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Solution of the capacitor allocation problem using an improved whale optimization algorithm

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Abstract

A superior optimization technique called whale optimization algorithm introduced in 2016 which belongs to swarm intelligence family is used and implemented in this paper with some improvements to solve the problem of capacitor allocation in radial distribution feeders. In order to show the effectiveness of the proposed technique, three test distribution feeders are used (15 bus, 34 bus and 69 bus test systems). The obtained results are compared with other optimization techniques prove that the proposed method gives the optimal results; most reduction in system power losses, voltage profile enhancement and lower annual cost among the other techniques applied to the same distribution feeders.

Keywords: Capacitor allocation, modified whale optimization technique, loss reduction, cost saving.

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1. Introduction

The distribution power network has many problems that researchers are trying to find solutions to overcome them. These problems include low power factor, power quality problems as voltage sag, high voltage drop, power flow control issues and high power losses of transmission. Some studies indicated that as much as 13% of total power generated in the electrical system is consumed as I^2R losses in distribution level (Ng *et al.,* 2000). The reactive power compensation represents a good solution for the previously mentioned problems where one of the reactive power compensation methods include the optimal location, type and sizing of shunt capacitors which is essential to improve the distribution power network evaluation factors such voltage profile, feeder power losses, system stability, power flow control and releasing KVA capacity of distribution equipment. There are four solution techniques in order to optimally allocate the capacitors (Ng *et al.*, 2000) which are: heuristic, numerical programming, analytical and artificial intelligence (AI). Many AI based methods have been attempted to optimally locate and size the capacitor banks which include the population based optimization methods inspired from nature which proved superiority in this field. A branch of artificial intelligence methods is the swarm intelligence which inspired the rise of the whale optimization technique.

Parsopoulos *et al*. (2002) states the principles of swarm intelligence which are: Adaptability, Diverse response, Proximity, Quality and Stability. Some examples of the nature inspired algorithms include: cuckoo search, particle swarm optimization, firefly algorithms, shark smell optimization, artificial bee colony, flower pollination algorithm, ant colony optimization, ant lion optimization, harmony search optimization and plant growth optimization. Its worth mentioning that the previously mentioned algorithms could be modified or used with other techniques as loss sensitivity factors or other optimization techniques as hybrid methods in the process of optimal location and sizing of capacitors in radial distribution feeders. Baysal *et al*. (2016) uses the traditional cuckoo search algorithm to minimize the power losses in the system and maximize annual net saving. To validate the method, it is applied to a 9 bus feeder system to show the technique merits. The disadvantage in this study is that it only studied one distribution feeder system which can't lead to general results. Alia *et al*. (2016) proposes an improved harmony algorithm for the optimal allocation of capacitors in 85 bus radial distribution system using loss sensitivity factor to determine the best buses where the capacitors would be installed to decrease the power losses and maximize the net saving. The demerit in this study is that the total losses in kW are higher than some other older techniques implemented on the same radial feeder as direct search algorithm in (Raju *et al*., 2012).

Mandal *et al*. (2016) solves the issue of optimal location for the sized capacitors placed in 9 bus distribution feeder using modified black hole particle swarm optimization. The method seems to be promising but to ensure the effectiveness of the proposed technique it should have been tested on one or more larger radial distribution test feeders. Gnanasekaran *et al*. (2016) proposes shark smell optimization technique for the optimal allocation of the capacitors in radial distribution feeder, the technique is verified by testing it on 118 bus system which showed its improved results regarding total power loss and total cost compared to some other methods, however the total installed KVAr of the capacitors is much higher compared to some other methods such as artificial bee colony (ABC) used in El-Fergany *et al*. (2014). Devabalaji *et al.,* 2016) the authors used hybrid method in which the voltage stability index determines the best locations for the installed capacitors and the sizes of capacitors are determined using cuckoo search algorithm, Unlike Baysal *et al.* (2016) where the cuckoo search was used to determine the optimal location and sizes of capacitors installed on radial distribution feeder, the method is implemented on 34 bus test feeder. The net saving seems to be promising compared to other techniques but the total kVAR of the installed capacitors is much higher than other previously implemented methods as particle swarm optimization (PSO) and plant growth simulation algorithm (PGS) (Prakash *et al.*, 2007; Rao *et al.,* 2011), while the minimum bus voltage in per unit. is lower than other techniques as heuristic method and mixed integer non-linear programming approach, (Chis *et al.,* 1997; Sayyad *et al*., 2014). Gholinezhad *et al.* (2017) proposes another hybrid method for solving the optimal allocation of capacitors. In the study, the power loss index is used to find the optimal number of capacitors location and the candidate buses while the particle swarm optimization (PSO) is used to find the appropriate locations and sizes of capacitors. The proposed technique is applied on 34 bus system. The pros of this method is its low computational time compared to other techniques while the cons is that other methods such as cuckoo search algorithm (CSA) leads to higher power loss reduction percentage.

In this study, a review and implement of improved whale optimization algorithm (IWOA) applied to three test radial distribution feeders. This method is intended to find the most approximate solutions to the hard problems it would be assigned to solve. It is set of well-known steps that ensure finding the global optimal solution. This new proposed technique has the capability to give the best results concerning maximum power loss reduction in system, and net saving with voltage profile enhancement without violating the problem constraints as voltage constraints, capacitor sizing constraint and over compensation constraint. The novelty factor in this study could be noticed in the algorithm itself, as the modifications applied to the traditional algorithm is implemented for the first time as a solution of the capacitor allocation problem which makes the study differs from other similar works.

The rest of the paper is divided as follows: Section 2 describes the whale optimization algorithm and the modifications introduced to it to be modified and enhanced. Also, the solution algorithm to implement the improved whale optimization algorithm to the problem of optimal allocation and sizing of capacitor banks in radial distribution feeder is explained in detail. Section 3 presents the implementation and computer based program simulation results compared to other optimization techniques .Finally Section 4 includes the conclusions.

2. Problem Formulation

2.1 Basic Concept of Whale Optimization Algorithm

2.1.1 Encircling the Prey

It is well known that the whales live in the seas and oceans around the world and they are intelligent creatures. Whales breathe from the surface of water. Mirjalili *et al*. (2016) states that some whales feed on other sea creatures as fishes. One of the species of whales is humpback whales which is large animal characterized by their unique technique of hunting which is called bubble net feeding method. Its favourite meal is a group of small fishes or group of krill close to the water surface. Figure1 presents the foraging behaviour of humpback whale in a nine shaped path.

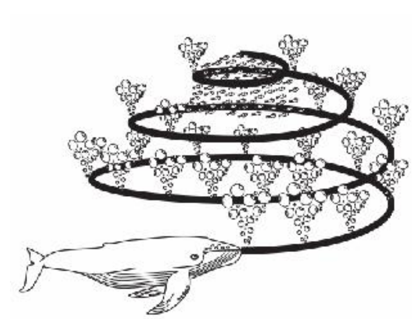

Figure 1. Bubble-net feeding behavior of humpback whales

Goldbogen *et al*. (2013) studied this behaviour using tag sensors. They discovered that the whale dive 12 m down and then start to create bubble around the group of krill or small fishes (the prey) and swim up toward water surface. The whale optimization algorithm is inspired from the nature of humpback whales. The location of the school of krill or small fishes can be determined by the humpback whales which encircle them. In case the position of the optimal design in the search space is unknown, then the prey would be the current best candidate solution. In the searching process each agent moves in the search space towards the best agent which is similar in the position update in the particle swarm algorithm.

The following equations in Prakash *et al.* (2017) represent the described behavior:

$$D = \left| C.X_{rand} - X \right| \quad (1)$$

$$X(t+1) = X_{rand} - A.D \quad (2)$$

$$A = 2.a.r - a \quad (3)$$

$$C = 2.r \quad (4)$$

$$D = \left| C.X^*(t) - X(t) \right| \quad (5)$$

$$K(t+1) = X^*(t) - A.D. \quad (6)$$

where

A is coefficient vectors — C is coefficient vectors — t is the current iteration

X is the position vector — a is linear decreasing from 2 to 0 — r is the random number between [0,1]

X* is the best value of the position vector

Equations (1) and (2) presents searching prey in case A≥1, while in any other case equations (5) and (6) are used which represent encircling the prey by shrinking mechanism.

2.1.2 Updating the Position Spirally

From Mirjalili *et al*. (2016), as mentioned before in the foraging behaviour of humpback whales which was shown in Fig. 1, the whales perform two movements simultaneously which are shrinking circle and moving in a path which takes a spiral shape. In (Mirjalili *et al.*, 2016; Prakash *et al.*, 2017) to model it mathematically how the whales update their position during optimization, an assumption is made that the probability to choose between either to shrink encircle or to move in spiral shaped path is 50%, so a variable (p) is introduced to indicate that probability, where (p) is a random number between [0, 1]. Another constant is introduced to represent the spiral shape path called (b). So to update the position, the following formula is utilized:

$$X(t+1) = \begin{cases} X^*(t) - A.D. & \text{if } p < 0.5 \\ D.e^{b.l}.\cos(2.pi.l) + X^*(t) & \text{if } p > 0.5 \end{cases} \quad (7)$$

where (l) is random number from [-1,1].

2.1.3 Exploration and Exploitation

Equations (1) and (2) represent the exploration phase where the humpback whales search randomly according to the position of each other, so the variation of vector A is used to represent the searching process for the prey. In the exploration phase the position update of a search agent is moving towards a random known search agent such that |A| > 1, so global search takes place. In the exploitation phase the position update of a search agent moves towards the best known candidate solution found so far which is cleared from equation (7).

2.2 Improved Whale Optimization Algorithm (IWOA)

From (Hu *et al.,* 2016*)* to improve the traditional whale optimization algorithm regarding the computational time and results obtained an inertia weight (ω) $\in$ [0,1] is added to introduce the improved whale optimization algorithm (IWOA) which is applied for the first time to solve the problem of capacitor allocation in radial distribution system , in this case equations (5) and (6) will be modified as follow:

$$D = \left| C.\mu.X^*(t) - X(t) \right| \quad (8)$$

$$X(t+1) = \mu.x^*(t) - A.D \quad (9)$$

Equation (7) which represents the update of the position in the spiral path would be modified as follow

$$X(t+1) = \begin{cases} \mu X^*(t) - A.D & \text{if } p < 0.5 \\ D.e^{b.l}.\cos(2.pi.l) + \mu X^*(t) & \text{if } p > 0.5 \end{cases} \quad (10)$$

The modified algorithm steps of the IWOA can be summarized as:

a. Initialize the whales' population X_i where i = (1, 2, 3, …, n) and set the Maxgen (maximum number of iterations). Set t = 1.
b. Work out the fitness value of X_i where i = (1, 2, 3, …, n), identify the superior seek candidate solution X*.
c. Repeat the following: For every X_i (1, 2, 3, …, n), update p, C, A, l, a. If $p < 0.5$,then if $|A| < 1$,update the position of the current search agent by Equation.(8) and if $|A| \geq 1$, select a random search solution $Xrand$ and update the position of the current search agent by equation.(2).But when $p \geq 0.5$,update the position of the current search by the Equation (10) Check if any search agent goes beyond the known search and modify it. Calculate the fitness of X_i (1, 2, 3, …, n), and if there is a better solution, find the best search solution X^*. Set $t = t + 1$.Until t reaches maximum number of iterations, the algorithm is finished.
d. Return the best optimization solution X^* and the best optimization value of fitness values.

2.3. The Power Flow Calculations

From Saadat (1999) and others, there are many techniques used for the power flow solution of a distribution feeder, for instance the gauss, Gauss Seidel, backward forward sweep, fast decoupled load flow and Newton-Raphson. In this paper the Newton-Raphson method is used to find the power flow solution of the test feeder. Figure 2 presents the single line diagram of a distribution feeder model. The governing load flow equations could be stated as follow: (Baran et al., 1989)

$$P_{i+1} = p_i - r_{i+1}(P_i^2 + P_i^2)/V_i^2 - P_{Li+1} \quad (11)$$

$$Q_{i+1} = Q_i - x_{i+1}(P_i^2 + Q_i^2)/V_i^2 - Q_{Li+1} + Q_{Ci+1} \quad (12)$$

$$V_{i+1}^2 = V_i^2 - 2(r_{i+1}P_i + x_{i+1}Q_i) + ((r_{i+1}^2 + x_{i+1}^2) * (P_i^2 + Q_i^2))/V_i^2 \quad (13)$$

$$P_{lossi+1} = r_{i+1}(P_i^2 + Q_i^2)/V_i^2 \quad (14)$$

$$P_{lossi+1} = x_{i+1}(P_i^2 + Q_i^2)/V_i^2 \quad (15)$$

where

P_i: real power flows into the sending of branch i+1 connecting node i and node i+1
Q_i: reactive power flows into the sending of branch i+1 connecting node i and node i+1
V_i: bus voltage magnitude at node i
$Q_{Ci+1:}$ reactive power injection from capacitor at node i+1
P_{Li+1}: real power load connected to node i+1
Q_{Li+1}: reactive power load connected to node i+1
$r_{i+1:}$ line resistance between node i and node i+1
x_{i+1}: line reactance between node i and node i+1
$P_{lossi+1:}$ real power losses of branch connecting node i and node i+1
$Q_{lossi+1:}$ reactive power losses of branch connecting node i and node i+1

2.4. Objective Function

The optimal target of the reactive power compensation which is presented as the capacitor sizing and placement problem in the radial distribution system is to maximize the savings in dollars, improve system voltage profile and minimize the active power loss in kW subject to some constraints. So, the optimization problem objective function can be stated as in Askarzadeh (2016) to minimize the cost function:

$$Cost = K_p P_{Totalloss} + \sum_{j=1}^{n} K_j Q_j \quad (16)$$

where

K_p is the cost per power loss ($/kW/year), j=1, 2… n represent the selected buses
$P_{Totalloss}$ is the total real power losses of distribution network K_j is the capacitor cost
Q_j is the capacitor size
According to the following constraints:
(i)Voltage constraints

$$V_{min} \leq V_i \leq V_{max} \quad (17)$$

where

V_{min}: minimum bus voltage limit V_{max}: maximum bus voltage limit

(ii) Reactive power constraints

$$Qc_{\ max} = L * Qc_0 \tag{18}$$

where $Qc_{\ max}$ is the maximum capacitor size in kVar

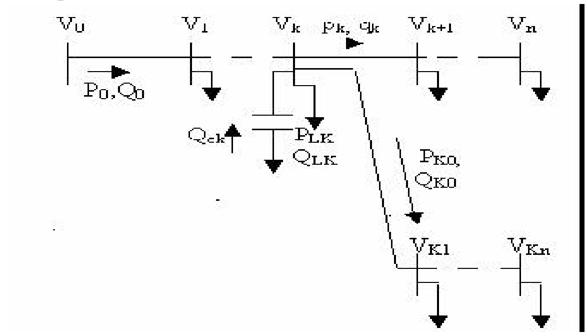

Figure 2. Single line diagram of a model of distribution feeder

L is an integer Qc_0 is the smallest available capacitor size in the market in kVAr

2.5. The Algorithm Steps

A brief summary of the applied algorithm in this study is presented as follow:

a. Calculate the real power losses of the uncompensated radial distribution feeder by performing the load flow calculations using Netwon-Raphson method.
b. Initialize the improved whales optimization algorithm IWOA by generating randomly (*n*) number of whales(agents) & set iteration counter =0
c. Evaluate objective function (fitness value) of each agent and identify the best search candidate solution using equation (16) without violating the constraints.
d. Update a, A, C, l and p using equations (3) and (4) for each search agent in the search space.
e. While (p<0.5) go to step (f) and in any other case go to step (h).
f. While | A| < 1, the position update of the search agent is done using equations (1) and (2).
g. While |A| > 1, the position update of the search agent and calculating the new search agent is done using equations. (8) and (9).
h. Using equation (10) update the position of the current search agent.
i. Go to step (j) when the maximum number of iterations is reached, otherwise go to step (c)
j. Output the optimal solution.

From the mentioned algorithm, it can be deduced that attention is placed on power loss minimization, cost reduction and voltage profile enhancement without violating the predetermined voltage and capacitor constraints

3. Implementation and Results

3.1The First Feeder

Commercially available capacitor sizes with $/kVAr are used in the study. Table 1 shows an example of such data. For reactive power compensation, the maximum capacitor size Qc max should be lower than the reactive load. This results in 27 possible capacitor sizes shown in Table 2 with their corresponding cost/kVAr. The values of the 27 choices are derived from Table 2 by assuming a capacitor life expectancy of 10 years (the operating costs are neglected) (Baghzouz et al., 1990). For the test feeder, *Kp* is selected to be $ 168/kW (Baghzouz et al., 1990).

Table 1. Available 3-phase capacitor sizes and cost

Size (kVAr)	150	300	450	600	900	1200
Cost ($)	750	975	1140	1320	1650	2040

The first studied feeder is the 15 bus test feeder shown in Fig.3, the distribution feeder data is given in Das *et al.* (1995). Applying the load flow calculations for this test feeder, before compensation, the power factor is 0.7. The total apparent power is 1752 kVA. The reactive power losses and the total active power losses are 57.297 kVAr and 61.954 kW respectively. The minimum and maximum buses voltages range is $0.946 \leq V_i \leq 1.0$ p.u.

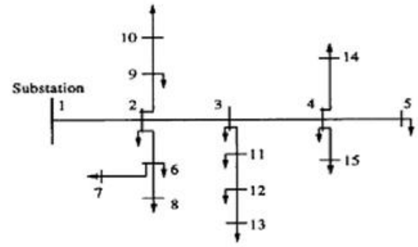

Figure 3. Single line diagram of 15 bus test system

Table2. Possible choices of capacitor sizes and cost/kVar

J **Q_c(kVAr)** **$/kVAr**	1 150 .500	2 300 .350	3 450 .253	4 600 .220	5 750 .276	6 900 .183	7 1050 .228
J **Q_c(kVAr)** **$/kVAr**	8 1200 .170	9 1350 .207	10 1500 .201	11 1650 .193	12 1800 .187	13 1950 .211	14 2100 .176
J **Q_c(kVAr)** **$/kVAr**	15 2250 .197	16 2400 .170	17 2550 .189	18 2700 .187	19 2850 .183	20 3000 .180	21 3150 .195
J **Q_c(kVAr)** **$/kVAr**	22 3300 .174	23 3450 .188	24 3600 .170	25 3750 .183	26 3900 .182	27 4050 .179	

The total cost calculated due to the power losses of the uncompensated system is 10,408$, where the voltage of the substation slack bus (bus no. 1) is set to be 1 pu, The improved whale optimization algorithm (IWOA) technique is implemented and the results seems to be superior. The real power loss has been decreased enormously from its initial loss value of 61.954 kW to 29.7 kW. Also, the cost per year has been decreased from 10,408 $ to 5,472$. Also, the voltage profile has been enhanced as the minimum bus voltage among all buses is 0.97 pu and the maximum bus voltage is 1 pu. The optimal locations of the selected capacitors are 4, 6, 9, 11, 15 with the sizes 300, 450, 150, 300 and 150 kVAr respectively. The algorithm optimized result has been compared with, some recently, published studies. Comparison is made with other methods that have been applied to same test feeder for the solution of the optimal sizing and placement of capacitors problem and results are tabulated in Table 3.

Table 3. Optimal results of 15 bus feeder

Parameter	**Before Capacitor Placement**	**After Capacitor Placement**			
		Flower pollination algorithm (Abdelaziz *et al.*, 2016)	Fuzzy Expert (Babu *et al.*,2016)	Analytical method (Babu *et al.*,2016)	Proposed Method
Year of method publication (as a ref. paper)		2015	2016	2016	implemented in Dec. 2017
Final power loss(kW)	61.95	30.71	29.92	32.6	29.7
Loss Reduction %		**50.4**	**51.58**	**47.24**	**52**
Minimum Bus Voltage	**0.94**	**0.967**	**0.969**	**0.966**	**0.97**
Annual Cost($/year)	10,408	5,492	5,129	6,179	5,463

3.2. The Second Feeder

The second feeder is a 34 bus radial distribution test feeder consisting of main feeder and four laterals, with rated voltage 11kV, presented in Figure 4.The data of that feeder regarding active loads, reactive loads and lines are given in (Chis *et al.*,1997). The uncompensated configuration for the system before reactive power compensation is as follow: the active and reactive loads of the test feeder are 4636.5 kW and 2873.5 kVAr respectively. The annual cost due to losses of the system and total active power loss for the base case are 37,248 $ and 221.72 kW respectively. The number of agents used is 30. While the minimum bus voltage in pu is 0.942 and maximum bus voltage is 0.99 pu.

After reactive power compensation by adding the capacitors to the system at selected locations the voltage profile has improved, and the minimum bus voltage is 0.95. pu, the active power losses has been reduced to 159.2kW and the annual cost decreases to 27,369$.The selected buses are 7 ,18 , 21 , 25 ,31 and the installed capacitor sizes in kVar are 600, 600, 450, 600 ,450 respectively. It can be clearly seen from Table 4 and Figure 5 that the proposed technique provides better system voltage profile improvement and real power losses reduction compared to other optimization methods and techniques after reactive power compensation process by defining the optimal locations and sizes of capacitors in the tested radial distribution 34 bus feeder. Comparison is made with other methods that have been applied to same test feeder.

The used algorithm IWOA in this paper to solve the optimization problem which uses an inertia weight which led to better results and performance than the traditional whale optimization algorithm (WOA) used in (Prakash et al.,2017). When both techniques applied to the same 34 bus test system, the proposed technique used in this paper led to better results regarding the system total real power loss in kW and minimum bus voltage in per unit which could be seen in Table 4.

3.3 The Third Feeder

The third radial distribution test feeder consists of 69 bus with rated voltage of 12.66 kV, Figure 6 shows the single line diagram of 69 bus feeder. The data of this feeder is given in (Sahoo *et al.,* 2006). Before reactive power compensation the system status is as follow the cost is $37,782; this is based on the previously defined cost function, and the total reactive and active loads are2694.6 kVAr and 3802.2 kW respectively. The active and reactive losses are 224.89 kW and 101.7 kVAr respectively. The voltage range of all buses is $0.9093 \leq Vi \leq 1.0$ p.u.

Using (IWOA), the capacitors of rating 450, 300, 1050 and 150 kVAr are placed at the optimal locations 9, 17, 50 and 53 respectively. The sizes and locations are determined using the proposed method. The active power loss is decreased to 145 kW from the base case of 224.89 kW which represents 35.52% of total active power loss reduction. The minimum voltage is 0.93 pu. The annual cost incurred for kW loss including placed capacitors to the system is calculated as 24,950 $. Also, the results in Figure 7, Figure 8 and Table 5 indicate the superior performance of the proposed algorithm. Comparison is made with other methods that have been applied to same test feeder.

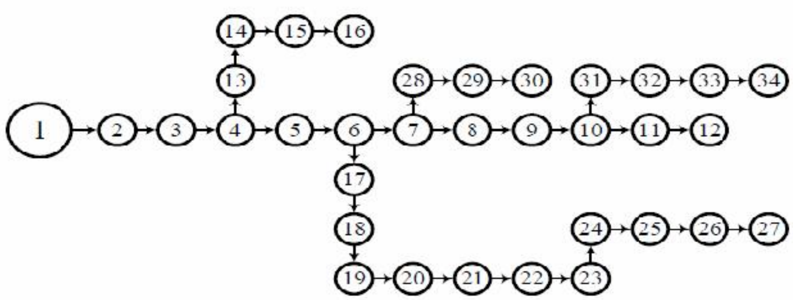

Figure 4. Single line diagram of 34 bus test system

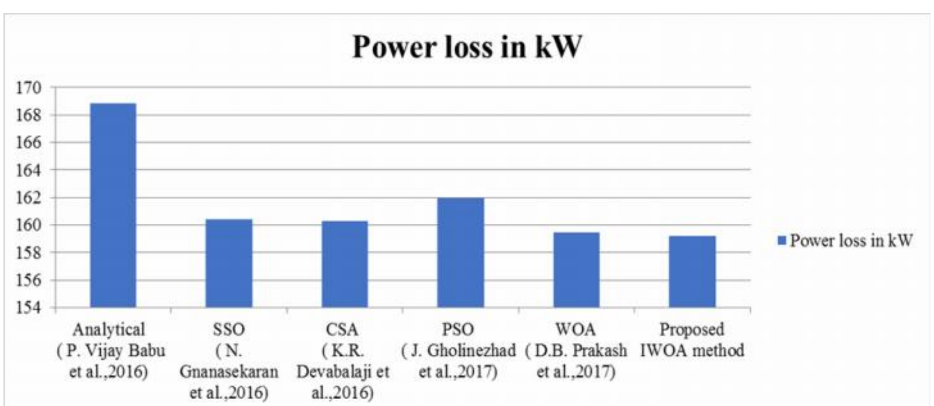

Figure 5. Comparison of the real power losses of the 34 bus test feeder after reactive power compensation using proposed method and other recent optimization methods

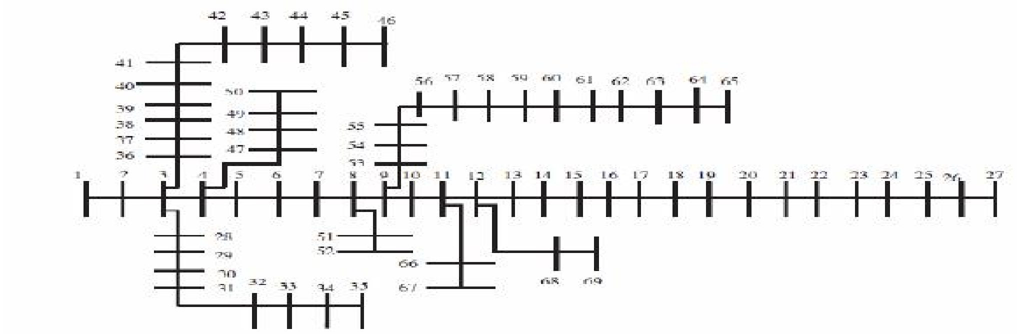

Figure 6. Single line diagram of 69 bus test system

Table 4. Optimal results of 34 bus test feeder

Parameter	Before Capacitor Placement	After Capacitor Placement					
		Analytical method (Babu *et al.*,2016)	Shark Smell method (SSO) (Gnanasekaran et al., 2016)	Cuckoo Search Algorithm (CSA) (Devabalaji et al.,2016)	Particle Swarm Optimization (PSO) (Gholinezhad et al., 2017)	Whale Optimization Algorithm (WOA) (Prakash et al., 2017)	Proposed Method
Year of technique publication (Reference)		2016	2016	2016	2017	2017	implemented in Dec. 2017
Final power loss(kW)	221.72	168.84	160.39	160.3	161.97	159.47	159.2
Loss Reduction %		**23.84**	**27.66**	**27.7**	**26.94**	**28**	**28.19**
Minimum Bus Voltage	**0.942**	**0.949**	**0.950**	**0.950**	**0.950**	**0.950**	**0.951**

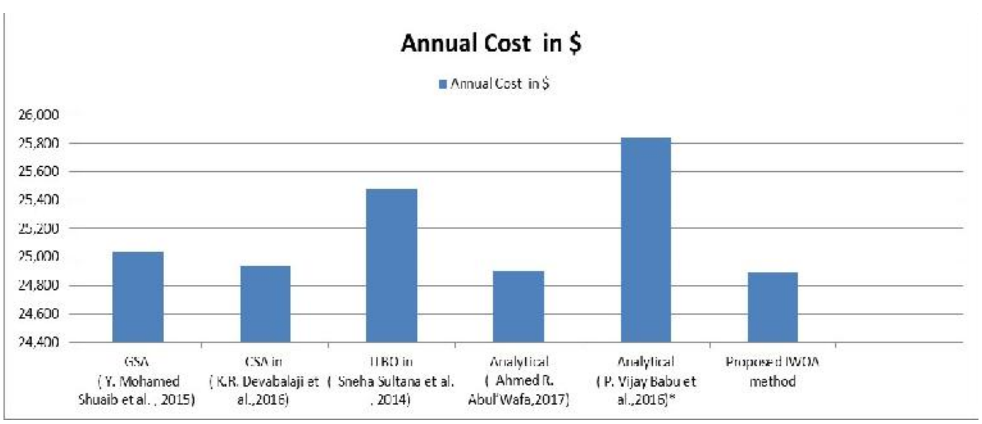

Figure 7. Comparison of the Annual Cost in $ of the 69 bus test feeder after optimal capacitor placement using proposed technique IWOA and other modern optimization techniques

Table 5. Optimal results of 69 bus test feeder

Parameter	Before Capacitor Placement	After Capacitor Placement					
		Gravitational Search Algorithm (GSA) (Shuaib et al., 2015)	Cuckoo Search Algorithm (CSA) (Devabalaji et al., 2016)	Teaching Learning Based Optimization (TLBO) (Sultana et al., 2014)	Analytical method (Abul'Wafa,2017)	Analytical method (Babu et al., 2016)*	Proposed Method
Year of technique publication		2015	2016	2014	2017	2016	implemented in Dec. 2017
Final power loss(kW)	224.89	145.9	146.1	146.35	145.91	151.54	145
Loss Reduction %		**35.1**	**35**	**34.9**	**35.1**	**32.6**	**35.52**
Minimum Bus Voltage	0.9093	0.95	0.93	0.93	0.93	0.92	0.93
Annual Cost ($/year)	**37,782**	**25,033**	**24,937**	**25,479**	**24,906**	**25,837**	**24,893**

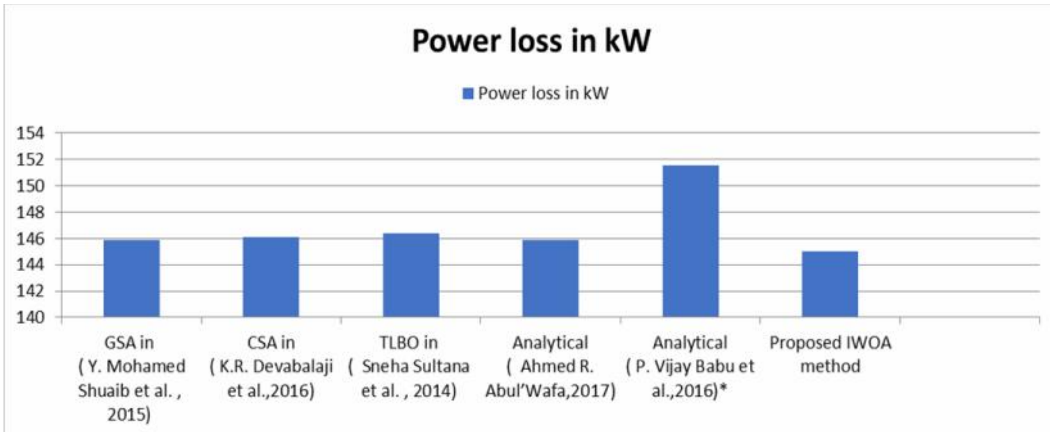

Figure 8. Comparison of the real power loss in the system in kW of the 69 bus test feeder after reactive power compensation using proposed technique IWOA and other modern optimization techniques

4. Conclusions

This research proposes a modern optimization algorithm called the improved whale optimization Algorithm (IWOA). For optimal placement and sizing of capacitor banks in radial distribution network in order to minimize the real power loss, decrease the annual cost in $/ year due to these losses and enhance the voltage profile of the system. The objective function used in this work describes two terms presenting the cost due to active power losses and the cost of installed KVAr compensators. The main advantage is when applying the improved whale optimization algorithm in this study to different test systems , it led to the lowest system total real power loss in kW for each test system (15 bus – 34 bus -69 bus test systems) compared to recent similar works in the same research point. Another advantage that modifying the traditional algorithm led to better computational time and convergence to the optimal solution. The performance of the proposed method is outstanding when compared to other recent optimization algorithms used in the same research point. The implementation and results of the proposed technique among different structured test radial distribution feeders and in comparison, with other recent algorithms such as SSO, CSA and FPA verified that the proposed optimization algorithm (IWOA) provides the lowest power loss in kW, the most improved system voltage profile and the least annual cost.

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