

Whale Optimization Algorithm Based Optimal Operation of Power Distribution Systems

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Abstract—This paper solves the optimal operation problem of distribution systems using renewable energy sources and voltage regulators. The developed model makes use of Whale Optimization Algorithm based optimization. We apply the proposed optimization model to a modified low voltage distribution system of Almaty, Kazakhstan. Three different cases were simulated. The cases considered are medium load level with medium PV power output, high load level with medium PV output, and high load level and low PV power outputs. The simulation results show that the proposed algorithm is able lower the active power losses.

Index Terms—distribution system, optimization, renewable energy sources, Whale Optimization Algorithm

I. INTRODUCTION

In recent decades, the number of distributed generators (DGs) has increased rapidly worldwide. Tasks related to the operational control of active and reactive power delivered to the electrical grid are becoming increasingly important. It is necessary to plan the optimal power output from PV systems, batteries, and capacitors during the day, so methods for optimal operation are needed.

Volt-Var optimization is a common method for operating inverters and capacitors [1]–[10]. For example, the article [1] shows the performance of volt-var controlled PV inverters using the circuit reduction method. In the paper [2], legacy voltage control devices and smart inverters are operated using the bi-level volt-var optimization (VVO) approach. The result of the study [3] is to improve the management system with a real-time volt-var droop-based algorithm. There is also research on the operation of conservative voltage reduction based on an optimal power flow method with monitoring of the distribution system operator's infrastructure [7]. In the paper [5], an optimal location and centralized operation framework for low-voltage static var capacitors were considered. In the paper [6], voltage control based on local optimization using battery storage in residential buildings was studied, and in the paper [8], PV control was used. A chronological operation based volt-var optimization for daily scenarios with piecewise linearization was shown in [10]. In the paper [9], reliability was enhanced using optimal operation of distributed generation. The daily operating limit for power converters with distributed voltage control was

determined for unbalanced three-phase power systems in [4].

Another study [11] applied bi-level optimization including robust optimization and non-cooperative game theory, because of the indeterminacy of PV-panel's power output, to reduce operation cost. Also, bi-level optimization was applied in the paper [12] to operate between the microgrids and distributions system according to marginal price-based aim.

The decentralized robust approach was used to operate private microgrids to minimize wholesale cost in worst uncertainties conditions [13]. There are several researches related to optimal operation in different weather conditions. For instance, in [14], the authors planned resilient architecture of distributed generation's backup performance during earthquakes or floods. Another study was performed for the optimal operation of distributed generation during windstorms to achieve resiliency [15].

Many heuristic optimization methods [16]–[20] are applied to solve different problems related to distributed generation. Generally, all of them mimic biological species' natural phenomena or behavior. For instance, in the papers [21] and [22] sizing and placement issues were solved, by Dragonfly Algorithm [19] and Salp Swarm Algorithm [20], respectively. Whale Optimization Algorithm (WOA) [23] replicates the hunting method of a humpback whale. WOA is widespread in solving power system issues. For instance, WOA was used in [24] to find locations and sizes of distributed generation, or in the paper [25], where authors aim to find optimal reactive power output.

This paper uses a free open source power system simulator; OpenDSS [26] to perform the unbalanced three-phase behavior of Almaty 0.4 kV distribution system. OpenDSS is widely used in solving distribution system related problems. For instance, in [27], the authors proposed a new deep reinforcement learning-based method to reach resilient distribution networks in conditions of three-phased unbalanced power flow using OpenDSS. Multi-area aggregation method was proposed in [28] for reducing the number of three-phase four-wire multi-grounded feeders using OpenDSS. The study [29], solved the optimal sizing of battery energy storage system problem considering technical and financial sides by a multi-objective approach.

In [30], the authors proposed a method of dividing the distribution system into several microgrids considering the demand side via switching loads between phases, as a result - solving unbalance problem.

This study uses WOA to solve the optimal operation problem. In this paper, we implemented WOA to solve the optimal operation issue of the modified Almaty 0.4kV distribution system. The rest of the paper is organized as follows. Section II gives the mathematical model of the considered optimization problem. In Section III we briefly explain the working philosophy of the WOA. Section IV is devoted to the implementation of the algorithm to the optimal operation problem. In Section V, we give the test system, and the numerical results. Then the paper is concluded.

II. MATHEMATICAL MODEL OF THE OPTIMIZATION PROBLEM

The mathematical model of the optimization of the operation of the distribution system is given below.

$$\underset{\text{w.r.t. } \vec{X}}{\text{minimize}} F(\vec{X}) = \alpha(V_i - 1)^2 + \beta P_{\text{loss}} \quad (1)$$

$$\vec{X} = \{x_1, x_2, \dots, x_d\}$$

$$\text{Subject to } \begin{cases} -16 \leq \text{Tap}_i \leq 16, i = 1, 2, \dots, n \\ Q_{j\min} \leq Q_j \leq Q_{j\max}, j = 1, 2, \dots, m \end{cases}$$

where n and m represent the number of the voltage regulators, and the number of the PV units in the distribution system. Voltage magnitudes of the nodes are shown with V_i . The total active power loss of the distribution system is shown P_{loss} . The composed objective function aims to minimize the voltage deviations on the nodes and the total active power loss. The α and β parameters show the user defined weights of the composed objective function.

III. WHALE OPTIMIZATION ALGORITHM

This paper applied the meta-heuristic optimization algorithm - Whale Optimization Algorithm (WOA) [23] to solve the operation issue of distributed generations (DGs) in the existing 0.4kV network in Almaty. WOA was inspired by the hunting method of a humpback whale. The humpback whales hunt by creating spiral bubble-net, so prey is in the center of the spiral.

The first phase of WOA is encircling prey. Since the best solution is not known at the beginning, the WOA considers the current solution to be the best one. After the completion of the work of the search agent, the rest of the agents update their position until the best solution is found. The following equations describe this phase [23]:

$$\vec{D} = |\vec{C} \cdot \vec{X}^*(t) - \vec{X}(t)| \quad (2)$$

$$\vec{X}(t+1) = \vec{X}^*(t) - \vec{A} \cdot \vec{D} \quad (3)$$

where t is iteration, \vec{A} and \vec{C} are vectors of coefficients, \vec{X}^* is best solution vector and \vec{X} is vector of position. \vec{A} and \vec{C} are calculated by following equations [23]:

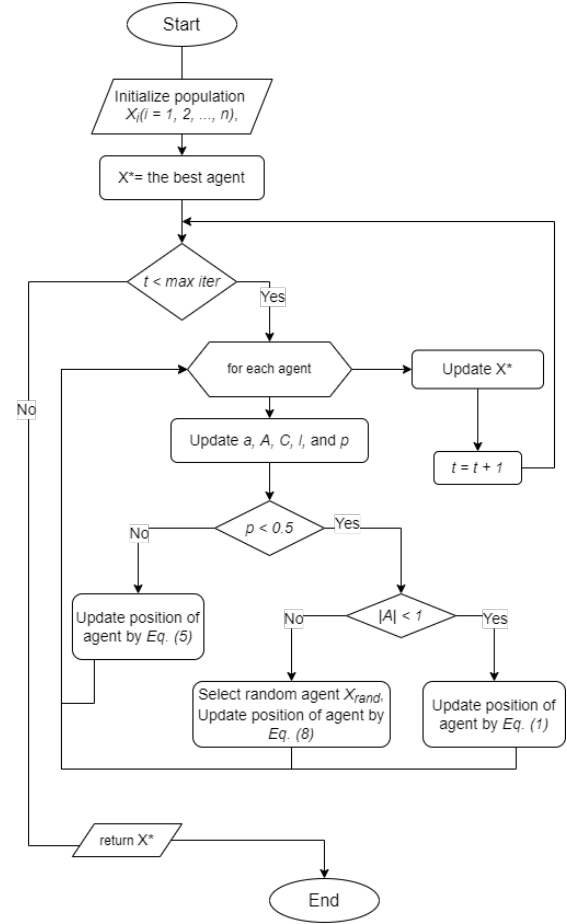


Fig. 1. Flowchart of the WOA method

$$\vec{A} = 2\vec{a} \cdot \vec{r} - \vec{a} \quad (4)$$

$$\vec{C} = 2 \cdot \vec{r} \quad (5)$$

Exploitation phase or bubble-net attacking method consists of the following steps: shrinking encircling mechanism and spiral updating position.

Shrinking encircling mechanism is performed by decreasing \vec{a} of (4). In other words \vec{A} changes randomly between $[-a, a]$.

Spiral updating position is calculating the interval between whale and prey. Spiral equation of whale's movement given as follows [23]:

$$\vec{X}(t+1) = \vec{X}^t \cdot e^{bl} \cdot \cos(2\pi l) + \vec{X}^*(t) \quad (6)$$

where b - is constant logarithmic spiral, l - is random value in range $[-1, 1]$ and \vec{X}^t is distance between i^{th} whale and prey and it equal to [23]:

$$\vec{X}^t = |\vec{X}^*(t) - \vec{X}(t)| \quad (7)$$

Exploration phase of search for prey - is movement of each whale randomly according to the location of each other. Hence, it means we change value of \vec{A} in random

way compare if it greater than 1 or less than -1. The mathematical descriptions are given as follows [23]:

$$\vec{D} = |\vec{C} \cdot X_{rand} - \vec{X}| \quad (8)$$

$$\vec{X}(t+1) = \vec{C} \cdot X_{rand} - \vec{A} \cdot \vec{D} \quad (9)$$

The flowchart of the overall algorithm is given in fig. 1.

IV. IMPLEMENTATION OF WHALE OPTIMIZATION ALGORITHM

The steps for solving the proposed model by using WOA is given below.

- Create initial solution candidates:

$$\text{Candidate} = \begin{bmatrix} \text{Can}_{1,1} & \text{Can}_{1,2} & \cdots & \text{Can}_{1,d} \\ \text{Can}_{2,1} & \text{Can}_{2,2} & \cdots & \text{Can}_{2,d} \\ \cdots & \cdots & \cdots & \cdots \\ \text{Can}_{k,1} & \text{Can}_{m,2} & \cdots & \text{Can}_{k,d} \end{bmatrix} \quad (10)$$

where $\text{Can}_{i,j}$ shows the values of the control values in the allowed ranges. The candidate matrix consists of k different candidate solution sets, each consist of d variables.

- Evaluate (1) for each of the solution candidate by running power flow model in OpenDSS through Matlab, using the set values. Then the best solution candidate is determined.
- Update the parameters of the WOA algorithm.
- Create new solution candidates. For this, a random number is created, if this is less than 0.5, there are two possibilities according to the value of $|A|$. If it is less than 1, the position of the current solution candidate is updated by using (2), otherwise a random solution candidate is formed and the the update operation is performed by using (9).
- Check if there is any violation of the search space for any of the control variables. If exists, methods like mirroring may be employed. Then the objective function value of the each solution candidate is calculated, and compared to the prefound best solution. If the former is better, it is replaced with the best solution.
- This process continues until a predefined stopping criterion is met.

V. TEST SYSTEM DATA PREPARATION

We used a modified Almaty low voltage distribution system. The single line schema of the distribution system is given in Fig. 2. For the base case, the total active and reactive loads are modified to be 253.08 kW and 127.27 kvar, respectively.

We modified the system and include 6 PVs. The locations of the PVs are assumed to be on nodes, 3, 30, 40, 50, 58 and 60. Only on node 3, a three phase PV was assumed to be installed. All other PVs were single phase PVs.

Three different set of simulations were performed. The system configurations for these cases are as follows:

- Case I: Medium Load Level (Total active loads: 253.08 kW, Total reactive loads: 127.27 kvar). Medium PV outputs (All PV outputs set to 3 kW with apparent powers of 5 kVA).
- Case II: High Load Level (Total active loads: 400 kW, Total reactive loads: 320 kvar). Medium PV outputs (All PV outputs set to 3 kW with apparent powers of 5 kVA).
- Case II: High Load Level (Total active loads: 400 kW, Total reactive loads: 320 kvar). Low PV outputs (All PV outputs set to 1 kW with apparent powers of 5 kVA).

VI. TESTS AND SIMULATION RESULTS

The proposed optimization algorithm was tested on a Intel(R) Core(TM) i5-10500 CPU 3.10GHz desktop with 8 GB RAM. The simulations are performed on Matlab incorporated with OpenDSS software.

In Case I, no controlled case shows that some node voltages are less than 0.95 pu, which needs to be brought close to 1 pu to improve the active power losses and a better voltage quality. The active power losses decreased from 2.6428 kW to 2.2948 kW. WOA determined the near optimal voltage regulator set points as 6, 8 and 7 for the voltage regulator installed between nodes 1 and 101. The near optimal reactive power outputs of the PVs were found as 4 kvar for three phase PV on node 3, 4 kvar for all other PVs except the PV on node 60. The reactive power output of the PV on node was found as 0.05 kvar. The change in the voltage magnitudes of the distribution system after near optimal solution is illustrated in Fig. 3.

Before optimization Case II power flow simulation shows that most of the voltage magnitudes on the nodes are even less than 0.90 pu. The reactive power capability of the PVs are used together with the tap changing voltage regulators to solve this issue. The near optimal simulation results show the improvement of the voltage magnitudes as depicted in Fig. 4. Before optimization the active power losses were calculated as 10.2573 kW, after the optimization this decreased to 8.8458 kW. The near optimal voltage regulator values and the reactive power outputs were determined as the maximum possible values: 16 for regulators and 4 kvar for all PVs.

Fig. 5 shows the simulation results of the Case III. This case is similar to Case II because of the load conditions. However since the active power outputs of the PVs are less, this gives more reactive power capability for controlling voltage magnitudes. As shown in Fig. 5, the near optimal voltage magnitudes are better compared to Case II. This time, the active power losses decreased more: 8.7377 kW. The near optimal voltage regulator values were determined as 16, 16 and 16. The reactive power outputs were found as 4.899 kvar for all PVs.

VII. CONCLUSION AND FUTURE WORK

This paper solved operation optimization problem of distribution networks by using WOA. The approach con-

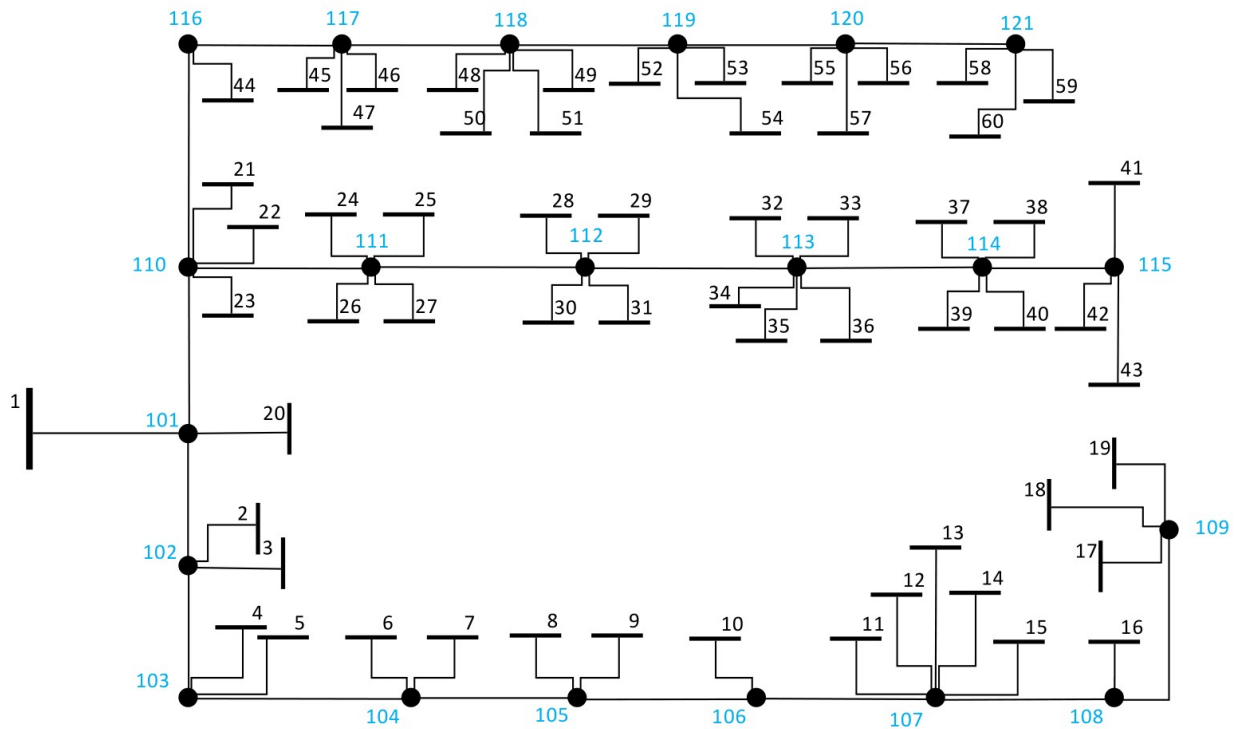


Fig. 2. Scheme of the Almaty 0.4 kV system.

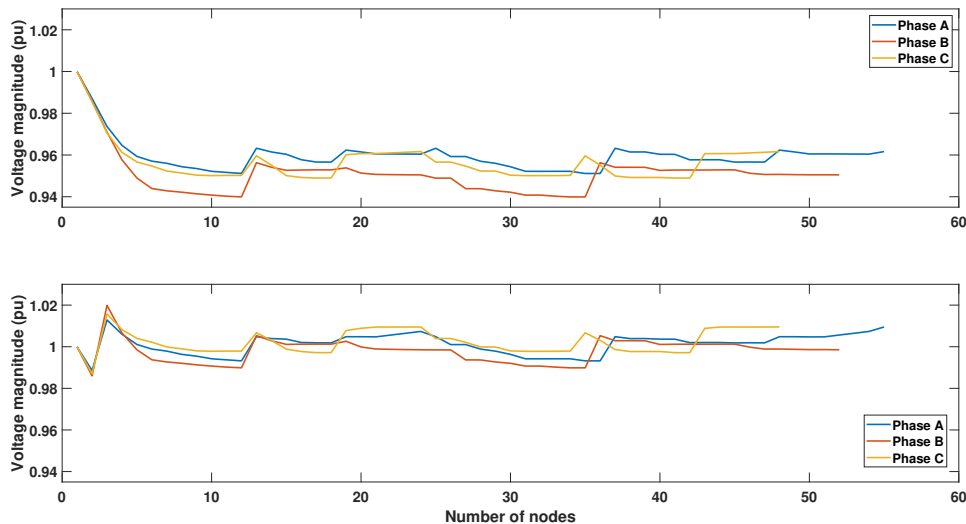


Fig. 3. Case 1 voltage magnitudes before and after optimization (Medium load, medium PV output)

sidered tap changing voltage regulators and reactive power capability of PVs. From the simulation results of three different cases, it is observed that the WOA based optimization approach is able to solve the model to minimize the voltage deviations and minimize the active power losses. Especially for high load cases, the near optimal solutions were determined as the maximum values of the solution space. In future, we are planning to include more renewable energy sources and new loads such as Electric Vehicles to the optimization model.

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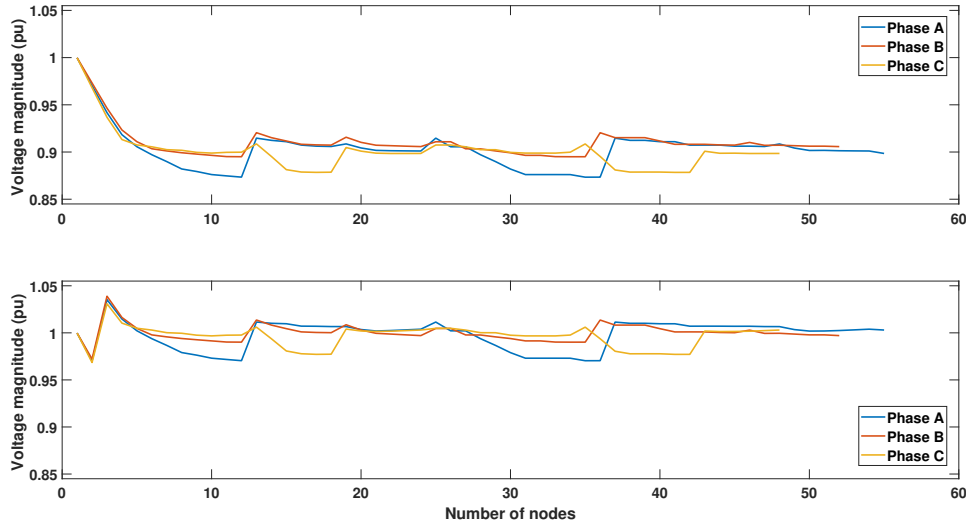


Fig. 4. Case 2 voltage magnitudes before and after optimization (High load, medium PV output)

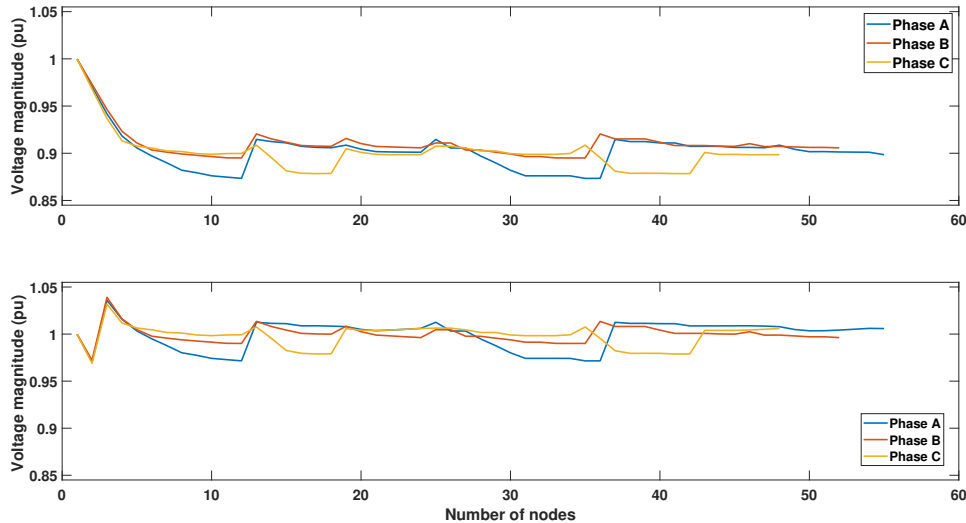


Fig. 5. Case 3 voltage magnitudes before and after optimization (High load, low PV output)

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