Optimal Network Reconfiguration via Improved Whale Optimization Approach

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Abstract:- Latterly, reduction of power loss in the distribution system is the objective of many researches due to its impact on total costs and voltage profiles. It can be handled by an optimal restructure of the Radial Distribution System (RDS). This article introduces an innovative approach to restructure of RDS by electing the optimal switches combination subject to the system operating constraints, which is Improved Whale Optimization Approach (IWOA). The suggested approach combines exploitation of WOA with exploration of Differential Evolution (DE), and thus it supplies a promising candidate solution. The suggested approach is tested on IEEE 33 and 69 bus RDS. The superiority of the suggested approach compared with other well-known approaches is verified through simulation results by examining total losses, cost and saving. Also, the impact of alterable loading is investigated to prove the effectiveness of the suggested IWOA.

KeyWords: Radial Distribution System; Restructure; IWOA; Ohmic Losses; Mitigation.

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1. Introduction

Mitigation of ohmic power losses in RDS is still the target of many researches. Installation of DG, capacitors, and restructure of RDS are presented as the three main scenarios to alleviate these losses. Restructure of RDS is presented as the most preferable scenario as the costs of operation and installation of DG, and capacitors are not included. The restructure process refers to the alteration of system switches combination and adjustment of the structure of network operation by closing or opening the disconnected sectional and tie switches with satisfied constraint [1-4]. These switches organize the status of feeders and have a pivotal impact on branch power flows and total power losses.

Since the charge of ohmic power loss presents plentiful value of operating charge in RDS, and thence considerable papers have objective function of active power loss. ANNs has been implemented in [5] to assort the proper network topology to reduce losses for small RDS. FEP has been considered in [6] as the solution mechanism to restructure of RDS to acquire the best voltage profile and least kW losses. In [7], a method for multi-objective restructure of RDS in FFW using AGA has been presented. A method to optimize the unbalanced systems to keep up the voltage profiles with respect to the consequence of solving the multi-objective restructure utilizing the FA in a fuzzy domain has been addressed in [8]. A two-stage solution technique based on a modified SA approach for general multi-objective optimization tasks has been discussed in [9]. A modified SA approach has been developed in [10] for network restructure in distribution systems for loss minimization. A method for optimal planning of RDS has been introduced in [11] based on a combination of the steepest descent and the SA programming. TS approach with some modifications has been mentioned in [12] for restructure of RDS. The application of a GA with variable population size to the restructure problem has been demonstrated in [13]. A new cycle break algorithm that utilizes elementary cycles or network adjacency matrix with GA to develop radial network restructure has been presented in [14]. AGA has been used in [15] to minimize real loss without involving any additional cost for the installation of capacitors, tap changing transformers, and concerned switching equipment. EGA has been utilized in [16] to solve the restructure problem, reduce power loss, and improve system reliability. In [17], an IGA has been developed to handle the restructure problem considering total voltage deviation and active power loss. ACA has been indicated in [18-19] to deal with the restructure problem of distribution systems while enforcing the technical constraints like the voltage limits and transmission capabilities. PSO has been applied on [20-21] to deal with the distribution feeder restructure problem considering the effect of DG units. In [22], PSO has been presented to find the solution of the two-stage technique, which solves the optimal network restructure at the first stage and phase balancing at second stage. MPSO has been suggested in [23-24] for system restructure to enhance voltage profiles and minimize losses. In [25-

26], HPSO has been proposed for network restructure with DG installation problems. The problem of system restructure has been framed in [27] as a nonlinear optimization problem and has been solved using MBFA. RRA has been developed in [28] for network restructure problems to lower real loss and load balance. HS has been given in [29] to obtain the perfect switching that leads to lower loss. Restructure of RDS based on GSO has been addressed in [30-31] to get the minimum losses and voltage profiles. QFA has been used in [32] to restructure RDS with different objective functions to improve the reliability and power quality. MHBMO has been managed in [33] for network restructure to minimize the voltage deviation. Restructure of the distribution network based on ABC has been utilized to get the optimal switching sequence in [34]. GSA has been recommended in [35] for restructure of the RDS to provide optimal performance with keeping the radial of the network. ALO has been investigated in [36] to find optimal restructure of the distribution network for voltage profile enhancement and power loss minimization. ICA in a fuzzy frame has been introduced in [37] to handle the network restructure problem. Reliability indices and power losses have been included in the objective function. Various optimization approaches as Jaya optimization, TLBO, and integrated PSO have been applied in [38] to optimize the RDS by optimal restructure and DG installation. FWA has been implemented in [39] to determine the optimal network restructure considering the operating constraints. MPGSA has been proposed in [40] for restructure and DG installation for small RDS. CSA has been shown in [41-42] for handling the restructure problem to reduce real losses and enrich voltage profile. BBO has been simulated in [43] to achieve minimum losses and good voltage deviations by restructure of the distribution system. In [44], the problem has been formulated as an optimization process and has been solved using GWOA. However, these algorithms may not ensure achieving the optimal solution and may trap in local minimum. In this article, the IWOA is suggested to handle the problem of restructure in RDS with an objective function to lessen the total losses by optimal electing switches combination to restructure the RDS. Also, the superiority of the suggested IWOA is proven through statistical analysis, and variable loading conditions. Furthermore, the IWOA is not been wasted.

2. Problem Formulation

Line losses mitigation during operation is the used objective function for restructure of RDS and it could be written as:

$$P_{Loss} = \sum_{m=1}^{N_b} I_m^2 R_m \quad (1)$$

Where

m : The branch number,
N_b : The total number of branches,
I_m : The current at branch m ,
R_m : The resistance at branch m ,
P_{Loss} : The total active losses in kW,

The annual cost due to power losses can be given from equation (2):

$$\text{Annual cost} = K_P * T * P_{Loss} \quad (2)$$

Where

K_P : The cost per kW-Hours and equals to 0.06 \$/kW-Hours,
T : The time in Hours and equals to 8760,

There are various constraints that should be respected during operation. These constraints are as:

- **Load flow constraints**

The load flow constraints are calculated by equations (3, 4):

$$P_{Swing} = P_{Loss} + \sum_{q=1}^{N} Pd(q) \quad (3)$$

$$Q_{Swing} = \sum_{m=1}^{N_b} I_m^2 X_m + \sum_{q=1}^{N} Qd(q) \quad (4)$$

Where

$Pd(q)$: The demand of active power at bus q ,
$Qd(q)$: The demand of reactive power at bus q ,
P_{Swing} : The active power of swing bus,
Q_{Swing} : The reactive power of swing bus,
X_m : The reactance at branch m ,

• Radially constraint
It means that no closed loops are incorporated through the network, and thence the number of branches can be stated by equation (5):

$$N_b = N - 1 \quad (5)$$

where
N : The number of total buses,

• Feasibility constraint
It assures that no loads are isolated during restructure tasks.

• Voltage constraint
At each bus, the magnitude of voltage should be controlled by equation (6), and is picked as 0.90, and 1.0 p.u respectively.

$$V_{\min} \le \left|V_i\right| \le V_{\max} \quad (6)$$

Where
$V_{\min}, V_{\max}$: The lower and upper voltages at bus i,

• Current constraint
Equation (7) sets the magnitude of branch current.

$$I_j < I_{j\max} \quad (7)$$

Where
$I_{j\max}$: The maximum allowed current in each branch,

3. Whale Optimization Algorithm

Humpback whales are brilliant mammals. Their hunting behaviour has three steps: encircling prey, spiral bubble-net feeding technique, and search for prey. These steps are addressed as following [45-48]:

- **Encircling Prey:**

Humpback whales detect the prey location as an initial position $\vec{X}(t)$ and encircle them. Since the optimal site is not realized, the WOA assumes that the current selected solution is the optimum. After the best search factor is recognized, the other search factors will upgrade their positions according to equations (8, 9) [49-50].

$$\vec{D} = (\vec{C}.\vec{X}_b(t) + \vec{X}(t)) \quad (8)$$

$$\vec{X}(t+1) = (\vec{X}_b(t) - \vec{A}.\vec{D}) \quad (9)$$

Where $\vec{X}_b(t)$ should be upgraded in each iteration. $\vec{A}$ and $\vec{C}$ are meant as equations (10,11) [51]:

$$\vec{A} = |2\vec{a}.\vec{r} - \vec{a}| \quad (10)$$

$$\vec{C} = 2.\vec{r} \quad (11)$$

Where
t : The current generation,
$\vec{X}_b(t)$: The best elected solution so far,
$\vec{a}$: Linearly decreased from 2 to 0,
$\vec{r}$: Random vector in scale [0, 1],

- **Spiral Bubble-net feeding technique**

There are two techniques:

a) Shrinking encircling technique
It's acquired by lowering the scale of $\vec{a}$. So the new position of search factors will be the area between the original position of the factor and the position of the current best factor [52-53].

b) Spiral updating position
A spiral equation between the whale position and prey position simulating the helix-shaped path of humpback whales as in equation (12):

$$\vec{X}(t+1) = \vec{D}'.e^{bl}.\cos(2\pi l) + \vec{X}_b(t) \quad (12)$$

where $\vec{D}' = \left|\vec{X}_b(t) - \vec{X}(t)\right|$ is the distance between i^{th} selected solution and the best one in the current iteration.
The humpback whales swim around the prey with probability (p) of 50% to select between either the shrinking encircling technique and spiral model to modernize their positions which qualified by the following equation [54-55]:

$$\vec{X}(t+1) = \begin{cases} \vec{X}_b(t) - \vec{A}.\vec{D} & if \;\; p < 0.5 \\ \vec{D}'.e^{bl}.\cos(2\pi l) + \vec{X}_b(t) & if \;\; p \ge 0.5 \end{cases} \quad (13)$$

Where
p : Random number between 0 and 1.
l : Random number between -1 and 1.
b : Parameter define the shape of the logarithmic spiral.

- **Search for prey**

In searching for prey instead of using $\vec{X}_b(t)$ a randomly candidate solution $\vec{X}_{rand}(t)$ is picked out by forcing search factors to shift from the reference whale via electing $\left|\vec{A}\right| > 1$ contrary to exploitation phase, exploration phase permits WOA to request a global search using equations (14,15) [55-56].

$$\vec{D} = \left|\vec{C}.\vec{X}_{rand}(t) - \vec{X}(t)\right| \quad (14)$$

$$\vec{X}(t+1) = (\vec{X}_{rand}(t) - \vec{A}.\vec{D}) \quad (15)$$

Where $\vec{X}_{rand}$ is a random position vector from the current population.

4. Differential Evolution

DE was mentioned by Price and Storn in 1995 [57] where mutation, crossover and selection were treated. The fittest offspring takes the place of its parents.

- **Mutation**

  A newly mutant solution vector will be created based on three random solution vectors (X_{r1}, X_{r2} and X_{r3}) and mutation factor (F [0-1]) according to the following equation:

$$\vec{V}_i = \vec{X}_{r1} + F(\vec{X}_{r2} - \vec{X}_{r3}) \quad (16)$$

- **Crossover**

  A newly produced solution vector U_{ij} from crossover between V_i and X_i based on crossover mutation (CR) and a random value (j_{rand} [1,2,…, problem dimension (dim)] according to the following equation:

$$\vec{U}_{ij} = \begin{matrix} \vec{V}_{ij} \\ \vec{X}_{ij} \end{matrix} \begin{cases} rand(0,1) \le CR \;\; or \;\; j = j_{rand} \\ \quad otherwise \end{cases} \quad (17)$$

Where

$rand(0,1)$: Random number between 0 and 1,

- **Selection**

  It's a selection of the fittest solution from original solution X_i and U_i according to the following equation:

$$\vec{U}_i(t+1) = \begin{cases} \vec{U}_i \;\; if \; f(\vec{U}_i) \ge f(\vec{X}_i) \\ \vec{X}_i \;\; if \; f(\vec{X}_i) \ge f(\vec{U}_i) \end{cases} \quad (18)$$

To perfect the exploration ability of WOA, mutation of DE is incorporated into WOA and another parameter called search mode is used to automatically change between exploration and exploitation phase which yields Improved WOA (IWOA).

Improved WOA

IWOA is a hybrid operator that merges encircling prey, search for prey, spiral updating position and mutation. The two main parts of IWOA are the exploration and exploitation part. When $rand < \lambda$ the exploration part changes the individuals. λ is controlled by equation (19) to a small value from 1 to 0.

$$\lambda = 1 - \frac{t}{t_{max}} \quad (19)$$

Where

t_{max} : The greatest number of generations,

In IWOA exploration part, a hyper mutation of DE and search for pray of the WOA while the exploitation part is similar to WOA [58]. For the next generation, the new position for i^th individual is the fittest one among both parents X_i and offspring U_i :

$$X_i(j) \begin{cases} \delta_j + rand(0,1)(\mu_j - \delta_j) \;\; if \;\; X_i(j) < \delta_j \\ \mu_j - rand(0,1)(\mu_j - \delta_j) \;\; if \;\; X_i(j) < \mu_j \end{cases} \quad (20)$$

Where

δ_j and μ_j : The lower and upper bounds of $X_i(j)$ respectively,

The flowchart of IWOA is described in Fig. (1).

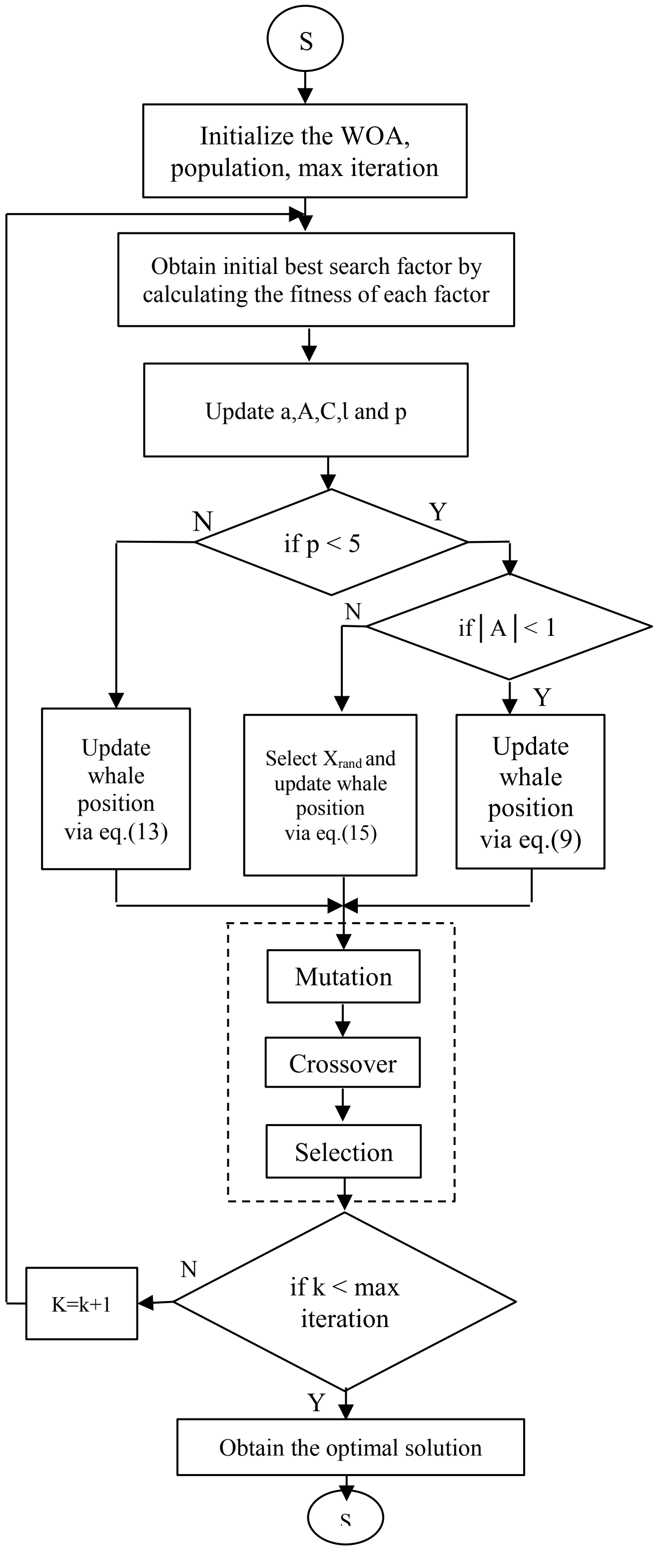

Figure (1) Flowchart of the proposed algorithm.

5. Results and Discussion

To prove the notability of the suggested IWOA, the results of two RDS are addressed below.

5.1 33-Bus distribution system

The 33 bus system [59] that contains thirty seven branches, thirty two normally closed switches and five normally open switches are given in Fig. 2. The premier ties are numbered from thirty three to thirty seven. By closing the premier five ties, five loops are established.

The effectiveness of the IWOA to recognize the best opened switches compared with those shown in [6, 15, 16, 17, 29, 31, 33, 42, 60-64] is demonstrated here. Switches S4, S14, S15, S22, and S33 are elected as an optimal solution by IWOA. Fig. 3, gives the system after restructure. The total active losses are diminished from 202.66 kW to 102.55 kW with active power saving of 100.11 kW. The percentage of minimization in ohmic losses is developed to 49.4%. Also, the total cost is reduced to 53900.2 $ which is the shortest one as obtained in Table 1. The net saving is upgraded to 52617.9 $ that is the greatest one compared with others. Moreover, the smallest voltage is increased to 0.9191 p.u. The improvement of voltage profile is seen in Fig. 4 due to the suggested restructure. Furthermore, the losses, net saving, and total cost using restructure techniques are better than those utilizing the installation of DG or shunt capacitors [65-66] as addressed in Table 2. Finally, the statistical analysis of the suggested IWOA is given in Table 3 to ensure its superiority compared with [23, 67, 68, and 69] in terms of the minimum, mean, standard deviations, number of iterations, and computational time.

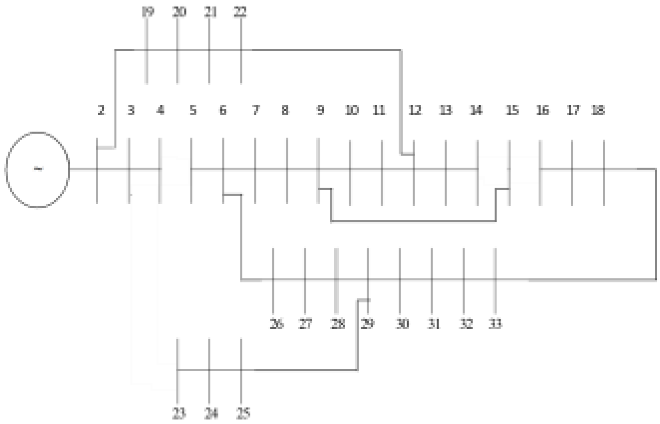

Figure (3) 33 bus system after restructure.

Table (1) Results for the first system using restructure.

Paper	Opened Switches	active losses (kW)	% Reduction	Cost ($)	Saving ($)
Base case	33,34,35,36,37	202.66	-	106518.1	------
[60]	7,10,14, 32, 37	141.54	30.16	74393.424	32124.67
[15]AGA	7, 9, 14, 32, 37	139.55	31.15	73347.48	33170.62
[16]EGA					
[17]IGA					
[61]HA					
[62]RGA					
[63]ACA					
[42]CSA					
[64]SPSO, BPSO	7, 9, 14, 32, 37	138.92	31.45	73016.35	33501.75
[31]GSO	7, 9, 14, 28, 32	139.26	31.28	73195.056	33323.04
[6]FEP	7, 9, 14, 28, 32	139.83	31	73494.65	33023.45
[29]ITS	7, 9, 14, 36, 37	145.11	28.4	76269.82	30248.28
[29]HSA	7, 10, 14, 36, 37	146.39	27.77	76942.58	29575.52
[33]MHBMO	7, 9, 14, 28, 32	134.26	33.75	70567	35951.1
Suggested method	**4, 14, 15, 22, 33**	**102.55**	**49.4**	**53900.2**	**52617.9**

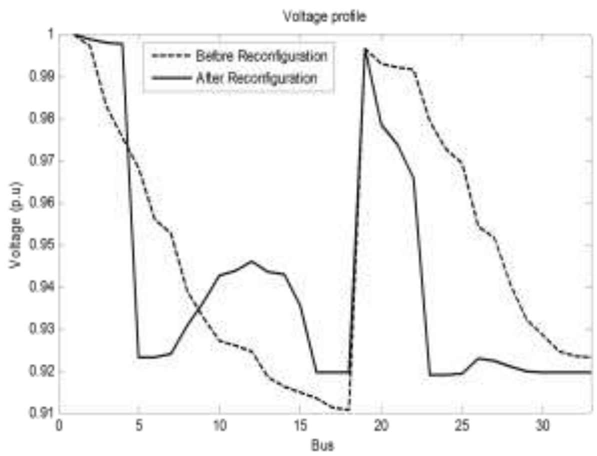

Figure (4) Impact of reconfiguration on voltage profiles for the first system.

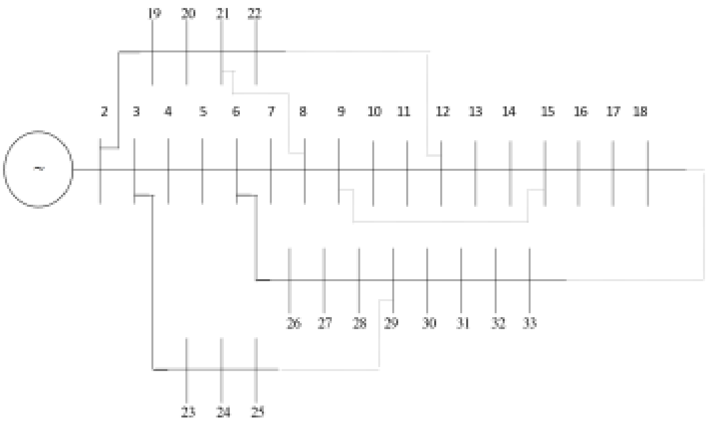

Figure (2) 33 bus system before restructure.

Table (2) Comparison between different methods for first the system.

Paper	Method	Description	Losses (kW)	% Reduction	Cost ($)
Base case	None	33,34,35,36,37	202.66	-	106518.1
[65]FPA	Capacitor placement	Bus 6 with 250 Kvar Bus 9 with 400 Kvar Bus 30 with 950 Kvar	134.47	33.65	70677.43
[66]ALO	DG	One PV system	103.053	49.14	54164.66
Suggested	Restructure	4,14,15,22,33	102.55	49.4	**53900.2**

Table (3) Statistical analysis for the first system.

Paper	Mean kW	SD kW	Min loss kW	Iteration number	Computational time (sec)
[23]	-	-	139.5	-	-
[67]	157.5	68.87	139.55	16	100.225
[68]	170.9	71.94	139.9818	17	106.489
[69]	156	68.52	138.6275	5	31.32
Suggested	112.1	63.13	102.55	5	29.97

5.2 69-Bus distribution system

Fig. 5 gives the 69 bus system [70] that comprises seventy three branches, sixty eight normally closed switches. The premier ties are numbered from sixty nine to seventy three. Five loops are arranged by closing the premier five ties.

The seniority of the IWOA to adjust the optimal opened switches compared with those cleared in [16, 17, 24, 25, 36, 39, 41, 60, 63, 64, and 71] is ensured here. Switches S14, S58, S61, S69, and S70 are selected by IWOA as the best solution. Fig. 6, presents the system after restructure. The total ohmic power losses are diminished from 224.95 kW to 98.5952 kW with active power saving of 126.3548 kW. The percentage of minimization in ohmic losses is 56.17%. Moreover, the value of total cost is 51821.63 $ that is the youngest one as explained in Table 4. The net saving with the suggested IWOA is reduced to 66412.1 $ which is the maximum one compared with others, and the minimum voltage is upgraded to 0.9495 p.u. The improvement of voltage profile is shown in Fig. 7 due to the suggested restructure. Also, the losses, cost, and net saving using restructure technique are better than the installation of shunt capacitors [65, 72-74] as seen in Table 5. Furthermore, the statistical analysis of the suggested IWOA is shown in Table 6 to confirm its effectiveness compared with [67, 68, 69, and 75] in terms of the minimum, mean, standard deviations, number of iterations, and computation time. Finally, Table 7 displays the comparison between the restructured systems, and compensated one for various loadings in terms of cost, and saving.

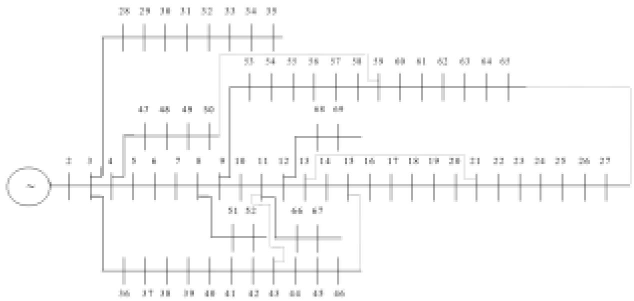

Figure (5) 69 bus system before restructure.

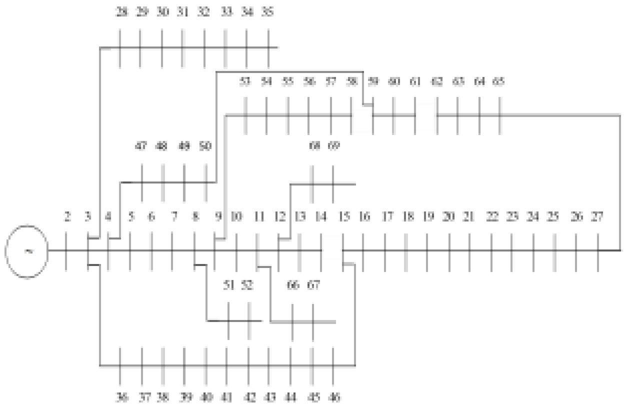

Figure (6) 69 bus system after restructure.

Table (4) Results for second system using restructure.

Paper	Opened Switches	Power losses (kW)	% reduction	Cost ($)	Saving
Base case	69,70,71,72,73	224.95	-	118233.72	--------
[60]	11,14,21,56,62	106.67	52.58	56065.75	62167.97
[71]HA	14,56,62,70,71	99.71	55.67	52407.57	65826.15
[63]ACA	14,55,61,69,70	99.519	55.76	52307.18	65926.54
[39]FWA	14,56,61,69,70	126.36	43.83	66414.82	51818.9
[64]BPSO	13,20,55,61,69	107.05	52.41	56265.48	61968.24
[64]SPSO	14,56,61,69,70	100.6	55.28	52875.36	65358.36
[41]CSA	14,57,61,69,70	126.38	43.82	66425.33	51808.39
[16]EGA	14,59,62,70,71	99.62	55.71	52360.27	65873.45
[25] MCPSO	12,18,58,61,69	103.62	53.93	54462.67	63771.05
[36]ALO	19,58,64,69,70	125.1	44.38	65752.56	52481.16
[24]MPSO	14,55,61,69,70	100.6	55.28	52875.36	65358.36
[17]IGA	10,14,58,63,70	104.91	53.36	55140.69	63093.03
Suggested	14,58,61,69,70	98.5952	56.17	51821.63	66412.1

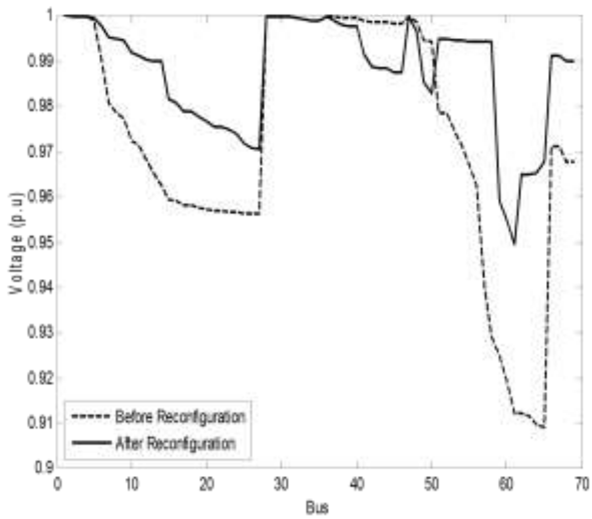

Figure (7) Impact of reconfiguration on voltage profiles for second system.

Table (5) Comparison between various methods for second system.

Paper	Method	Power losses (kW)	% Reduction
Base case	None	224.94	--
[65]FPA	Capacitor placement	150.28	33.2
[72]FPA	Capacitor placement	145.777	35.2
[73]IHA	Capacitor placement	145.3236	35.38
[74]FPA	Capacitor placement	145.14	35.46
Suggested	Restructure	98.5952	56.17

Table (6) Statistical analysis for second system.

Approach	Mean kW	SD kW	Min. loss kW	Iteration number	Computational time (sec)
[75]	-	-	99.59	-	-
[67]	158.3	178.2	98.6174	16	79.1242
[68]	231.3	245.9	99.5997	12	59.3442
[69]	171.5	168.1	98.6	11	54.3979
Suggested	169.4	164.2	98.5952	9	47.8473

Table (7) Effect of different loading on second system.

Loading		Uncompensated	Compensated [73]	Restructure
100 %	Min voltage	0.9092	0.937	0.9495
	Total losses	224.95	145.3236	98.5952
	Cost	118233.72	76382.1	51821.6
	Saving	---	41851.6	66412.1
75%	Min voltage	0.9343	0.949	0.9826
	Total losses	120.8808	82.57	34.5448
	Cost	63534.95	43398.79	18156.75
	Saving	--	20136.16	45378.2
50%	Min voltage	0.9569	0.9652	0.9884
	Total losses	51.5682	35.9451	15.1985
	Cost	27104.25	18892.74	7988.33
	Saving	--	8211.5	19115.9

6. Conclusions

In this article, IWOA has been successfully implemented to handle the restructure problem of RDS. The problem of optimal reconfiguration of RDS has been formulated as an objective optimization task to minimize the active losses. The major contributions of this article can be defined as:

1. IWOA is developed to select the optimal switches combination subject to the system operating constraints.
2. The superiority of IWOA is emphasized through successfully applying on two systems configuration.
3. The ohmic loss with the suggested IWOA is reduced by 49.4% in the first system, while, and the loss is diminished by 56.17% in the second system compared with the original one. Thus, it provides a notable and promising performance over other approaches in terms of active power losses, and net saving.
4. The effectiveness of IWOA for different load conditions is proved.
5. The validity of IWOA than other new approaches is verified through statistical analysis, and computational time, since the number of iterations, and the computational time with the suggested IWOA are smaller, and faster than other reported approaches.

Applications of the network reconfiguration to large system with the most recent approaches, and renewable DG are the future scope of this article.

List of abbreviations

DG	Distributed Generation,
RDS	Radial Distribution System,
IWOA	Improved Whale Optimization Approach,
ANNs	Artificial Neural Networks,
FEP	Fuzzy Evolutionary Programming,
FFW	Fuzzy Frame Work,
SA	Simulated Annealing,
TS	Tabu Search,
GA	Genetic Algorithm,
AGA	Adaptive Genetic Algorithm,
EGA	Enhanced Genetic Algorithm,
IGA	Improved Genetic Algorithm,
ACA	Ant Colony Algorithm,
PSO	Particle Swarm Optimization,
MPSO	Modified Particle Swarm Optimization,
HPSO	Hybrid Particle Swarm Optimization,
MBFA	Modified Bacterial Foraging Algorithm,
RRA	Runner Root Algorithm,
HS	Harmony Search,
GSO	Group Search Optimization,
QFA	Quantum Firefly Algorithm,
MHBMA	Modified Honey Bee Mating Algorithm,
ABC	Artificial Bee Colony,
GSA	Gravitational Search Algorithm,
ALO	Ant Lion Optimizer,
ICA	Imperialist Competitive Algorithm,
HA	Heuristic Algorithm,
FWA	Fireworks Algorithm,
MPGS	Modified Plant Growth Simulation,
CSA	Cuckoo Search Algorithm,
BBO	Biogeography Based Optimization,
GWOA	Grey Wolf Optimization Algorithm,
WOA	Whale Optimization Algorithm,
DE	Differential Evolution,
FPA	Flower Pollination Algorithm,
IHA	Improved Harmony Algorithm,
TLBO	Teaching Learning-Based Optimization Algorithm

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