# Improved Whale Optimization Algorithm for Optimal Network Reconfiguration

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**Abstract**: Recently, minimization of power losses in distribution system is the objective of many researches due to its effect on voltage profiles and total cost. This problem can be handled by optimal reconfiguration of radial distribution system (RDS). Improved Whale Optimization Algorithm IWOA which is inspired from social behavior of humpback whales, is proposed to restructure the RDS by selecting the optimal switches combination subject to the system operating constraints. The proposed algorithm combines exploitation of WOA with exploration of Differential Evolution (DE) and therefore it provides a promising candidate solution. The proposed algorithm is tested on IEEE 33 and 69 bus RDS. The effectiveness of the proposed method comparing with other well-known optimization techniques is proved through simulation results by examining total losses, cost and saving. Also, the effect of variable loading is considered to ensure the superiority of the proposed IWOA.

**Keyword-** Radial Distribution Network; Reconfiguration; IWOA; Power Losses; Minimization.

## 1. Introduction

Minimization of active power losses in RDS is still the aim of many researchers. Installation of capacitors, DG, and reconfiguration of RDS were presented as the three main scenarios to decrease these losses. Reconfiguration of RDS is presented as the most preferable scenario since the costs of installation and operation of capacitors and DG are not included. The reconfiguration process refers to the change of system switches combination and adjustment the structure of network operation by closing or opening the disconnected sectional and tie switches with satisfied constraint [1-4]. These switches control status of feeders and have a vital effect on branch power flows and total power losses.

Since the cost of active power losses occupies abundant value of operating cost in RDS, and therefore many papers have objective function of active power loss. ANNs [5], FEP [6], FFW [7], FF [8], SA [9-11], TS [12], GA [13-14], AGA [7,15], EGA [16], IGA [17], ACA [18-19], PSO [20-22], MPSO [23-24], HPSO [25-26], MBFA [27], RRA [28], HS [29], GSO [30], QFA [31], MHBMA [32], ABC [33], GSA [34], ALO [35], ICA [36], HA [37], FWA [38], MPGS [39], CSA [40], BBO [41] and GWOA [42] are developed to discuss the reconfiguration problem. To overcome the drawbacks of the previous algorithms, Improved Whale optimization algorithm (IWOA) is introduced to solve the problem of reconfiguration in RDS with an objective function to decrease the total losses by optimal selecting of switches combination to restructure the RDS. Moreover, the notability of the proposed IWOA is confirmed through variable loading conditions.

## 2. General problem formulation

Line losses minimization during operation is the objective function used for RDS reconfiguration problem and it could be described as:

$$P_{Loss} = \sum_{m=1}^{N_b} I_m^2 R_m \tag{1}$$

The annual cost due to power losses can be calculated from the following equation:

$$\text{Annual cost} = K_P * T * P_{Loss} \tag{2}$$

There are many constraints must be considered during operation. These constraints are as:

- **Load flow constraint**

The equality constraint is given by equations (3,4) :

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

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

- **Radiality constraint**

It assures that no closed loops are included through the network, and therefore the number of branches can be specified by equation (5):

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

- **Feasibility constraint**

It means that no loads are isolated during reconfiguration task.

- **Voltage constraint**

The magnitude of voltage at each bus must be limited by equation (6) and taken as 0.90 and 1.0 p.u respectively.

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

- **Current constraint**

Equation (7) gives the magnitude of branch current.

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

## 3. Whale Optimization Algorithm

Humpback whales are brilliant mammals. Their hunting behavior has three steps: encircling prey, spiral bubble-net feeding technique and search for prey. These steps are discussed as following: [43-46]

- Encircling Prey:

Humpback whales detect the prey location as an initial position $\vec{X}(t)$ and encircle them. Since the optimal location is not known, the WOA assumes that the current selected solution is the optimum. After the best search factor is known, the other search factors will update their positions according to equations (8,9) [47-48].

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

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

Where $\vec{X}_b(t)$ should be updated in each iteration. $\vec{A}$ and $\vec{C}$ are calculated as equations (10,11) [49]:

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

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

- Spiral Bubble-net feeding technique

There are two techniques:

a) Shrinking encircling technique

It's attained by decreasing the range 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 [50-51].

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 $\vec{D}' = |\vec{X}_b(t) - \vec{X}(t)|$ is the distance between $i^{th}$ selected solution and the best one in the current iteration. $b$ defines the shape of the logarithmic spiral, and $l$ is a random number in the range $[-1,1]$.

The humpback whales swim around the prey with probability (p) of 50% to select between either the shrinking encircling technique and spiral model to update their positions which described by the following equation as in [52-53]:

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

- Search for prey

In searching for prey instead of using $\vec{X}_b(t)$ a randomly candidate solution $\vec{X}_{rand}(t)$ is selected by forcing search factor to move from the reference whale via selecting $|\vec{A}| > 1$ contrary to exploitation phase, exploration phase allows WOA to apply a global search using equations (14,15) [53-54)].

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

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

Where $\vec{X}_{rand}$ is a random position vector from the current population. The flow chart of WOA is described in Fig. (1).

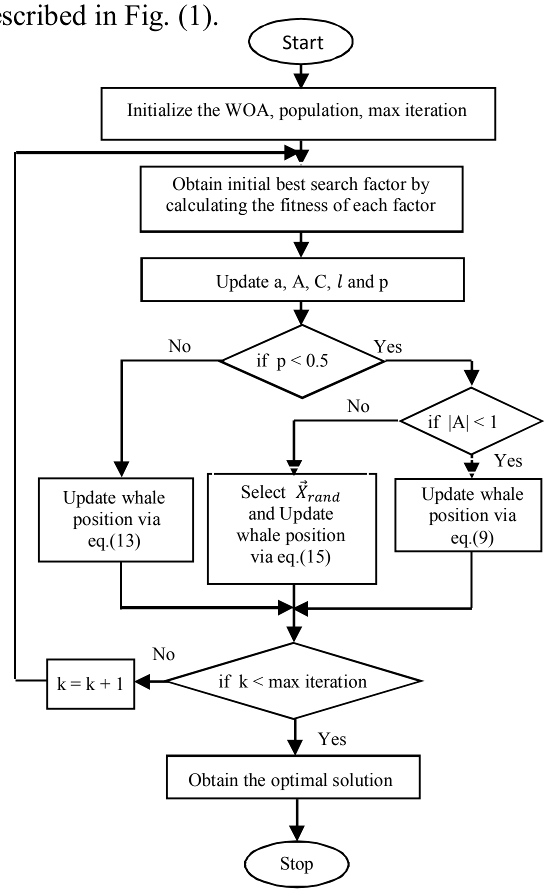


Figure (1) Flow chart of whale optimization algorithm.

## 4. Differential Evolution

DE was introduced by Storn and Price in 1995 [Brest (2006)] where mutation and crossover were considered. The fittest offspring takes a place of its parents. To improve the exploration ability of WOA, mutation of DE is integrated into WOA and another parameter that called search mode is used to automatic change between exploration and exploitation phase which yield to Improved WOA.

### Improved WOA

IWOA is a hybrid operator that combines 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. $\lambda$ is adjusted by equation (16) to a small value from 1 to 0.

$$\lambda = 1 - \frac{t}{t_{max}} \quad (16)$$

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

$$X_i(j) = \begin{cases} \delta_j + rand(0,1)(\mu_j - \delta_j) & if \;\; X_i(j) < \delta_j \\ \mu_j - rand(0,1)(\mu_j - \delta_j) & if \;\; X_i(j) < \mu_j \end{cases} \quad (17)$$

## 5. Results and Discussion

The effectiveness of the IWOA is applied on two RDS. The results of 33 bus and 69 bus RDS are discussed below.

### 5.1 33-Bus test distribution system

Fig. 2 shows the 33 bus system in [56] that consists of thirty seven branches, thirty two normally closed switches and five normally open switches. The initial ties are from thirty three to thirty seven. Five loops are formed by closing the initial five ties.

The superiority of the IWOA to decide the best opened switches compared with those obtained in [6, 15, 16, 17, 29, 32, 57-61] is verified here. IWOA selects switches S4, S14, S15, S22 and S33 as an optimal solution. Fig. 3 shows the system after reconfiguration. The total power losses are minimized from 202.66kW to 102.55kW with power saving of 100.11kW. The percentage of reduction in losses is increased to be 49.4%. Moreover, the value of total cost is 53900.2$ which is the smallest one as shown in Table 1. Also, the net saving is enhanced to 52617.9$ that is the maximum one compared with the others. Also, the minimum voltage has been increased to 0.9191p.u. The enhancement of voltage profile is cleared in Fig. 4 due to the proposed reconfiguration. Moreover, the losses, cost and saving using reconfiguration methodology are better than those using the installation of capacitors and DG [62-63] as in Table 2.

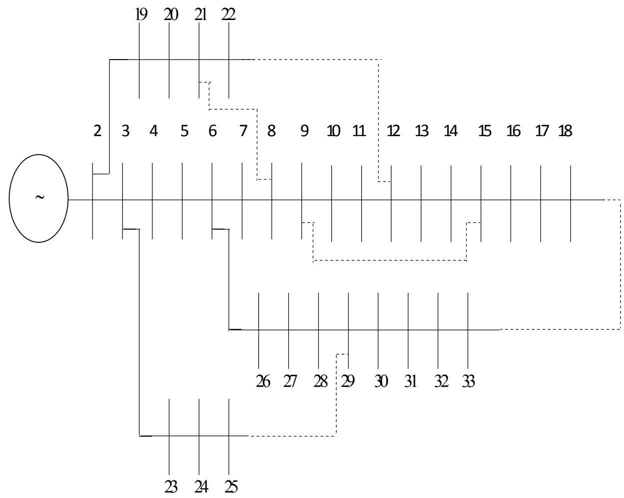


Figure (2) 33 bus system before reconfiguration.

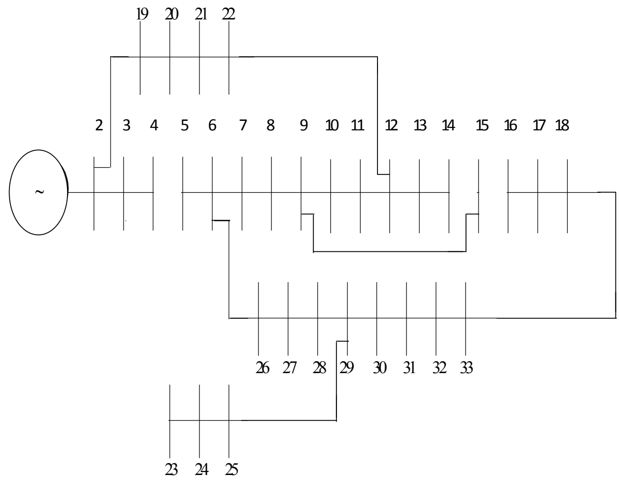


Figure (3) 33 bus system after reconfiguration.

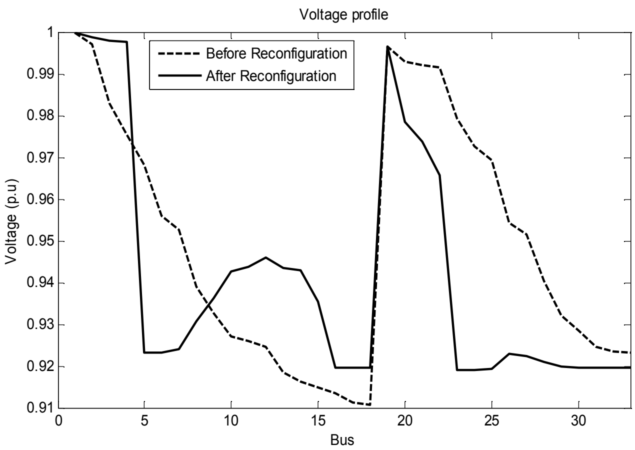


Figure (4) Effect of reconfiguration on voltage profiles for 33 bus system.

### 5.2 69-Bus test distribution system

Fig. 5 shows the 69 system as in [64] that consists of seventy three branches, sixty eight normally closed switches. The initial ties are from sixty nine to seventy three. Five loops are formed by closing the initial five ties.

The notability of the IWOA to detect the optimal opened switches compared with those given in [[16, 17, 24, 25, 35, 38, 40, 57, 60, 61, 65] is confirmed here. IWOA selects switches S14, S58, S61, S69 and S70 as the best solution. Fig. 6 shows the system after reconfiguration. The total power losses are minimized from 224.95kW to 98.5952kW with power saving of 126.3548kW. The percentage of reduction in losses is increased to be 56.17%. Moreover, the value of total cost is 51821.63$ that

Table (1) Results for 33 bus system using reconfiguration.

| **Paper** | **Year** | **Opened Switches** | **Power losses (kW)** | **% Reduction** | **Cost ($)** | **Saving ($)** |
|---|---|---|---|---|---|---|
| **Base case** | | 33,34,35,36,37 | 202.66 | - | 106518.1 | -------- |
| **[57]** | 1989 | 7,10,14, 32, 37 | 141.54 | 30.16 | 74393.424 | 32124.67 |
| **[15] AGA** | 2010 | 7, 9, 14, 32, 37 | 139.55 | 31.15 | 73347.48 | 33170.62 |
| **[16] EGA** | 2015 | | | | | |
| **[17] IGA** | 2019 | | | | | |
| **[58] HA** | 2008 | | | | | |
| **[59] RGA** | 2002 | | | | | |
| **[60] ACA** | 2008 | | | | | |
| **[6] FEP** | 2003 | 7, 9, 14, 28, 32 | 139.83 | 31 | 73494.65 | 33023.45 |
| **[29] ITS** | 2011 | 7, 9, 14, 36, 37 | 145.11 | 28.4 | 76269.82 | 30248.28 |
| **[29] HSA** | 2011 | 7, 10, 14, 36, 37 | 146.39 | 27.77 | 76942.58 | 29575.52 |
| **[32] MHBMO** | 2012 | 7, 9, 14, 28, 32 | 134.26 | 33.75 | 70567 | 35951.1 |
| **[61] SPSO, BPSO** | 2014 | 7, 9, 14, 32, 37 | 138.92 | 31.45 | 73016.35 | 33501.75 |
| **Proposed method** | **--** | **4, 14, 15, 22, 33** | **102.55** | **49.4** | **53900.2** | **52617.9** |

Table (2) Comparison between various methods of power losses reduction for 33 bus system.

| Paper | Method | Description | Losses (kW) | % Reduction | Cost ($) |
|---|---|---|---|---|---|
| Base case | None | 33,34,35,36,37 | 202.66 | - | 106518.1 |
| [62] FPA | Capacitor placement | Bus 6 with 250 Kvar<br>Bus 9 with 400 Kvar<br>Bus 30 with 950 Kvar | 134.47 | 33.65 | 70677.43 |
| [63] ALO | DG | One PV system | 103.053 | 49.14 | 54164.66 |
| **Proposed** | **Reconfiguration** | **4,14,15,22,33** | **102.55** | **49.4** | **53900.2** |

is the smallest one as shown in Table 3. Also, the net saving with the IWOA is enhanced to 66412.1$ which is the maximum one compared with the others. Also, the minimum voltage has been increased to 0.9495p.u. The enhancement of voltage profile is cleared in Fig. 7 due to the proposed reconfiguration. Moreover, the losses, cost and net saving using reconfiguration methodology are better than the installation of capacitors in [62, 66-68] as seen in Table 4. In addition, Table (5) introduces the comparison between the reconfigured system and compensated one for various loadings in terms of cost and saving.

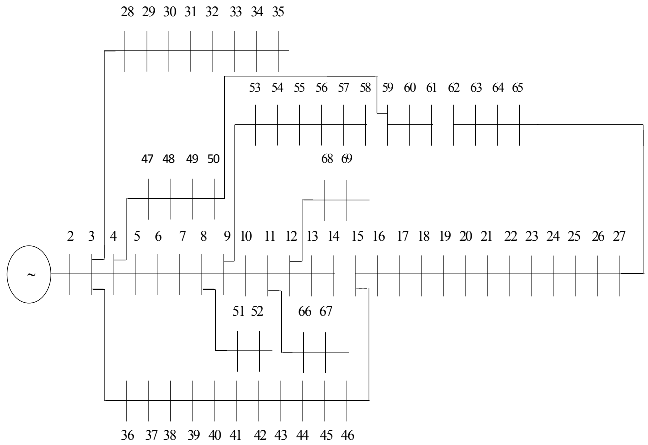


Figure (6) 69 bus system after reconfiguration.

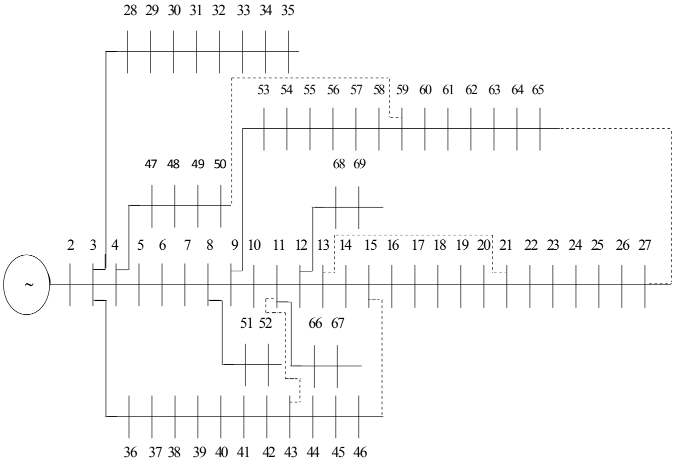


Figure (5) 69 bus system before reconfiguration.

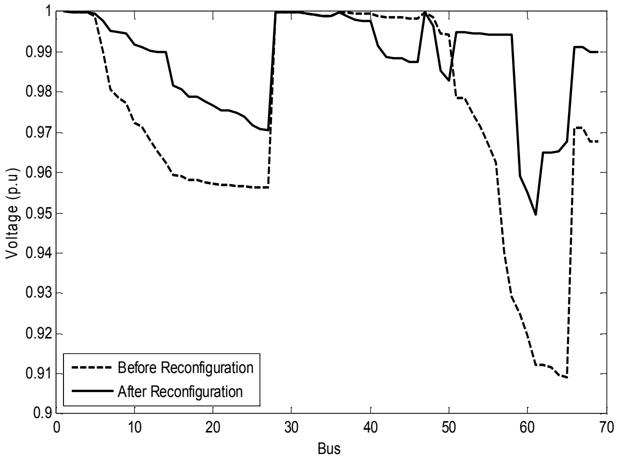


Figure (7) Effect of reconfiguration on voltage profiles for 69 bus system.

Table (3) Results for 69 bus system using reconfiguration.

| Paper | Year | Opened Switches | Power losses(kW) | % reduction | Cost ($) | Saving |
|---|---|---|---|---|---|---|
| **Base case** | | 69,70,71,72,73 | 224.95 | - | 118233.72 | -------- |
| **[57]** | 1989 | 11,14,21,56,62 | 106.67 | 52.58 | 56065.75 | 62167.97 |
| **[65] HA** | 2005 | 14,56,62,70,71 | 99.71 | 55.67 | 52407.57 | 65826.15 |
| **[60] ACA** | 2008 | 14,55,61,69,70 | 99.519 | 55.76 | 52307.18 | 65926.54 |
| **[38] FWA** | 2014 | 14,56,61,69,70 | 126.36 | 43.83 | 66414.82 | 51818.9 |
| **[61] BPSO** | 2014 | 13,20,55,61,69 | 107.05 | 52.41 | 56265.48 | 61968.24 |
| **[61] SPSO** | 2014 | 14,56,61,69,70 | 100.6 | 55.28 | 52875.36 | 65358.36 |
| **[40] CSA** | 2015 | 14,57,61,69,70 | 126.38 | 43.82 | 66425.33 | 51808.39 |
| **[16] EGA** | 2015 | 14,59,62,70,71 | 99.62 | 55.71 | 52360.27 | 65873.45 |
| **[25] MCPSO** | 2016 | 12,18,58,61,69 | 103.62 | 53.93 | 54462.67 | 63771.05 |
| **[35] ALO** | 2017 | 19,58,64,69,70 | 125.1 | 44.38 | 65752.56 | 52481.16 |
| **[24] MPSO** | 2017 | 14,55,61,69,70 | 100.6 | 55.28 | 52875.36 | 65358.36 |
| **[17] IGA** | 2019 | 10,14,58,63,70 | 104.91 | 53.36 | 55140.69 | 63093.03 |
| **Proposed** | **---** | **14,58,61,69,70** | **98.5952** | **56.17** | **51821.63** | **66412.1** |

Table (4) Comparison between various methods of power losses reduction for 69 bus system.

| Paper | Algorithm | Method | Power losses (kW) | % reduction |
|---|---|---|---|---|
| **Base case** | -- | None | 224.94 | -- |
| [66] | FPA | Capacitor placement | 145.777 | 35.2 |
| [68] | FPA | Capacitor placement | 145.14 | 35.46 |
| [62] | FPA | Capacitor placement | 150.28 | 33.2 |
| [67] | IHA | Capacitor placement | 145.3236 | 35.38 |
| **Proposed** | IWOA | **Reconfi_guration** | **98.5952** | **56.17** |

## 6. Conclusions

In this paper, a new algorithm for reconfiguration of RDS for real power loss minimization is presented. The problem of optimal reconfiguration in RDS has been established as an objective optimization task. The superiority of the IWOA is clarified by using two RDS. Moreover, the results have been compared with those obtained using HA, RGA, EGA, AGA, IGA, FEP, SPSO, BPSO, PGSA, CSA, FPA, IHA and ALO techniques. Also, it provides a preferable performance over others in terms of active power losses, total cost, and saving for different loadings. Applications of the network reconfiguration to large system with the most recent algorithm are the future scope of this work.

Table (5) Effect of variable loading on 69 bus system.

| Loading | | Uncompensated | Compensated [ 67] | **Reconfiguration (proposed)** |
|---|---|---|---|---|
| 100% | Min voltage | 0.9092 | 0.937 | **0.9495** |
| | Total real 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 real 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 real losses | 51.5682 | 35.9451 | **15.1985** |
| | Cost | 27104.25 | 18892.74 | **7988.33** |
| | Saving | -- | 8211.5 | **19115.9** |

**Conflict of interest**

The authors declare no conflict of interest.

**Nomenclature**

| | |
|---|---|
| $m$ | The branch number |
| $N_b$ | The total number of branches |
| $I_m$ | The current at branch $m$ |
| $R_m$ | The resistance at branch $m$ |
| $K_P$ | The cost per kW-Hours and equals to 0.06 $/kW-Hours |
| $P_{Loss}$ | The total active losses in kW |
| $T$ | The time in Hours and equals to 8760 |
| $V_{\min}, V_{\max}$ | The minimum and maximum voltages at bus $i$ |
| $I_{j\max}$ | The maximum allowed current in each branch |
| $P_{Swing}$ | The active power of swing bus |
| $Q_{Swing}$ | The reactive power of swing bus |
| $X_m$ | The reactance at branch $m$ |
| $Pd(q)$ | The demand of active power at bus $q$ |
| $Qd(q)$ | The demand of reactive power at bus $q$ |
| $N$ | The number of total buses, |
| $t$ | The current generation |
| $t_{max}$ | The maximum number of generations |
| $\delta_j$ and $\mu_j$ | The lower and upper bounds of $X_i(j)$ respectively |

| | |
|---|---|
| $\vec{X}_b(t)$ | The best selected solution so far |
| $\vec{a}$ | Decreased linearly from 2 to 0 |
| $\vec{r}$ | Random vector in range [0, 1] |
| $rand(0,1)$ | Random number between 0 and 1 |
| p | Random number between 0 and 1 |

**List of abbreviations**

| | |
|---|---|
| DG | Distributed Generation |
| RDS | Radial Distribution System |
| IWOA | Improved Whale Optimization Algorithm |
| 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 |

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