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Optimal Network Reconfiguration via. Improved Whale Optimization Algorithm

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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.

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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 by Das[1], Dolatdar[2], Tang[3] and Kumar[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, 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.

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 form the following Eq. 2:

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

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

Load flow constraint: The equality constraint is given by Eq. 3 and 4 :

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

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

Radiality constraint: It assures that no closed loops are included through the network and therefore the number of branches can be specified by Eq. 5:

$$N_b = N\text{-}1 \tag{5}$$

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 Eq. 6 and taken as 0.90 and 1.0 p.u, respectively:

$$V_{min} \leq |V_i| \leq V_{max} \tag{6}$$

Current constraint: Equation 7 gives the magnitude of branch current:

$$I_j < I_{j\,max} \tag{7}$$

MATERIALS AND METHODS

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 by Mirjalili[43], Kaur[44], Ling[45] and Sun[46] as following.

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 Eq. 8 and 9[47, 48]:

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

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

Where:

$\vec{X}_b(t)$ = Should be updated in each iteration

$\vec{A}$ and $\vec{C}$ = Are calculated as Eq. 10 and 11[49]

$$\vec{A} = |2\vec{a}.\vec{r} - \vec{a}| \tag{10}$$

$$\vec{C} = 2.\vec{r} \tag{11}$$

Spiral bubble-net feeding technique: There are two technique.

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 Aljarah[50] and Abd El Aziz[51].

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

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

Where $\vec{D} = |\vec{X}_b(t) - \vec{X}(t)|$ is the distance between ith 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 by Medani *et al*.[52] and Yu *et al*.[53]:

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

Search for prey: In searching for prey instead of using $\vec{X}_b(t)$ a randomly candidate solution $\vec{X}_{rand}(t)$ is

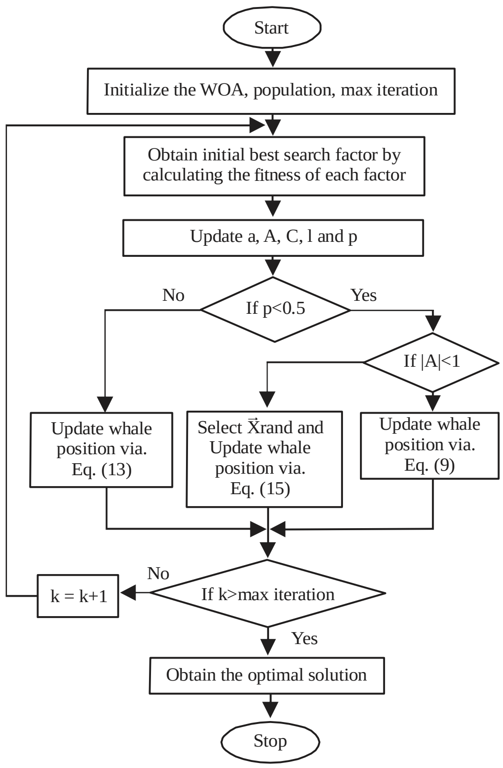

Fig. 1: Flow chart of whale optimization

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 Eq. 14 and 15[53, 54]:

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

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

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

Differential evolution: DE was introduced by Storn and Price in 1995[55] 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 m ain parts of IWOA are the exploration and exploitation part. When rand <h the e xploration part changes the individuals. h is adjusted by Eq. 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 ith individual is the fittest one among both parents Xi and offspring U_i:

$$X_i(j) = -\left[\begin{array}{ll}\delta_j + rand(0,1)(\mu_j-\delta_j) & \text{if } X_i(j)<\delta_j \\ \mu_j-rand(0,1)(\mu_j-\delta_j) & \text{if} X_i(j)<\mu_j\end{array}\right. \quad (17)$$

RESULTS AND DISCUSSION

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

Bus test distribution system: Figure 2 shows the 33 bus system by Das *et al*.[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 by Venkatesh and Ranjan[6], Swarnkar *et al*.[15], Duan[16], Abubakar *et al*.[17], Rao *et al*.[29], Olamaei *et al*.[32], Shirmohammadi and Hong[57], Martin and Gil[58], Zhu[59], Ghorbani *et al*.[60] and Tandon and Saxena[61] is verified here. IWOA selects switches S4, S14, S15, S22 and S33 as an optimal solution. Figure 3 shows the system after reconfiguration. The total power losses are minimized from 202.66-102.55 kW 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.

Bus test distribution system: Figure 5 shows the 69 system as by Baran and Wu[64] that consists of seventy three branches, sixty eight normally closed switches. The initial ties are from 69-73. 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 by

Table 1: Results for 33 bus system using reconfiguration

Study	Algorithm	Opened switches	Power losses (kW)	Reduction (%)	Cost ($)	Saving ($)
Base case	-	33, 34, 35, 36, 37	202.66	-	106518.1	-
Shirmohammadi and Hong[57]	-	7, 10, 14, 32, 37	141.54	30.16	74393.424	32124.67
Swarnkar *et al*.[15]	AGA	7, 9, 14, 32, 37	139.55	31.15	73347.48	33170.62
Duan *et al*.[16]	EGA					
Abubakar *et al*.[17]	IGA					
Martín and Gil[58]	HA					
Zhu[59]	RGA					
Ghorbani *et al*.[60]	ACA					
Venkatesh and Ranjan[6]	FEP	7, 9, 14, 28, 32	139.83	31	73494.65	33023.45
Rao *et al*.[29]	ITS	7, 9, 14, 36, 37	145.11	28.4	76269.82	30248.28
Rao *et al*.[296]	HSA	7, 10, 14, 36, 37	146.39	27.77	76942.58	29575.52
Olamaei *et al*.[32]	MHBMO	7, 9, 14, 28, 32	134.26	33.75	70567	35951.10
Tandon and Saxena[61]	SPSO					
	BPSO	7, 9, 14, 32, 37	138.92	31.45	73016.35	33501.75
Proposed method	IWOA	4, 14, 15, 22, 33	102.55	49.4	53900.2	52617.90

Table 2: comparison between various methods of power losses reduction for 33 bus system

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

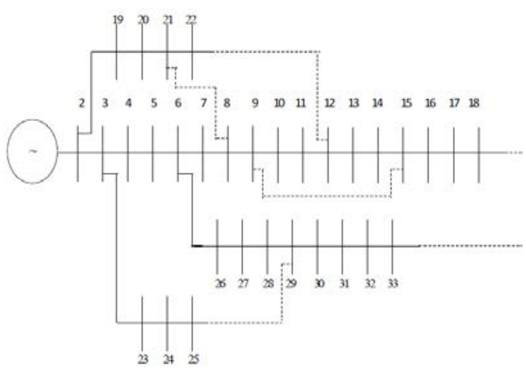

Fig. 2: The 33 bus system before reconfiguration

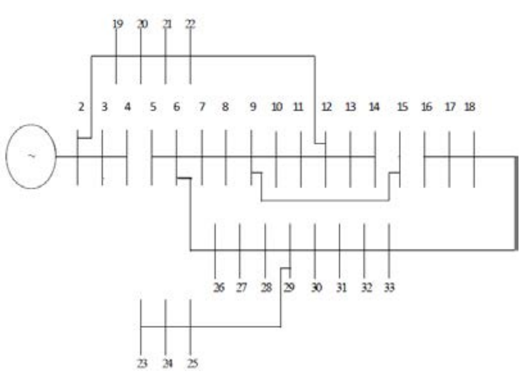

Fig. 3: The 33 bus system after reconfiguration

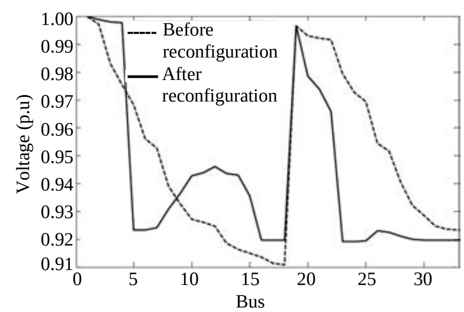

Fig. 4: Effect of reconfiguration on voltage profiles for 33 bus system

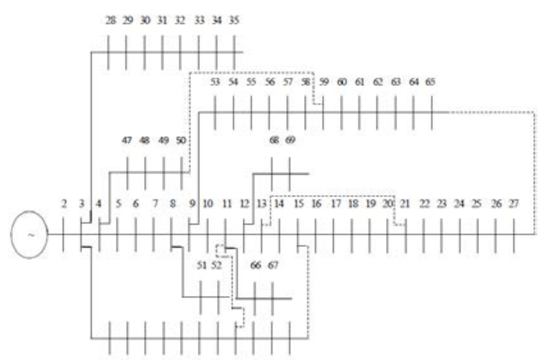

Fig. 5: The 69 bus system before reconfiguration

Duan *et al*.[16], Abubakar *et al*.[17], Atteya *et al*.[29], Jena and Chauhan[25], Zainal *et al*.[35], Imran and Kowsalya[38], Nguyen and Truong[40], Shirmohammadi and Hong[57], Ghorbani *et al*.[60], Tandon and Saxena[61] and Gomes et al.[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 224.95-98.5952 kW with

Table 3: Results for 69 bus system using reconfiguration

Study	Algorithm	Opened switches	Power losses (kW)	Reduction (%)	Cost ($)	Saving
Base case	-	69, 70, 71, 72, 73	224.95	-	118233.72	-
Shirmohammadi and Hong[57]	-	11, 14, 21, 56, 62	106.67	52.58	56065.75	62167.97
Gomes *et al*.[65]	HA	14, 56, 62, 70, 71	99.71	55.67	52407.57	65826.15
Ghorbani *et al*.[60]	ACA	14, 55, 61, 69, 70	99.519	55.76	52307.18	65926.54
Imran and Kowsalya[38]	FWA	14, 56, 61, 69, 70	126.36	43.83	66414.82	51818.9
Tandon and Saxena[61]	BPSO	13, 20, 55, 61, 69	107.05	52.41	56265.48	61968.24
Tandon and Saxena[61]	SPSO	14, 56, 61, 69, 70	100.6	55.28	52875.36	65358.36
Nguyen and Truong[40]	CSA	14, 57, 61, 69, 70	126.38	43.82	66425.33	51808.39
Duan *et al*.[16]	EGA	14, 59, 62, 70, 71	99.62	55.71	52360.27	65873.45
Jena and Chauhan[25]	MCPSO	12, 18, 58, 61, 69	103.62	53.93	54462.67	63771.05
Zainal *et al*.[35]	ALO	19, 58, 64, 69, 70	125.1	44.38	65752.56	52481.16
Atteya *et al*.[24]	MPSO	14, 55, 61, 69, 70	100.6	55.28	52875.36	65358.36
Abubakar *et al*.[17]	IGA	10, 14, 58, 63, 70	104.91	53.36	55140.69	63093.03
Proposed	IWOA	14, 58, 61, 69, 70	98.5952	56.17	51821.63	66412.1

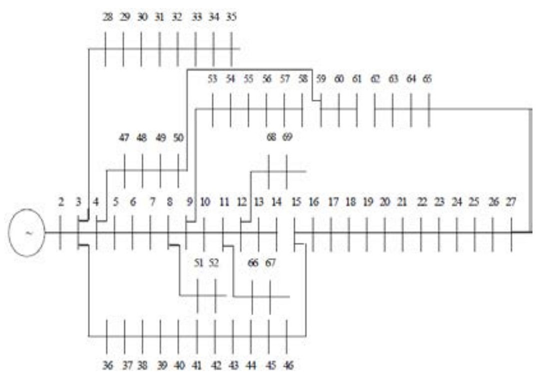

Fig. 6: The 69 bus system after reconfiguration

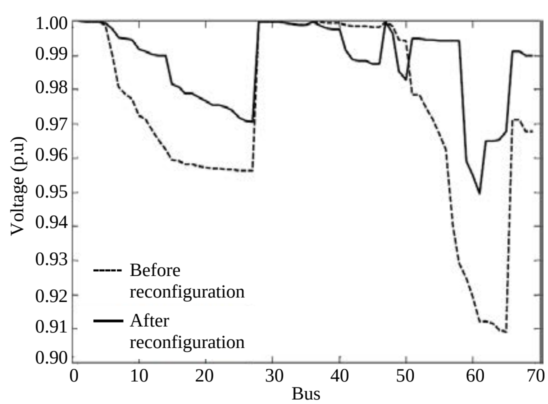

Fig. 7: Effect of reconfiguration on voltage profiles for 69 bus system.

power saving of 126.3548 kW. The percentage of reduction in losses is increased to be 56.17%. Moreover, the value of total cost is 51821.63$ that 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 0.9495 p.u. The enhancement of voltage profile is cleared in Fig. 7 due to the proposed

Table 4: Comparison between various methods of power losses reduction for 69 bus system

Study	Algorithm	Method	Power losses (kW)	Reduction (%)
Base case	-	None	224.94	-
Abdelaziz *et al*.[66]		Capacitor placement	145.777	35.2
Abdelaziz *et al*.[67]	FPA	Capacitor placement	145.14	35.46
Abdelaziz *et al*.[62]		Capacitor placement	150.28	33.2
Ali *et al*.[62]	IHA	Capacitor placement	145.3236	35.38
Proposed	IWOA	Reconfi_guration	98.5952	56.17

Table 5: Effect of variable loading on 69 bus system

Loading	Uncompensated	Compensated Ali *et al*.[63, 68]	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

reconfiguration. Moreover, the losses, cost and net saving using reconfiguration methodology are better than the installation of capacitors by Abdelaziz[62, 66, 67] and Ali *et al*.[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.

CONCLUSION

In this study, 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.

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
Pswing	=	The active power of swing bus
Qswing	=	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
δ_j andμ_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

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