Distribution power system reconfiguration using whale optimization algorithm

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ABSTRACT
This study discusses how to enhance the power distribution system and one of the most important ways to do that is by reconfiguration of the power system. Reconfiguration means changing the topology of the radial distribution network by changing the status of switches. The objective is to minimize the total power loss and enhance the voltage profile. Many optimization techniques were used to solve this problem such as classical optimization which is proven to be time consuming method and heuristic methods which are more efficient in our problem here. In this paper, the whale optimization algorithm (WOA) which is one of the modern heuristic optimization techniques and it has high efficiency to solve discrete optimization problems, is used to get the optimum case in reconfiguration problem. WOA is applied to (33 bus system, 69 bus system, and 118 bus system) and results are compared to other heuristic methods.

Keywords:
Network distribution
Power loss
Reconfiguration
Whale optimization

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1. INTRODUCTION
Electric utilities are interested in reducing power loss to be more competitive. The voltage drop problem can occur when using radial systems with long distances feeder and large loads. To overcome such a problem, different methods can be applied such as: installing distributed generators (DGs) [1, 2], capacitor placement [3] and network reconfiguration which is introduced in this paper. Network reconfigurations mean changing the topology of the network by varying the status of switches (open/closed). There are two types of switches in the distribution power systems:
– Sectionalized switches (normally closed)
– Tie switches (normally open)
These switches in power systems are used for:
– Protection in case of faults
– Reconfiguration of the power system.

The distribution network reconfiguration is considered as a mixed integer non-linear optimization problem. There are many types of optimization techniques:
– Classical optimization: Depends on some mathematical methods to solve optimization problems such as linear programming, Lagrange method. For large scale problem such as the problem here (reconfiguration), the classical methods consume much time and may be trapped to local optimum solution not the global.

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- Heuristic optimization: This type depends on the behavior of something in the nature such as ant colony, grey wolf method, whale optimization method...etc. The main advantage in heuristic methods is less time consuming to solve large scale problems unlike classical methods. The disadvantage in it is that it gives less accurate results.

- Artificial intelligence: Depends on programming and machine learning such as particle swarm.

The network reconfiguration for power loss reduction was firstly introduced by Merlin and Back in 1975 [1]. They used heuristic approach called a branch and-bound-type optimization technique. This technique has a main disadvantage that it is a very time consuming as it has to try 2^n configuration where n is the number of branches in the power system. The whale optimization algorithm (WOA) [4] presented in this study mimics the behavior of whales in exploring and hunting the prey. The main difference between this method and other heuristic methods is in the hunting mechanism to catch the prey using either spiral net mechanism or circular net mechanism. WOA has proved its efficiency in solving 29 mathematical optimization problems and 6 structural optimization problems [4]. At section 2 in this article, reconfiguration problem will be formulated in mathematical form. The whale optimization algorithm will be expressed in a mathematical form at section 3, section 4 is dedicated for the implementation of the proposed algorithm to minimize power loss of 33, 69, and 118 bus systems. Then the obtained results are compared to previously applied heuristic methods to prove its efficiency at section 5.

In the last few years, many researchers tried to solve the reconfiguration problem using different methods trying to reach less time-consuming methods and looking for the global optimum. Authors of [5] use grey wolf optimization algorithm which is inspired from hunting strategy of grey wolves to solve reconfiguration problem for (33 bus system, 69 bus system, and 118 bus system). Authors of [6] use fireworks algorithm for solving reconfiguration problem on 33 and 119 bus system. The fireworks algorithm depends on the sparks generated in the explosion. This algorithm selects some quality points at each generation and the search process continues until a spark reaches the optimum. The authors also mentioned that the main disadvantage of the previous methods is represented in the computational time and work done under normal conditions.

Authors of [7] use a binary group search algorithm to solve the reconfiguration problem on IEEE 33 and 69 bus systems. This algorithm depends on animal searching behavior and scanning methodology to get the optimum searching strategy. Authors of [8] use gravitational search algorithm (GSA) to apply on reconfiguration problem 33 and 69 bus system. This algorithm depends on the law of gravity and mass interaction due to Newton’s law. Authors of [9] use ant colony optimization and musician’s behavior inspired to apply on 33 and 118 bus system reconfiguration problems. The ant colony optimization method depends on the behavior of ant to find the shortest path between food and nest via pheromone as indirect communication. The harmonic search optimization depends on the harmony between musicians to come up with a nice harmony. Authors of [10] use a modified particle swarm as a metaheuristic optimization algorithm to solve the reconfiguration problem on 32 nodes and 69 nodes system. This algorithm developed by Kennedy and Eberhart in 1995 and it is inspired by the social behavior of bird flocks and fish schools.

Authors of [11] use bacteria foraging behavior optimization algorithm to solve the reconfiguration problem. This optimization technique is inspired from social foraging behavior of *Escherichia coli* and it has high ability to solve real optimization applications. This method was applied to 33 bus system. Authors of [12] use bee colony optimization algorithm which is inspired from intelligent foraging behavior of honeybee swarm to solve reconfiguration problem on 33 and 119 bus system. Authors of [13] use cuckoo search optimization algorithm which is inspired from brood parasitism of cuckoo species to lay their eggs in the nests of the other species of birds for optimization problems. This algorithm is applied on three different power systems and it proves its efficiency. In this paper, a new heuristic optimization technique is used which is called whale optimization algorithm (WOA). This algorithm is inspired from the whale hunting behavior. It is was proven its efficiency in solving many mathematical optimization models and its high ability to avoid local optimal and its fast convergence. In this article, at section 2 the reconfiguration problem is being formulated in mathematical model. At section 3, the WOA is being illustrated in detail in a mathematical form. At section 4, the algorithm of applying the WOA on the reconfiguration problem is being stated. At section 5, the results are discussed and compared to other heuristic methods.

2. PROBLEM FORMULATION FOR NETWORK RECONFIGURATION

Objective function: minimize power loss $P_{loss} = \sum I^2R$ for all connections between buses.

Constraints:

Voltage constraint: $V_{min} < V_i < V_{max}, \quad i = 1,2,\ldots, \text{number of buses}$

Load constraint: $I_{min} < I_i < I_{max}, \quad i = 1,2,\ldots, \text{number of branches}$

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Topology constraint: the system must be radial after reconfiguration

Note:
- $P_{loss}$: total power loss in the system
- $I_i$: the magnitude of the current flowing through branch $i$
- $V_i$: voltage of bus $i$

The objective function is calculated from the solution of power flow equations such as the Newton Raphson method. To check system radiality, incidence matrix $A$ is formed with dimensions equal to the number of branches ($M$) * number of buses ($N$) and the elements of this matrix can be formed as follows:

$$
A_{ij} = \begin{cases} 
0 & \text{in case of the branch } i \text{ not connected to bus } j \\
-1 & \text{in case of the branch } i \text{ from bus } j \\
1 & \text{in case of the branch } i \text{ to bus } j 
\end{cases}
$$

Then the column referring to the reference node (usually first column) must be omitted. If determinant ($A$) equals 1 or -1 then the system is radial. If det ($A$) equals zero, then the system is not radial, and some loads may be disconnected.

3. WHALE OPTIMIZATION ALGORITHM

It is a heuristic method discovered in 2016 and it mimics humpback whale hunting strategy. It has many advantages such as local optimum avoidance and fast convergence. Search agents are initialized firstly to search for the optimum (prey) (exploration phase) and then update their positions toward the best search agent near the optimum. We can mathematically express that by (1).

3.1. Exploration phase

$$
D^t = |C\bar{x}(t) - \bar{x}(t)| \\
\bar{x}(t+1) = \bar{x}(t) - \bar{A}.\bar{D} \\
\bar{A} = 2\bar{a} - \bar{A} \\
\bar{C} = 2\bar{r}
$$

Where $t$ is the current iteration, $\bar{A}$, $\bar{C}$ are the coefficient vectors, $\bar{x}(t)$ is the position of best search agent, $\bar{x}(t)$ is the position vector, $\bar{a}$ is linear decrease from 2 to 0 and $\bar{r}$ is random vector in [0,1].

3.2. Exploitation phase

In exploitation phase, whales use a bubble net attacking method to catch the prey. There are 2 mechanisms for bubble net as shown in Figure 1.

- Shrinking encircling mechanism

$$
\bar{x}(t+1) = \bar{x}(t) - \bar{A}.\bar{D}
$$

- Spiral updating position

$$
\bar{x}(t+1) = D^t e^{ib} \cos(2\pi l) + \bar{x}(t)
$$

where $D^t = |\bar{x}(t) - \bar{x}(t)|$ is the distance between search agent and the prey.
- $b$: constant (usually 1)
- $l$: random number in [0,1]

Usually, humpback uses each mechanism with probability 50% so we can summarize the exploitation phase in the following equations:

$$
\bar{x}(t+1) = \begin{cases} 
\bar{x}(t) - \bar{A}.\bar{D} & \text{if } p < 0.5; \\
D^t e^{ib} \cos(2\pi l) + \bar{x}(t) & \text{if } p \geq 0.5,
\end{cases}
$$

where $p$ is random number in [0,1]
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Figure 1. Bubble-net search mechanism implemented in WOA (X* is the best solution obtained so far), (a) shrinking encircling mechanism, (b) spiral updating position

The WOA algorithm can be summarized in the following pseudo code:

```plaintext
Initialize the whales population X1 (1 = 1, 2, ..., n) 
X* = the best search agent 
while (t < maximum number of iterations) 
   for each search agent 
      Update a, A, C, l, and p 
      if1 (p < 0.5) 
         if2 (|A| < 1) 
            Update the position of the current search agent by the Eq. (1) 
         else if2 (|A|) 
            Select a random search agent (Xrand) 
            Update the position of the current search agent by the Eq. (2) 
         end if2 
      else if1 (p > 0.5) 
         Update the position of the current search by the Eq. (3) 
      end if1 
   end for 
   Check if any search agent goes beyond the search space and amend it 
   Calculate the fitness of each search agent 
   Update X* if there is a better solution 
   t=t+1 
end while 
return X*
```

4. FORMULATION OF WOA FOR SOLVING MINIMUM POWER LOSS RECONFIGURATION PROBLEM

The distribution systems can be described as a matrix with dimensions MxL. Where M is number of branches and L is number of buses. It can be assumed that whales move between branches and select which one is to be open.

Step (1): Initializing the position of search agents

Initial random positions for each search agent are set and selecting random switches to be opened (tie switches). Then the initial configuration is checked whether it is a radial system or not. If the system is radial, we can run a power flow analysis on it to calculate total power loss in the system and minimum bus voltage. Now, we can assume that the best configuration is the initial configuration and then start the next step to change the reconfiguration of the system.

Step (2): Updating positions of search agents

In each iteration (i), a new configuration is produced using (WOA) by selecting some switches to be open. The configuration must be evaluated by 3 important actions:

1. Check system radiality: by forming incidence matrix (A), the system is checked if it is radial or not if the system is not radial, the configuration is discarded and the fitness function (power loss) is set to equal infinity.

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2. Run power flow analysis: “Newton Raphson method” is the method used for load flow of the system and check the bus voltage limit. $V_{\text{min}} > 0.91$ and $V_{\text{max}} < 1$. If the system does not satisfy voltage limit condition, the configuration is discarded also, and the fitness function is set to equal infinity.

3. Evaluate fitness function ($P_{\text{loss}}$)

Step (3): Determination of best configuration to get minimum power loss

The process continues until reaching the maximum number of iterations. At each iteration, if fitness function<initial fitness function, then the current configuration is set to be the best configuration

5. RESULTS AND COMPARING WITH OTHER HEURISTIC METHODS

Applying the WOA on 33, 69, and 118 bus systems respectively for minimum power loss reconfiguration problem using MATLAB V2019 executed on processor core i5-7200u @2.5GHz with 8 GB RAM. The number of search agents used in the reconfiguration optimization problems at this study is between (30-50) search agents and the maximum number of iterations equals 500. Newton Raphson power flow algorithm is used in power flow analysis during reconfiguration process to get power loss and minimum voltage of the system. The time consumed to simulate the 33-bus system and get the optimum solution is 3.3 seconds, for 69 bus system 8.8 seconds, and for 118 bus system is 18.34 seconds.

5.1. For 33 bus system

The specifications of the system are shown in Table 1 and initial configuration of 33 bus system is shown in Figure 2. From simulation, as shown in Figure 3 and Table 2 that power loss decreased by 31.1% and voltage profile improved to 0.9372. The results of applying WOA on 33 bus system are compared to other heuristic techniques on the same system in Table 3 and the results were very competitive.

| $S_{\text{base}}$ (MVA) | $V_{\text{base}}$ (kV) | $Z_{\text{base}}$ (ohms) | Resistance and Reactance (ohms) | Resistance and Reactance (pu) | Conductance and Reactance (pu) | Maximum Line Capacity |
|-------------------------|------------------------|--------------------------|-------------------------------|-------------------------------|-------------------------------|----------------------|
| 100                     | 12.66                  | 1.002756                 |                               |                               |                               |                      |

Table 1. Specifications of 33 bus system [14-17]
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5.2. For 69 bus system

The initial configuration of 69 bus system is shown in Figure 4 and the specifications of the system are shown in Table 4. It is shown from simulation results in Figure 5 and Table 5 that power loss reduced by 55.57% and voltage profile improved to 0.9427. It is shown from simulation results that applying WOA on 69 bus reconfiguration problem helps in reducing power loss by 55.58% and improving voltage profile to 0.942 instead of 0.909. The results of applying WOA on 69 bus system are compared to other heuristic techniques on the same system in Table 6 and the results were very competitive.
| Bus Number | Nominal Load (P) (kW) | Nominal Load (Q) (kvar) |
|------------|----------------------|------------------------|
| 1          | 0                    | 0                      |
| 2          | 0                    | 0                      |
| 3          | 0                    | 0                      |
| 4          | 0                    | 0                      |
| 5          | 0                    | 0                      |
| 6          | 0                    | 0                      |
| 7          | 0                    | 0                      |
| 8          | 0                    | 0                      |
| 9          | 0                    | 0                      |
| 10         | 0                    | 0                      |
| 11         | 0                    | 0                      |
| 12         | 0                    | 0                      |
| 13         | 0                    | 0                      |
| 14         | 0                    | 0                      |
| 15         | 0                    | 0                      |
| 16         | 0                    | 0                      |
| 17         | 0                    | 0                      |
| 18         | 0                    | 0                      |
| 19         | 0                    | 0                      |
| 20         | 0                    | 0                      |
| 21         | 0                    | 0                      |
| 22         | 0                    | 0                      |
| 23         | 0                    | 0                      |
| 24         | 0                    | 0                      |
| 25         | 0                    | 0                      |
| 26         | 0                    | 0                      |
| 27         | 0                    | 0                      |
| 28         | 0                    | 0                      |
| 29         | 0                    | 0                      |
| 30         | 0                    | 0                      |
| 31         | 0                    | 0                      |
| 32         | 0                    | 0                      |
| 33         | 0                    | 0                      |
| 34         | 0                    | 0                      |
| 35         | 0                    | 0                      |
| 36         | 0                    | 0                      |
| 37         | 0                    | 0                      |
| 38         | 0                    | 0                      |
| 39         | 0                    | 0                      |
| 40         | 0                    | 0                      |
| 41         | 0                    | 0                      |
| 42         | 0                    | 0                      |
| 43         | 0                    | 0                      |
| 44         | 0                    | 0                      |
| 45         | 0                    | 0                      |
| 46         | 0                    | 0                      |
| 47         | 0                    | 0                      |
| 48         | 0                    | 0                      |
| 49         | 0                    | 0                      |
| 50         | 0                    | 0                      |
| 51         | 0                    | 0                      |
| 52         | 0                    | 0                      |
| 53         | 0                    | 0                      |
| 54         | 0                    | 0                      |
| 55         | 0                    | 0                      |
| 56         | 0                    | 0                      |
| 57         | 0                    | 0                      |
| 58         | 0                    | 0                      |
| 59         | 0                    | 0                      |
| 60         | 0                    | 0                      |
| 61         | 0                    | 0                      |
| 62         | 0                    | 0                      |
| 63         | 0                    | 0                      |
| 64         | 0                    | 0                      |
| 65         | 0                    | 0                      |
| 66         | 0                    | 0                      |
| 67         | 0                    | 0                      |
| 68         | 0                    | 0                      |
| 69         | 0                    | 0                      |
| 70         | 0                    | 0                      |
| 71         | 0                    | 0                      |
| 72         | 0                    | 0                      |
| 73         | 0                    | 0                      |
| 74         | 0                    | 0                      |
| 75         | 0                    | 0                      |
| 76         | 0                    | 0                      |
| 77         | 0                    | 0                      |
| 78         | 0                    | 0                      |
| 79         | 0                    | 0                      |
| 80         | 0                    | 0                      |
| 81         | 0                    | 0                      |
| 82         | 0                    | 0                      |
| 83         | 0                    | 0                      |
| 84         | 0                    | 0                      |
| 85         | 0                    | 0                      |
| 86         | 0                    | 0                      |
| 87         | 0                    | 0                      |
| 88         | 0                    | 0                      |
| 89         | 0                    | 0                      |
| 90         | 0                    | 0                      |

**Table 4.** The specifications of 69 bus system [16, 17]
Figure 4. 69-bus single-line diagram

Figure 5. Voltage profile of each bus (69 bus system)

Table 5. Simulation results for applying WOA on 69 bus system

| Simulation results of 69 bus distribution network | Before reconfiguration | After reconfiguration |
|--------------------------------------------------|------------------------|-----------------------|
| Tie switches : 69 70 71 72 73 | 12 13 55 61 69 |
| Power loss : 225.0007 kW | 99.949 kW |
| Power loss reduction: - | 55.5784 % |
| Minimum voltage : 0.90919 pu | 0.94275 pu |

Table 6. Comparing results with other heuristic methods

| Heuristic method used in 69 bus case | Before reconfiguration | After reconfiguration |
|-------------------------------------|------------------------|-----------------------|
| Grey wolf optimizer [5] | $P_{\text{Loss}} = 224.78$ kW | $P_{\text{Loss}} = 99.58$ kW |
| | $V_{\text{min}} = 0.909$ | $V_{\text{min}} = 0.942$ |
| Binary group search [7] | Tie switches: 11-43, 13-21, 15-46, 50-59, 27-65 | $P_{\text{Loss}} = 98.78$ kW |
| | $P_{\text{Loss}} = 224.99$ kW | $V_{\text{min}} = 0.9495$ |
| | $V_{\text{min}} = 0.909$ | |
| Gravitational search algorithm [8] | $P_{\text{Loss}} = 225.007$ kW | $P_{\text{Loss}} = 98.5718$ kW |
| | $V_{\text{min}} = 0.909$ | |
| Modified particle swarm [10] | $P_{\text{Loss}} = 20.89$ kW | $P_{\text{Loss}} = 9.4$ kW |
| | $P_{\text{Loss}} = 225.007$ kW | Tie switches: 12, 13, 55, 61, 69 |
| WOA (proposed method) | $V_{\text{min}} = 0.909$ | $P_{\text{Loss}} = 99.949$ kW |
| | | $V_{\text{min}} = 0.942$. |

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5.3. For 118 bus system

The initial configuration of 118 bus system is shown in Figure 6. The specification of the 118 bus distribution system is mentioned in [18]. It is shown from Table 7 and Figure 7 that reconfiguration of 118 bus system contributes to decrease power loss of the system by 32.999% and enhance the minimum voltage profile of the system from 0.8686 per unit to 0.932 per unit. The results of applying WOA on 118 bus system are compared to other heuristic techniques on the same system in Table 8 and the results were very competitive.

Table 7. Simulation results after reconfiguration of 118 bus distribution system

| Simulation results of 69 bus distribution network | Before reconfiguration | After reconfiguration |
|--------------------------------------------------|-----------------------|-----------------------|
| Tie switches                                    | 118 119 120 121 122 123 124 125 | 23 26 34 39 42 51 58 71 74 95 |
| Power loss                                      | 1298.0861 kW           | 869.7271 kW           |
| Power loss reduction                            | -                     | 32.9993 %             |
| Minimum voltage                                 | 0.8698 pu              | 0.93229 pu            |
6. CONCLUSION

This paper introduces the whale optimization algorithm as a new heuristic technique for reconfiguration of distribution systems. The main advantages of this heuristic method is its simplicity and saving time for solving large size problems as 33 bus system and 69 bus system. The obtained results in 33 bus system are very competitive to other heuristic methods and WOA is the fast and saving time for solving large size problems as 33 bus system. The main advantages of this heuristic method is its simplicity and optimum avoidance and fast convergence. The results in 118 bus system are competitive and close to other heuristic methods as minimum results are 869.7 kW with enhanced minimum voltage profile 0.932 per unit.

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Table 8. Comparing results with other heuristic methods

| Heuristic method used in 118 bus case | Before reconfiguration | After reconfiguration |
|--------------------------------------|------------------------|-----------------------|
| Fireworks Algorithms (FWA) [6]       | $P_{loss} = 1298.09\ kW$ | $P_{loss} = 854.06\ kW$ |
| Binary group search [7]              | $P_{loss} = 1294.3\ kW$ | $P_{loss} = 806.3\ kW$ |
| Ant colony optimization algorithm [9]| $P_{loss} = 1294.3\ kW$ | $P_{loss} = 865.32\ kW$ |
| Tabu search algorithm [18]           | $P_{loss} = 1294.3\ kW$ | $P_{loss} = 884.63\ kW$ |
| Improved tabu search (ITS) [18]      | $P_{loss} = 1294.3\ kW$ | $P_{loss} = 905.19\ kW$ |
| Grey wolf optimizer [5]              | $P_{loss} = 1298.09\ kW$| $P_{loss} = 877.15\ kW$ |
| Whale optimization algorithm (proposed method) | $P_{loss} = 8688\ kW$ | $P_{loss} = 0.9323$ |