (2012): 31-36.

[23] Abou El-Ela, Adel A., Ragab A. El-Sehiemy, and Ahmed Samir Abbas. "Optimal placement and sizing of distributed generation and capacitor banks in distribution systems using water cycle algorithm." *IEEE Systems Journal* 12, no. 4 (2018): 3629-3636. https://doi.org/10.1109/JSYST.2018.2796847

[24] Naruei, Iraj, and Farshid Keynia. "Wild horse optimizer: A new meta-heuristic algorithm for solving engineering optimization problems." *Engineering with computers* 38, no. Suppl 4 (2022): 3025-3056. https://doi.org/10.1007/s00366-021-01438-z