 ISSN: 2251-9246
EISSN: 2345-6221

pp. 89:96

A New Approach for Planning a Hybrid AC/DC Distribution Network Using Gray Wolf Optimization Algorithm

Reza Khalilzadeh*, Hassan Majidi, Mahmoud Reza Haghifam

Department of Electrical Engineering, Tarbiat Modares University, Tehran, Iran, r.khalilzadeh@modares.ac.ir

Abstract

In this paper, the Gray Wolf Optimization Algorithm (GWO) will be used for planning a hybrid AC/DC distribution network, and results from the economical and technical point of view will be compared to those of conventional methods, such as Genetic Algorithm (GA). In the proposed model, the objective function is to minimize the Net Present Value (NPV) of the optimal solution. The planning will be done for an empty area, which already doesn't have any distribution network, at the LV level. In the proposed method, the buses and feeders of the network could be AC or DC. Also, there are AC and DC load points and Distributed Generations (DGs) in the planning area. It should be mentioned that in this paper, the uncertainty of load demand and production of DGs has been regarded. Finally, after planning the distribution network as a pure AC and a hybrid AC/DC configuration for a 14-bus test network, NPV, loss of system and the convergence time of the GWO algorithm will be compared to ones from GA, and advantages of the prior will be shown.

Keywords: Distribution Network, Gray Wolf Optimization, Hybrid AC/DC Distribution Network, Planning Distribution Network, Genetic Algorithm

Article history: Received 16-Feb-2021; Revised 20-Feb-2021; Accepted 01-Mar-2021.

1. Introduction

Due to the expansion of distributed generation (DG) sources with DC outputs, such as photovoltaic panels and various types of batteries, increasing reduction of fossil fuel sources, increase of greenhouse gases in the atmosphere, and the emergence of more DC-powered loads, distribution networks planners have shown particular tendency to use DC configurations. Energy incentive policies have been another important factor in increasing the trend toward using DGs with DC output. Hence, it cannot be conclusively claimed that planning of future distribution networks consisting of a significant number of loads and DGs with DC outputs in conventional pure AC configurations is technically and economically viable [1].

From the past to the present, many works have been done in the field of planning a distribution network. For example [2] has proposed a simple way to optimal MV feeder routing and determining the capacity of these feeders, which is based on the Dynamic Programming method using the Markov principle. The authors of [3] have been used a Multi-Objective Genetic Algorithm (GA) to optimal planning of an AC distribution network for an empty area or extending an existing distribution network. The authors of [4] have been used a direct approach based on the Principle of Optimality for optimal planning of an AC distribution network and optimal MV feeder routing. In [5], optimal planning of an AC MV distribution network is performed using Ant Colony Optimization Algorithm. This approach could be used for planning a new distribution network for an empty zone, or for extending an existing one. In [6], a discrete Particle Swarm Optimization (PSO) based approach has been proposed for optimal planning of a distribution network. Authors of [7] have considered the possibility of DGs existence in the planning area, and planning has been performed with GA.

Due to the uncertainties in urban planning, in [8], load points have not been directly used in the planning problem. In this paper, load points with lower uncertainty and higher accessibility have been used as embranchment points, representing some of the load points. In [9], a combination of PSO and Shuffled Frog Leaping Algorithm (SFLA) has been used for planning an AC distribution network.

The authors of [10] have been proposed a GA-based approach for planning a hybrid AC/DC network consisting of DGs, AC and DC residential, commercial, and industrial load points. In [11], the main focus is on optimal MV feeder routing using the Bacterial Foraging Algorithm. The authors [12] used the Multi-objective Imperialist Competitive Algorithm (ICA) to MV feeders routing considering the uncertainty of load prediction. The authors of [13] have been used Minimum Spanning Tree (MST) method for optimal planning of LV feeders and planning a hybrid AC/DC distribution network. In [14], a new stochastic method has been proposed for planning a hybrid AC/DC network. This method finds the optimal hybrid AC/DC configuration of the buses and lines, considering that each bus or line can be AC or DC. Authors of [14] have filled the research gap of their previous work by presenting a new method of simultaneously minimizing the cost of planning and operating an AC/DC hybrid distribution network and minimizing the expected not supplied energy in [15]. In [16], a probabilistic method for running optimal power flow on a hybrid AC/DC distribution network consisting of AC and DC load points, photovoltaic panels, and electric vehicle charging stations has been proposed.

The proposed method in this paper for planning distribution networks tends to minimize the net present value (NPV) of the distribution system considering loads and DGs existing in the planning area, using Gray Wolf Optimization (GWO) Algorithm and comparing the results with conventional optimization algorithms such as GA. The remainder of this paper is organized follows: Section 2 deals with modeling the configuration of the hybrid AC/DC distribution network. The nested optimization problem, the objective functions, and constraints are introduced in section 3. Section 4 examines the gray wolf algorithm. Section 5 includes the optimization procedure and solving the planning problem. Using a 14-bus test network, which is proposed in section 6, NPV, power loss, and convergence time of the proposed model have been evaluated and compared to results of GA. Finally, the conclusion of the paper has been presented in section 7.

2. Configuration of the hybrid AC/DC network

Distribution networks consist of different types of AC and DC loads with different demands, and DGs with AC and DC outputs. To achieve the optimal configuration for supply all load points existing in the planning area, developing an algorithm, which depends on the geographical location of load points and DGs, its output could be a pure AC, a pure DC, or a hybrid AC/DC configuration. Such a network may consist of AC or DC buses and feeders and also necessary converters to convert electrical energy. Various possible configurations for connecting load points and DGs are represented in Figure 1.

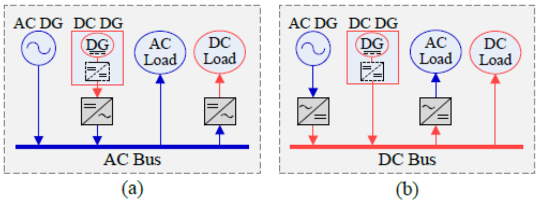

Fig. 1. Connection of loads and power sources to (a) an AC bus and (b) a DC bus [14]

The main goal of this work is finding the optimal configuration (from the NPV point of view), for planning a hybrid AC/DC network in an area consisting of different types of load points and DGs.

The configuration of the planning network in this paper is defined with three binary matrices, which are represented by W, U and D [14]. In other words, these matrices are decision variables in solving the optimization problem. W with N_b rows and one column determines the type of each bus. If each element of this matrix equals 1, the corresponding bus is DC and if it equals 0, the corresponding bus is AC. U with N_b rows and N_b columns determines the connection situation of two buses. If each of the elements of this matrix equals 1 it means that two corresponding buses are connected, otherwise there is no connection between them. D with N_b rows and N_b columns represents the type of connection between buses. If each of the elements of this matrix equals 1, the connection between them is DC, otherwise it is AC.

3. Modeling the optimization problem

As mentioned before, the main goal of solving the optimization problem is minimizing the NPV of the planned distribution network. The optimization problem, which is defined in this paper, is a mixed-integer non-linear problem (MINLP) and will be solved with GWO and GA. The results will be compared in section 4. Because many factors and variables affect this problem, solving it cannot be done by one problem. So the optimization problem should be defined in the main optimization problem and a sub-optimization one. The objective functions and constraints of these two problems will be proposed in the next sub-sections.

A) The main optimization problem

As mentioned, the main objective in this paper is to minimize the NPV of the planned distribution network. The objective function of the main optimization problem is defending as follow:

$$\min \; C_{NPV} \tag{1}$$

In which

$$C_{NPV} = C_{INV} + \sum_{t \in T_p} \frac{C_{AOM,t}}{(1+d)^t} \tag{2}$$

$$C_{AOM,t} = 8760 \times (C_{OPF,t}) + \beta_m \times C_{INV} \tag{3}$$

The calculation method of C_{INV} is described in [15]. In these formulas, C_{INV} is the investment cost of equipment, $C_{AOM,t}$ is annual operation cost of the network, d is the discount rate, t is planning horizon, $C_{OPF,t}$ is annual optimal power flow cost, and β_m is the maintenance factor of equipment.

Because W, U, and D, which represent the network configuration, are binary matrices, their elements must be either 1 or 0. In other words:

$$W_n \in \{0,1\}, \quad \forall n \in \square_B \tag{4}$$

$$U_{nm} \in \{0,1\}, \quad \forall n,m \in \square_B \tag{5}$$

$$D_{nm} \in \{0,1\}, \quad \forall n,m \in \square_B \tag{6}$$

Also to avoid the network from isolating or over connectivity in any of the network buses, (7) and (8) constraints will be defined:

$$\sum_{m=1}^{N_b} U(n,m) \le L^{\max}, L^{\min} \le L^{\max} \le N_b - 1, \forall n \in N_B \tag{7}$$

$$\sum_{m=1}^{N_b} U(n,m) \ge L^{\min}, 1 \le L^{\min} \le L^{\max}, \forall n \in N_B \tag{8}$$

Choosing L^{min} and L^{max} depends on the type of the distribution network's configuration (radial, ring, etc.) and required reliability level. In this paper, to avoid the network from being isolated and keep it in a radial configuration, these two parameters are chosen 1 and 2, respectively. In these constraints, N_B is a set of buses and N_b represents the number of the network's buses.

B) The sub-optimization problem

In the sub-optimization problem defined in this paper, the objective function is minimizing the total cost of energy production, while supplying all load points. The objective function of this sub-problem will be defined as follow:

$$C_{OPF} = \min\left(\sum_{j \in N_G^{ac}} C_{G_j}^{ac} P_{G_j}^{ac} + \sum_{l \in N_G^{dc}} C_{G_l}^{dc} P_{G_l}^{dc} \right) \tag{9}$$

In this objective function, C^{ac}_{Gj} is the price of AC power from each AC power source, P^{ac}_{Gj} is the amount of power supplied from each AC power source, C^{dc}_{Gj} is the price of DC power from each DC power source, and P^{dc}_{Gj} is the amount of power supplied from each DC power source.

There are also some constraints for the production of active and reactive power from each AC or DC power source, which are defined in (10) to (12):

$$P_{G_i}^{ac-\min} \le P_{G_i}^{ac} \le P_{G_i}^{ac-\max} \tag{10}$$

$$P_{G_j}^{dc-\min} \le P_{G_j}^{dc} \le P_{G_j}^{dc-\max} \tag{11}$$

$$Q_{G_i}^{ac-\min} \le Q_{G_i}^{ac} \le Q_{G_i}^{ac-\max} \tag{12}$$

In these constraints, P^{ac-min}_{Gj} and P^{ac-max}_{Gj} are minimum and maximum active AC power, P^{dc-min}_{Gj} and P^{dc-max}_{Gj} are minimum and maximum DC power, and Q^{ac-min}_{Gj} and Q^{ac-max}_{Gj} are minimum and maximum reactive AC power which could be produced from each power source, respectively.

The active and reactive power balance in each bus is one of the essential constraints in solving the sub-optimization problem. These constraints are defined in (13) and (14):

$$P_n^{inj} = P_n^{cal}, \quad \forall n \in \square_b \tag{13}$$

$$Q_n^{inj} = Q_n^{cal}, \quad \forall n \in \square_b \tag{14}$$

The calculation method of injected and consumed active and reactive power in each bus is described in [17]. In these constraints, P^{inj}_n is injected active power in each bus, P^{cal}_n is consumed active power in each bus, Q^{inj}_n is injected reactive power in each bus, and Q^{cal}_n is consumed reactive power in each bus, respectively.

The security constraints of the distribution network, including constraints in voltage magnitude, voltage angle, and the maximum capacity of feeders, are defined in (15) to (18):

$$V_n^{\min} \le V_n \le V_n^{\max}, \forall n \in \square_b \tag{15}$$

$$\theta_n^{\min} \le \theta_n \le \theta_n^{\max}, \; \forall n \in \square_b \tag{16}$$

$$S_{nm} \le S_{nm}^{\max}, \; \forall n,m \in \square_b \tag{17}$$

$$S_{nm} = \sqrt{P_{nm}^2 + Q_{nm}^2} \tag{18}$$

In these constraints, V^{min}_n and V^{max}_n are minimum and maximum permissible voltage magnitude in each bus, θ^{min}_n و θ^{max}_n are minimum and maximum permissible voltage angles in each bus, and S_{nm} is maximum apparent power, which could be flow in each feeder.

Converters have some constraints, which must be considered while solving the sub-optimization problem, too. These constraints are defined in (19) to (21):

$$S_c \le S_c^{\max}, \quad \forall c \in N_c \tag{19}$$

$$M_{nm}^{\min} \le M_{nm} \le M_{nm}^{\max}, \; \forall n,m \in N_b \tag{20}$$

$$S_c = \sqrt{P_c^2 + Q_c^2} \tag{21}$$

In above mentioned constraints, N_c is the set of converters, S^{max}_c is the maximum apparent power of each converter, and M^{min}_{nm} and M^{max}_{nm} are the minimum and maximum modulation index of each converter, respectively.

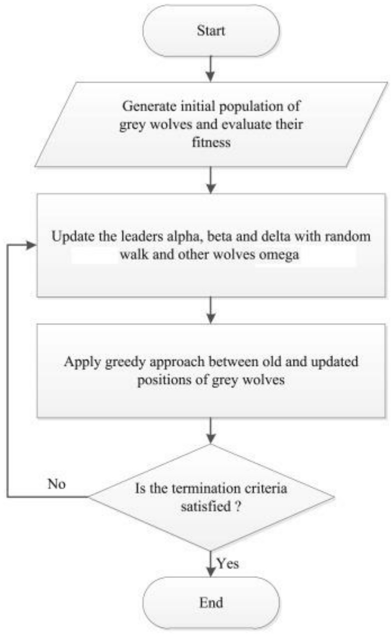

Fig. 2. Gray Wolf Optimization Algorithm flowchart [19]

4. Gray Wolf Optimization Algorithm

The grey wolf algorithm is inspired by the grey wolves which often live and hunt in a pack of 5–12 wolves and follow a certain hierarchy. Hierarchically, grey wolves are divided into four groups: Alpha, Beta, Delta, and Omega. Alpha leads the group and is always in the best position to the prey (optimum point); beta is the alpha's right hand and executes his commands in the group and has a high chance of being selected as an alpha in the following stages; the delta is higher than Omega and lower than beta and last of all is Omega which is bait map in hunting and has no proper position to the prey [18].

In addition to the wolves' hierarchy, their hunting procedure is also interesting, which can use be used for optimization problems; their hunting procedure is generally as follow [19]:

Tracing, chasing and approaching the prey

Surrounding and harassing the prey until it gets exhausted

Attacking the prey

The mathematical modulation of wolf behavior and hunting involves the solution quality ranking based on the wolf hierarchy and has been described in [19]. Flowchart of the GWO algorithm has shown in Figure 2.

5. Planning Approach

In this paper, the network configuration will be achieved by determining W, U, and D matrices. These configurations are flexible and depend on load points and DGs which could change. After running the GWO algorithm and achieving the optimal configuration of the distribution network, results will be compared with those from GA. The flowchart of the planning approach is presented in Figure 3.

This flowchart is described step by step as follow:

- Generating an initial population. Each member of the initial population includes binary matrices (W, U, and D) and it will show a candidate configuration for a hybrid AC/DC network.
- Proceeding with steps 3 to 6 for each member of the initial population with GWO and GA.
- Solving the sub-optimization problem [17].
- Calculating investment cost for each confirmed member of the current population.
- Calculating NPV for every member of the current population, and then checking every constraint of the main optimization problem.
- Evaluating the stopping criteria for optimization algorithm (GA or GWO). If these criteria aren't achieved, the operators of the optimization algorithm will be used to updating the population.

Steps 2 to 6 will be repeated until stopping criteria of the optimization algorithm will be achieved.

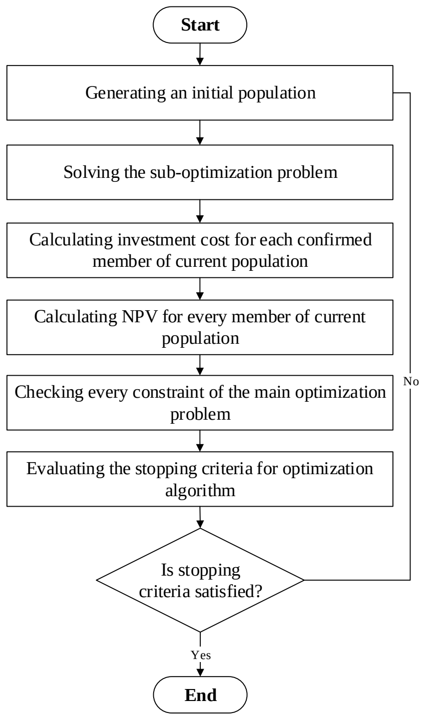

Fig. 3. Flowchart of the proposed method

Table.1.
Input parameters for planning model [14]

Parameters	***Values and Limits***
Base Values (S_{Base}, V_{Base}^{ac},V_{Base}^{dc})	10 MVA, 4.16 kV, 6.8 kV
Voltage magnitude limits (p.u)	V^{min}=0.95, V^{max}=1.05
Voltage angle limits (rad)	Θ^{min}=-π/4, Θ^{max}=π/4
Capacity of feeders	2.0 MVA
Modulation index limits [20]	M^{min}=0.77,M^{max}=1.0
The efficiency of the AC-DC converters	95%
Bus connectivity constraints	L^{min}=1, L^{max}=2
Type of the DC system	Unipolar
Cost of feeders [21]	28,000 $/mile
Cost of converters [22]	170 $/kVA
Annual maintenance cost	5% IC
Planning period	15 years
Discount rate	7.5%

6. Test Network and Results

In order to evaluate the proposed model and comparing results with conventional approaches (in this paper GA), a 14-bus test network will be used. This test network will be planned as a pure AC network and a hybrid AC/DC network with both the GWO algorithm and GA. This network includes subtransmission AC/AC substations, AC and DC load points, photovoltaic panels with DC outputs, wind turbines with AC outputs, and electrical vehicle charging stations. It should be mentioned that in this study electrical vehicle charging stations are only DC consumers and cannot be connected to the grid as an energy producer. The geographical location of network elements has been shown in Figure 4.

In this network, distances of buses from each other, maximum and minimum active and reactive power which could be generated by DGs, load demands and other assumptions, are just like [14] and [15]. An important difference in this study and [14] and [15] is that in this work, the uncertainty of load demands and generation capability of DGs are not considered. In this study, it is assumed that all DGs are capable to generate any amount of active or reactive power between their minimum and maximum power limits. These data, parameters, limitations, and assumptions have been proposed in Table 1 to Table 3.

In order to planning a hybrid AC/DC distribution network and comparing results with those of GA, the test network of Figure 5 is planned as a pure AC network and a hybrid AC/DC network with both GWO algorithm and GA. After achieving configuration matrices (W, U and D), and optimal NPV of planned networks, schematics of pure AC and hybrid AC/DC networks are represented in Figure 5 and Figure 6, respectively. According to achieved matrices from both the GWO algorithm and GA, it can be seen that the optimal configuration of the distribution network is the same, but the time required for achieving the optimal solution and magnitude of the objective functions are different.

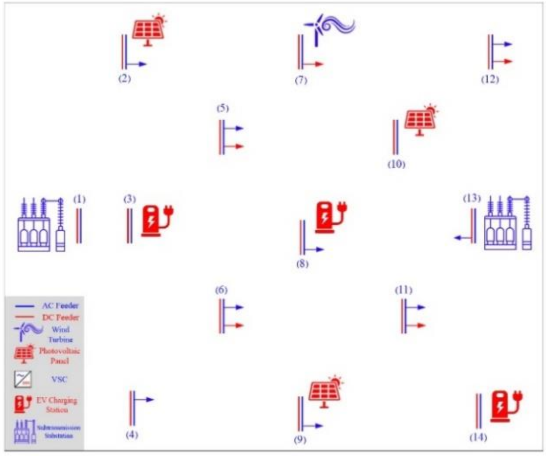

Fig. 4. 14-bus test network

Table.2.
Demand of AC and DC loads [15]

Bus No.	***AC Loads***		***DC Loads***
	P (kW)	***Q (KVAR)***	***P***
1	-	-	-
2	0.50	0.25	-
3	-	-	1.25
4	1.0	0.45	-
5	0.75	0.35	0.75
6	0.50	0.25	0.50
7	-	-	0.85
8	0.50	0.25	1.25
9	0.50	0.25	-
10	-	-	-
11	0.50	0.25	0.5
12	0.50	0.25	0.5
13	0.75	0.35	-
14	-	-	1.25

Table.3.
Data for system power sources [14]

Power Source	***Type***	***Max Active Power (MW)***	***Max Reactive Power (MVAR)***	***Energy Price ($/MWh)***
SS1	AC	10	4.8	92.2
SS13	AC	2	0.96	92.2
PV2	DC	1.5	-	209
PV9	DC	1.5	-	209
PV10	DC	1.5	-	209
WT7	AC	1	-	128

It can be seen from the optimal configuration that planning the distribution network as a pure AC network using GA will be done after 1 hour and 52 minutes. Also, the NPV of this solution and loss of system will be 46.472 M$ and 24.2 MW, respectively. On the other hand, it can be seen that planning the distribution network as a hybrid AC/DC network using GA will be done after 3 hours and 12 minutes. In this case, the NPV of the distribution network will be 43.328 M$ and loss of system will be 21.92 MW.

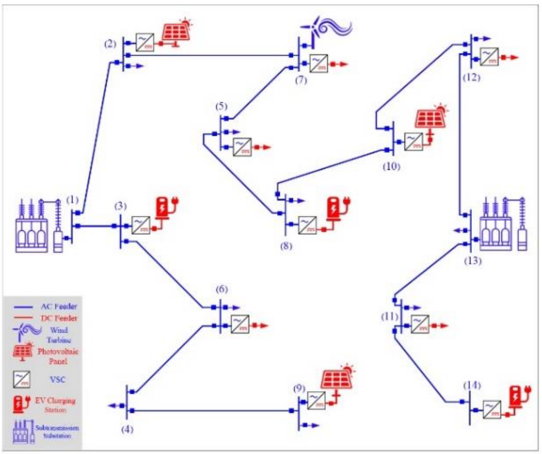

Fig. 5. Optimal configuration of pure AC distribution network

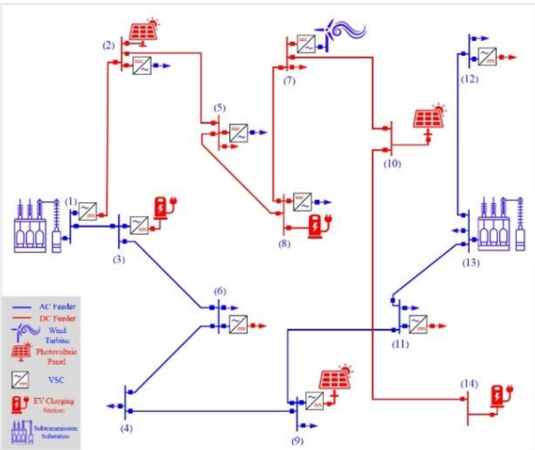

Fig. 6. Optimal configuration of hybrid AC/DC distribution network

If the planning is done with the GWO algorithm, the convergence time, NPV, and loss of system in pure AC and hybrid AC/DC configurations will be 1 hour and 12 minutes, 41.528 M$, 22.87 MW, 2 hours and 16 minutes, 38.886 M$, and 20.367 MW, respectively.

Per unit comparison of NPV, loss, and the time of convergence of planning distribution network as a pure AC, and a hybrid AC/DC network with GWO algorithm and GA has been represented in Figure 7 and Figure 8, respectively. Also per unit comparison of these results for the GWO algorithm and GA in a pure AC and a hybrid AC/DC network has been shown in Figure 9 and Figure 10.

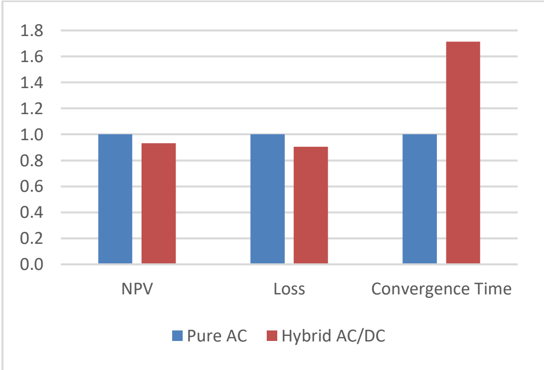

Fig. 7. Per unit comparison of NPV, loss, and convergence time of planning distribution network with GA

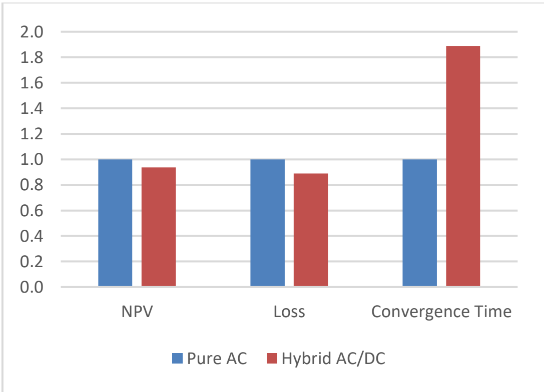

Fig. 8. Per unit comparison of NPV, loss, and convergence time of planning distribution network with GWO algorithm

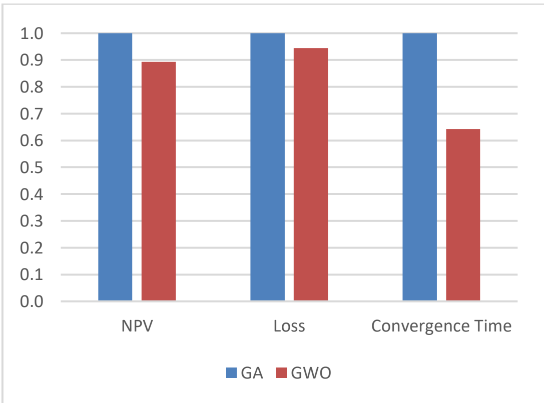

Fig. 9. Per unit comparison of NPV, loss, and convergence time of planning a pure AC distribution network between GWO algorithm and GA

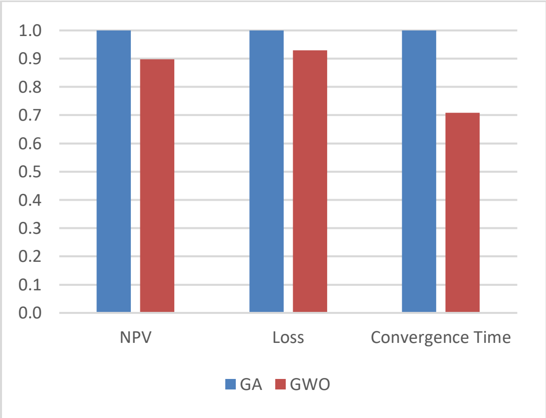

Fig. 10. Per unit comparison of NPV, loss, and convergence time of planning a hybrid AC/DC distribution network between GWO algorithm and GA

7. Conclusion

In this paper, the GWO algorithm used for planning a hybrid AC/DC distribution network and results have been compared to those from GA and pure AC configurations. The introduced model in this work considering the situation of load points and DGs existing in an area is capable of choosing between pure AC, pure DC, and hybrid AC/DC configuration for planning distribution networks. The objective function of the proposed model is to minimize the NPV of a distribution network. In the proposed model, load demands and DGs uncertainties have been regarded. After that, the optimal configuration has been achieved by solving the main optimization problem and a sub-optimization problem.

Finally, a 14-bus test network has been used to evaluate the results of the planning distribution network as a pure AC or a hybrid AC/DC network with both GWO algorithm and GA. After comparing results, it can be seen that regardless which optimization algorithm has been used to plan a distribution network, if different types of AC and DC load points and DGs exist in an empty area, a hybrid AC/DC solution reached lower NPV, loss, and time of convergence than a pure AC one. Of course, the proposed approach highly depends on the situation of load points and DGs existing in the planning area and the type of them.

For future works, we suggest that uncertainty of load demands and DGs will be considered. Also, a fast and effective algorithm could be proposed to plan much bigger networks with many buses, load points, and DGs. Reliability of the system, expected energy not supplied and reliability indexes are also important concepts that can be considered in future works in this field.

References

[1] http://fit.powerauthority.on.ca/fit-program

[2] N. G. Boulaxis and M. P. J. I. T. o. P. D. Papadopoulos, "Optimal feeder routing in distribution system planning using dynamic programming technique and GIS facilities," vol. 17, no. 1, pp. 242-247, 2002.

[3] E. G. Carrano, L. A. Soares, R. H. Takahashi, R. R. Saldanha, and O. Neto, "Electric distribution network multiobjective design using a problem-specific genetic algorithm," vol. 21, no. 2, pp. 995-1005, 2006.

[4] A. Samui, S. Samantaray, G. J. I. G. Panda, Transmission, and Distribution, "Distribution system planning considering reliable feeder routing," vol. 6, no. 6, pp. 503-514, 2012.

[5] J. Gomez et al., "Ant colony system algorithm for the planning of primary distribution circuits," vol. 19, no. 2, pp. 996-1004, 2004.

[6] I. Ziari, G. Ledwich, and A. Ghosh, "Optimal integrated planning of MV–LV distribution systems using DPSO," vol. 81, no. 10, pp. 1905-1914, 2011.

[7] C. L. T. Borges, P. Martins, and E. Systems, "Multistage expansion planning for active distribution networks under demand and distributed generation uncertainties," vol. 36, no. 1, pp. 107-116, 2012.

[8] J. Salehi, M.-R. Haghifam, and E. Systems, "Long term distribution network planning considering urbanity uncertainties," vol. 42, no. 1, pp. 321-333, 2012.

[9] A. Samui, S. Singh, T. Ghose, and S. J. I. t. o. p. d. Samantaray, "A direct approach to optimal feeder routing for radial distribution system," vol. 27, no. 1, pp. 253-260, 2011.

[10] S. Mousavizadeh and M. R. Haghifam, "Integrated AC/DC network planning," 2013.

[11] S. Singh, T. Ghose, and S. J. I. T. o. P. D. Goswami, "Optimal feeder routing based on the bacterial foraging technique," vol. 27, no. 1, pp. 70-78, 2011.

[12] H. Khatami, S. N. J. I. G. Ravadanegh, Transmission, and Distribution, "Probabilistic optimal robust multistage feeder routing under load forecasting uncertainty," vol. 9, no. 14, pp. 1977-1987, 2015.

[13] A. Ghadiri, M. R. Haghifam, S. M. M. J. I. G. Larimi, Transmission, and Distribution, "Comprehensive approach for hybrid AC/DC distribution network planning using genetic algorithm," vol. 11, no. 16, pp. 3892-3902, 2017.

[14] H. M. Ahmed, A. B. Eltantawy, and S. G. Salama, "A planning approach for the network configuration of AC-DC hybrid distribution systems," vol. 9, no. 3, pp. 2203-2213, 2016.

[15] H. M. Ahmed, A. B. Eltantawy, P. Salama, and E. Systems, "A reliability-based stochastic planning framework for AC-DC hybrid smart distribution systems," vol. 107, pp. 10-18, 2019.

[16] R. Zhong, Y. Teng, X. Wang, Y. Zhu, and H. Zhang, "Probabilistic optimal power flow calculation of AC/DC hybrid distribution network with photovoltaic power and electric vehicles," in 2018 International Conference on Power System Technology (POWERCON), 2018, pp. 20-27: IEEE.

[17] H. M. Ahmed, A. B. Eltantawy, and P. S. Salama, "A generalized approach to the load flow analysis of AC–DC hybrid distribution systems," vol. 33, no. 2, pp. 2117-2127, 2017.

[18] L. K. Panwar, S. Reddy, A. Verma, B. K. Panigrahi, and R. Kumar, "Binary grey wolf optimizer for large scale unit commitment problem," Swarm and Evolutionary Computation, vol. 38, pp. 251-266, 2018.

[19] S. Mirjalili, S. M. Mirjalili, and A. Lewis, "Grey wolf optimizer," Advances in engineering software, vol. 69, pp. 46-61, 2014.

[20] M. Kirik, "VSC-HVDC for long-term voltage stability improvement",Master's thesis, Royal Institute of Technology (KTH), School of Electrical Engineering, Department of Electric Power Systems, Stockholm, 2009.

[21] http://www.onestopbuy.co/wire-cable/PENGUIN-41245.asp

[22] McConnell, B.W., "Applications of high temperature superconductors to direct current electric power transmission and distribution." IEEE transactions on Applied Superconductivity, 15(2), pp.2142-2145, 2005.