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Reactive Power Optimization of Distribution Network Considering DG Based on Improved Ant Lion Algorithm

Yuan Hu [1,a], Jing Yang[2,b*], Yuehua Cui[2,c], Xingjun Tian[2,d], Pan He[3,e], Peng Wu[1,f], Fusheng Zhang[2,g] and Jianpeng Bian[2,h]

[1]State Grid Hebei Economic and Technological Research Institute, Shijiazhuang, Hebei Province, 050000, China
[2]School of Electrical and Electronic Engineering, Shijiazhuang Tiedao University, Shijiazhuang, Hebei Province, 050043, China
[3]Hengyang Power Supply Section of China Railway Guangzhou Bureau Group Co., Ltd., Hengyang, Hunan Province, 421000, China

Abstract

Large-scale and high-proportion access of distributed generation to distribution network breaks the original power flow structure of distribution network, which affects the power quality and safe operation of distribution network system. Voltage stability can be maintained through reactive power optimization, and the system operation economy can be improved. In this paper, the influence of distributed generation access on the stability of distribution network is analyzed. On this basis, the mathematical model of reactive power optimization is established with the comprehensive consideration of active power loss and node voltage deviation of distribution network with distributed generation access, and the improved ant lion algorithm with dynamic weight coefficient is used to solve the model. Finally, the simulation analysis is carried out in IEEE33-bus system, and the improved ant lion algorithm and standard ant lion algorithm are used to solve the reactive power optimization of distribution network. The comparison of the optimization results of the two algorithms proves the feasibility and superiority of the improved ant lion algorithm in solving the reactive power optimization problem.

Keywords: Distributed generation, Ant lion algorithm, Reactive power optimization

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1. Introduction

With the increasing global energy crisis, the energy consumption structure has gradually changed from traditional fossil energy to a high proportion of green energy, and distributed power generation has attracted more and more attention and attention. At the same time, China's "peak carbon dioxide emissions, carbon neutral" strategy and the "14th Five-Year Plan" energy plan presented higher demands for the power system to use renewable energy to generate electricity[1]. In 2024, relevant policies to vigorously promote the construction of distributed photovoltaic and decentralized wind power projects were successively issued throughout the country, such as the pilot project of distributed photovoltaic in rural counties, the pilot project of distributed photovoltaic in parks and the "Wind Control Action" in thousands of villages and townships, to promote the realization of dual control of carbon emissions in 2030[2]. As an important part of renewable energy, DG such as scenery will still have a strong development trend in the future, and will gradually replace traditional thermal power units and become a new carrier of energy consumption, in order to accelerate the high quality of distribution networks.

The negative impact of large-scale hierarchical access of distributed wind and scenery on the manipulation of regional network is increasingly prominent. Although the grid connection of DG can realize the balance of region network energy and reduce the investment and loss of long-distance transmission, the logical power of DG such as wind and scenery is random and fluctuating, which has a great lash on

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[a]2830399599@qq.com, [b*]Corresponding author: 711yangjing@163.com, [c]550947705@qq.com, [d]tianxingjun66@163.com, [e]1573585735@qq.com, [f]wupeng11@126.com, [g]zhangfusheng020@126.com, [h]bjp210@126.com

the voltage quality of the electric grid and increases the pressure and complexity of reactive power regulation[3-5]. Especially when photovoltaic power is connected to 10 kV or even 400 V power grid, the impact on user voltage is particularly serious, thus increasing the economic and safe operation of the power grid. Considering the multi-objective premise of economy and efficiency, it is an urgent problem to realize reactive power majorization of region network with region generation under the background of large-scale hierarchical access of wind, light and new energy[6-8].

Reactive power majorization is an indispensable part of the smooth operation of distribution network, which has good help in assure the safe manipulation of the system, improving the quality of power supply and reducing the cost of power supply. At present, the reactive power majorization of distribution network is mainly studied by artificial intelligence algorithm. Literature [9] applies adaptive focused particle swarm majorization to reactive power majorization of power system. Although the refined particle swarm majorization has good global search ability, the mathematical foundation of adaptive focused particle swarm majorization is weak. Literature [10] uses chaotic bat algorithm to refine reactive power of power system, and the refined algorithm strengthens the search ability of optimal value. In reference [11], Pareto entropy multi-objective particle swarm majorization algorithm is applied to reactive power majorization of distribution network, and redundant set strategy is added again to avoid falling into local majorization. Literature [12] introduces singular value decomposition theory and adaptive inertia weight into particle swarm majorization, which promtes the cluster performance of the algorithm and increases the decrement reduction rate by 38.6%. Literature [13] adopts the refined bat algorithm to refine reactive power, which effectively improves the voltage equilibrium of the system and reduces the network decrement. Literature [14] uses genetic algorithm to refine the reactive power of offshore wind farm by improving crossover, mutation operator and disturbance vector weight, which ensures the voltage stability with minimum compensation capacity. Literature [15] uses the refined bacterial foraging algorithm based on immune algorithm to refine reactive power, and the established model has good convergence characteristics in solving the optimal reactive power solution set under the traditional region network. Aiming at the difficulty of reactive power improvement of region network with distributed power provision, this paper studies the influence of distributed power provision on reactive power parameters, establishes a multi-objective majorization mathematical model of static reactive power majorization considering active power decrement and node voltage bias of distribution network by using weighting method, and solves the model with refined ant lion algorithm, and finally realizes reactive power majorization of region network considering region power provision.

2. Analysis of distributed power provision connected to distribution network

In practical engineering applications, distributed generation is mainly connected with region photovoltaic and region wind power, and establishing an effective model with the above-mentioned connected power provision as variables is the basis for analyzing the connection of distributed power provision to distribution network[16].

2.1. Distributed power grid-connected model

2.1.1 Distributed photovoltaic grid-connected model

Distributed photovoltaic uses the electric energy generated by photovoltaic matrix to provide power to DC demands through converter, and provides power to AC demands through converter and inverter and connects to power grid[17]. Excess electric energy can be stored through allocation and storage. Grid-connected photovoltaic power generation adopts two-stage control, and the former stage adopts DC/DC boost. Considering the instability of photovoltaic power generation, the latter stage adopts DC inverter, and the inverter usually uses current-source inverter, which outputs AC current. The equivalent circuit diagram of grid-connected network justs in Figure 1.

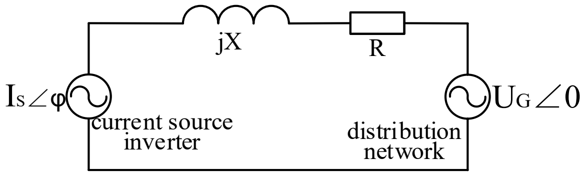

Figure 1. Equivalent Circuit Diagram of Current Source Inverter Connected to Distribution Network

Through the analysis of equivalent circuit, it can be known that the active power and reactive power input by inverter into the power grid are related to its output current and phase angle, and the active and reactive output equations of distributed photovoltaic connected to the distribution network can be obtained[18-20].

$$\begin{cases} P_{\mathrm{pv}} = P_{stc}\dfrac{G_{ac}}{10002}[1+0.45(T_c - 25℃)] \\ P = P_{\mathrm{pv}} \\ P = U_G I_S \cos\varphi \\ Q = -U_G I_S \sin\varphi \end{cases} \tag{1}$$

Where: P_{pv} is the output power of photovoltaic cell at ambient temperature. If the internal loss of the cell is ignored, the output power of current-source inverter is equal to the output power of the cell. P_{stc} is the output power of photovoltaic cells at standard temperature. G_{ac} is the light intensity perceived by the battery. T_c is the ambient temperature. It can be seen that the active power of photovoltaic power generation input into the grid is related to the light intensity, and the reactive power can be controlled by adjusting the amplitude and phase of the output current of the inverter.

2.1.2 Distributed wind power grid-connected model

Wind turbines can operate independently without external force, which is convenient for independent power provision in special areas; It can also be mixed with other new energy sources to generate electricity, which can effectively make up for the instability of wind energy and promote the reliability and coordination of power provision for the side. According to the aerodynamic theory, the mechanical power formula of fan output can be deduced:

$$P_{\mathrm{f}} = \frac{1}{2} A v^3 \rho C_{\mathrm{p}} \tag{2}$$

Where: P_{f} is the mechanical power output of the wind turbine, A is the swept area of the blade,v is the wind speed,ρ is the density of air, and C_{p} is the wind energy utilization coefficient of the wind turbine. Without considering the energy decrement in the process of power generation and grid connection, the active power of wind power input into the distribution network is equal to the sum of the active power output by stator winding and rotor winding, and the reactive power output is equal to the imaginary power export by stator. The formula is as follows:

$$\begin{cases} P = P_{\mathrm{s}} + P_{\mathrm{r}} = (1-s)P_{\mathrm{f}} \\ Q = Q_{\mathrm{s}} \end{cases} \tag{3}$$

Where: P_{s} is the active power output by the stator winding, P_{r} is the active power output by the rotor winding, Q_{s} is the reactive power output by the stator winding and s is the slip rate, which can be obtained according to the characteristics of doubly-fed asynchronous motor.

$$\begin{cases} P_{\mathrm{s}} = U_{\mathrm{s}} i_{\mathrm{sd}} = \dfrac{U_{\mathrm{s}} L_{\mathrm{m}} i_{\mathrm{rd}}}{\left(L_{\mathrm{s}} + L_{\mathrm{m}}\right)K} \\ \mathrm{Q}_{\mathrm{s}} = U_{\mathrm{s}} i_{\mathrm{sq}} = \dfrac{U_{\mathrm{s}} L_{\mathrm{m}} i_{\mathrm{rq}}}{\left(L_{\mathrm{s}} + L_{\mathrm{m}}\right)K} - U_{\mathrm{s}} i_{\mathrm{sq0}} \end{cases} \tag{4}$$

Where: i_{sd} is the d-axis component of stator winding current, i_{sq} is component of stator win current in q axis, i_{sq0} is stator no-load current, L_{s} is leakage inductance of stator winding, L_{m} is that mutual inductance of stator winding and K is the turns ratio.

2.2. The impact of distributed power grid-connected on active power loss

When the region power provision is connected to the region network, the voltage and power of the access point change, and the power flow of the system is affected. In order to analyze the change of active power flow after the region power provision is connected to the distribution network, the circuit diagram of the reigon power provision is established, as shown in Figure 2[21].

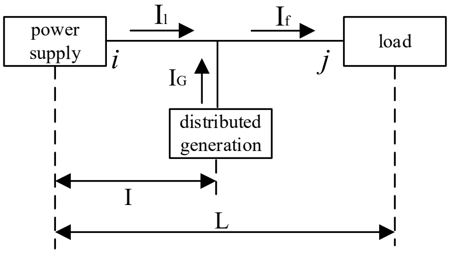

Figure 2. Wiring diagram of access distributed power provision

When line ij is not connected to distributed power provision, the active power decrement is:

$$P_{\mathrm{loss1}} = 3rLI_{\mathrm{L}}^2 = \frac{rL\left(P_{\mathrm{f}}^2 + Q_{\mathrm{f}}^2\right)}{3U^2}$$

Where r is the line resistance, P_{f} and Q_{f} are the active power and reactive power consumed by the load respectively. After the line ij is connected to the distributed power provision, its active decrement is:

$$P_{\mathrm{loss2}} = \frac{rL}{3U^2}\left[P_{\mathrm{f}}^2 + Q_{\mathrm{f}}^2 + \left(P_{\mathrm{G}}^2 + Q_{\mathrm{G}}^2 - 2P_{\mathrm{f}}P_{\mathrm{G}} - 2Q_{\mathrm{f}}Q_{\mathrm{G}}\right)\left(\frac{l}{L}\right)\right] \tag{5}$$

Where: P_G and Q_G are the active power and reactive power injected by distributed power provision respectively.

By comparing the line active power decrement before and after the access of distributed power provision to line ij, it can be known that the access of distributed power provision will change the active power decrement of distribution network system; The active power decrement of distribution network system is related to the output power of distributed power sources and the location where distributed power sources are connected to distribution network.

3. Reactive power optimization model considering DG access

3.1. Objective function

High-quality development of region network is a significant measure to accelerate the construction of new power scheme. Perfecting the coordinated development mechanism between distribution network and distributed new energy sources, and guiding distributed new energy sources to be connected nearby and absorbed locally, the connection capacity of distributed power sources is still on the rise in the future. The objective function should fully consider the security and economy of the electric grid. When solving reactive power majorization of distribution network, it is a multi-objective problem to assue that the network loss and node voltage fluctuation are as small as possible. Focusing on the large-scale application of distributed access distribution network, this paper erects a logical model of effective electric majorization with the comprehensive consideration of active electronic loss and region voltage bias of distributed power access distribution network as the goal, and adopts penalty factor to deal with the voltage exceeding the limit, with the objective function as follows:

$$\mathrm{minf} = \lambda_a \Delta P + \lambda_b U_{d0} + \lambda_U \sum_{i=1} \left(\frac{\Delta U_i}{U_{i,\max} - U_{i,\min}} \right)^2 \tag{6}$$

Where: λ_a and λ_b are the weight factors, respectively. $\lambda_a + \lambda_b = 1$. ΔP is the active cost for power system; U_{d0} is the initial deviation rate of distribution network and λ_U is the penalty factor of voltage exceeding limit.

3.2. Constraint condition

3.2.1 Equality constraints

The equation constraint mainly considers the power balance of the whole system, including the active power and reactive power of the original system and the active power and reactive power put into by the distributed power provision. Due to the intermittent output of the distributed power provision, the active power and reactive power bu used in the distributed power provision have a large of dynamic change characteristics and affect the power flow change of the whole system. In addition, there is the influence of the reactive power indemnity device, which depends on the capacity and location of the reactive power indemnity device. The equation constraint equation after accessing the distributed power provision is as follows:

$$\begin{cases} P_i + P_{DGi} = U_i \sum_{N}^{j=1} U_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) + P_{Di} \\ Q_i + Q_{DGi} + Q_{Ci} = U_i \sum_{N}^{j=1} U_j \left(G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij} \right) + Q_{Di} \end{cases} \tag{7}$$

Where: P_i and Q_i are the active power and reactive power of distribution line node I, P_{DGi}, Q_{DGi} are the active power and reactive power of the among distributed power provision node; Q_{Ci} is the reactive power of the reactive power compensation device at node I.

In the reactive power majorization model of distribution network, the influence of DG on distribution network is embodied in the influence of active and reactive power output of distributed power sources on power flow, especially in the distribution network with high permeability distributed power provision access, the model solution will be more complicated, and it is appropriate by using DSSC and other devices for flexible control.

3.2.2 Inequality constraints

Inequality constraints are mainly affected by the upper and lower limit requirements of equipment parameters related to power flow calculation in power system. The distribution network without distributed power provision mainly includes generator terminal voltage, generator output reactive power, load node voltage and reactive power compensation capacitor. Because the application of SVG equipment in distribution network is relatively low at present, the constraints brought by it are not considered,namely:

$$\begin{cases} Q_{Cimin} \le Q_{Ci} \le Q_{Cimax} \\ U_{Gmin} \le U_G \le U_{Gmax} \\ Q_{Gmin} \le Q_G \le Q_{Gmax} \\ T_{min} \le T \le T_{max} \end{cases} \tag{8}$$

Where: *min* and *max* are the upper and lower limits of the corresponding parameters. By using the region power provision tandemed together it is necessary to consider whether the injected reactive power overtakes the limit, and the constraint conditions are:

$$Q_{Di,min} \le Q_{Di} \le Q_{Dimax} \tag{9}$$

4. Research on reactive power optimization of distribution network based on improved ant lion algorithm

4.1. Improved ant lion algorithm

The ant lion algorithm imitates the behavior of the ant lion preying on ants. The ant lion preying on ants will first create a trap and hide it at the bottom of the trap, waiting for the ants to fall into the trap. When the ants fall into the trap, their survival response will make them try to crawl outward. Faced with this situation, the ant lion will throw the soil up and make the ants slide down until the bottom, and they are successfully captured by the ant lion. After catching ants, the ant lion will ambush at the bottom of the trap again, waiting for new ants. The elitism of ant lion population makes it possible to converge to the optimal solution. In the standard ant lion algorithm, the elite ant lion is selected through its fitness. In the process of random walk, ants are affected by the selection of ant lions and elite ant lions in roulette. The position of ants after iteration is:

$$A_i^t = \frac{R_{\mathrm{A}}^t + R_{\mathrm{E}}^t}{2} \tag{10}$$

Where: A_i^t is the position of the ant in the iteration, R_{A}^t is the wandering component of ant lion selected by ants around roulette and R_{E}^t is the weight of ants swimming around elite ant lions. The iterative updating formula of position is:

$$AL_i^t = A_j^t, \text{ if } f\left(A_j^t\right) < f\left(AL_i^t\right) \tag{11}$$

There are some shortcomings in the standard ant lion algorithm. Ants are influenced by the selection of ant lions and elite ant lions in roulette. Because the fitness of elite ant lions is higher than that of ordinary ant lions, they are more likely to be selected in roulette, which will lead to the phenomenon that the positions of ants are mostly concentrated around the elite ant lions, and may fall into local majorization and premature convergence. The algorithm lacks a regeneration mechanism. In the iterative process, individuals with lower computational efficiency can't help for the population renewal and can't search randomly in space, which promotes the efficiency reduction of the algorithm.

If the weight coefficient of the algorithm is a fixed value, it can not meet the needs of global and local search ability in the iterative process of the algorithm, so the fixed weight coefficient proposed by the standard ant lion algorithm is not optimal. The research focuses on global search at the beginning of the algorithm iteration and local search at the end of the algorithm iteration, which can assue the diversity of the population in the early stage of the algorithm to avoid falling into local majorization and enhance the convergence ability in the later stage of the algorithm iteration. For improving the search ability of ant lion algorithm, dynamic weight coefficient is introduced and trigonometric function is used to improve the weight coefficient. The specific elite weight of ant lion is refined as follows:

$$A_i^t = \omega R_{\mathrm{A}}^t + (1-\omega) R_{\mathrm{E}}^t \tag{12}$$

$$\omega = \frac{1}{4}\cos\left(\frac{t}{\mathrm{T}}\pi\right) + \frac{1}{2} \tag{13}$$

Where: t is the iteration number at present and T is the maximum number of iterations. The change curve of dynamic weight coefficient is shown in Figure 3.

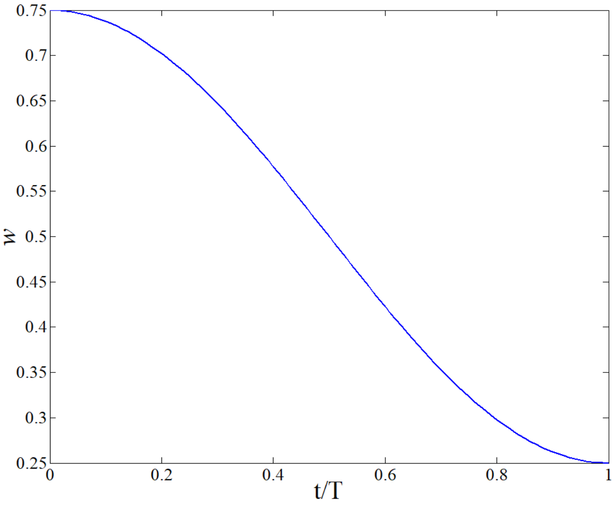

Figure 3. Dynamic weight coefficient curve

In the iterative process of the algorithm, the initial dynamic weight is set to be large, focusing on the global search, that is, the random walk of ants focuses on the influence of the selected ant lion in roulette. When the number of iterations is increasing, ants' random walk begins to focus on the influence of elite ant lions and improve local search ability.

In the standard ant lion algorithm, the initial position of individual population is random, which causes the initial population not to be evenly distributed in space, the population is sparsely distributed near the optimal solution, or the population is excessively concentrated, which affects the majorization effect. In order to prevent this kind of phenomenon, Sobol sequence is used for generating the initial population and improve the diversity of the initial population. The method for generating initial population by Sobol sequence is as follows:

$$x_i = x_{\min} + a\left(x_{\max} - x_{\min}\right) \tag{14}$$

Where: $x_{\max}$ and $x_{\min}$ are the upper and lower limits of population position; a is a random number of [0,1].

4.2. Algorithm implementation steps

The refined ant lion algorithm is to deal with the majorization model, and the initial population size, iteration times, ant lion trap size and other parameters of the model are set. The Sobol sequence is used to initialize the population position and calculate the fitness. Calculate the position of ants after each iteration by Formula (10), calculate the fitness of each ant lion in the ant lion population, and select the elite ant lion. After the ant lion preys on the ant, the position of the ant and the ant lion is exchanged. Selecte an ant lion individual with poor fitness, and updating that position through a Cubic chaotic map; Update the population status of ants and ant lions and re-select elite ant lions. According to whether it meets the optimal reactive power value as the termination condition, the flow chart is in Figure 4.

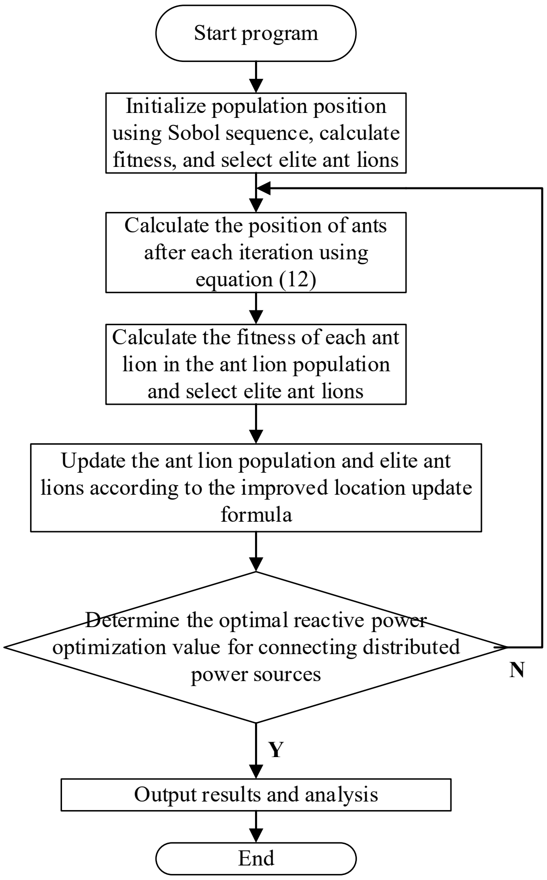

Figure 4. Flow chart of improved ant lion algorithm

5. Example analysis

For the sake of verifying the reactive power majorization affect of the improved ant lion algorithm in the power grid with DG, this paper installs two distributed power sources and two parallel capacitor banks on the basis of the original system through the IEEE33-node system(Figure 4). Two distributed power sources are installed at node 15 and node 30 respectively. It is assumed that both distributed power sources can output active energy and reactive energy to the distribution network system, and the capacity of both region electric loads is 500kW and reactive power is 500kVar. Two 6X100kVa parallel capacitor banks are installed at node 13 and node 29 respectively, and the structural diagram of IEEE33 system after installing distributed power provision and parallel capacitor banks is shown in Figure 5. The reference voltage is 12. 66kV and the power reference value is 500kW.

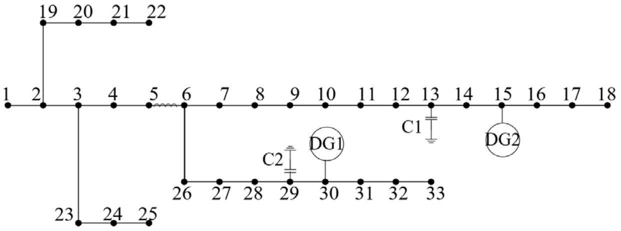

Figure 5. IEEE33-node system model considering DG

Two majorization algorithms, the improved ant lion algorithm and the standard ant lion algorithm, are respectively used to refine the IEEE33-node distribution network system with distributed power provision and reactive power compensation device. The number of iterations is set to 20, and the curve of the objective function with the number of iterations is shown in Figure 6.

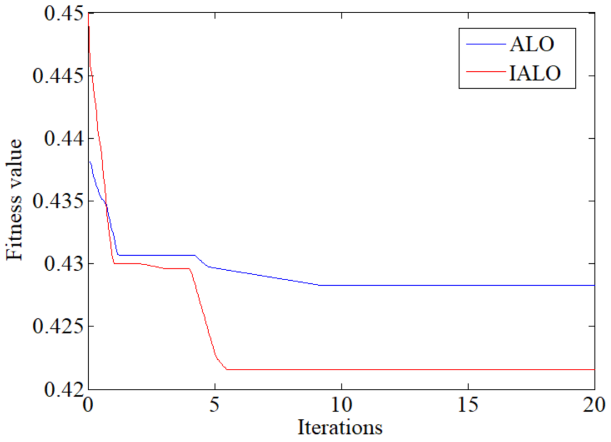

Figure 6. Fitness value of two ant lion algorithm

The improved ant lion algorithm is superior to the standard ant lion algorithm in convergence speed. In the convergence process of the algorithm, the clump curve of the improved ant-lion algorithm basically does not fall into the local optimum for a long time, even if it drop-in the local optimum, it can jump out quickly, and the standard ant-lion algorithm directly drop-in the region consistent during the convergence process; In terms of convergence accuracy, the refined ant lion algorithm is better than the standard ant lion algorithm, and the optimal solution of the improved ant lion algorithm is 0.422, and the optimal consequence of the standard majorization outcome is 0.429.

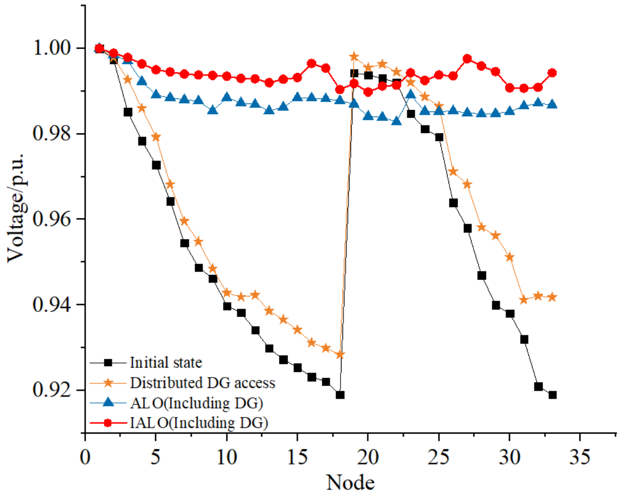

Figure 7. Voltage of each node after optimization by improved ant lion algorithm

The differentiate of node voltages before and after majorization is shown in Figure 7. When the region network is not interlinkaged to the distributed power provision, the voltage level of the original distribution network system is low, and the voltage amplitude of 26 nodes is lower than the specified level, and only 7 nodes reach the standard, accounting for only 21% of the total, of which the voltage amplitude of the 17th node is the lowest, with the minimum value of 0.9221pu ; After the region power provision is connected, the node voltages of distribution network are refined, which all exceed the specified minimum value; When the standard ant lion algorithm and the refined ant lion algorithm are used for optimization, the voltage amplitudes of 33 nodes in the distribution network system are all within the specified range, and the refined ant lion algorithm makes the voltage level of each node in the region network system higher than the standard ant lion algorithm.

According to the results in Table 1, when the distribution network is connected to DG for optimization, its network decrement is 238.5kW; After the standard ant lion algorithm is used to refine the distribution network, the active power decrement of the distribution network system is 148.7kW, and the reduction rate of the active power decrement of the distribution network is 37.7%. After the refined ant lion algorithm is used to refine the distribution network, the active power decrement of the region network system is 125.8kW, and the reduction rate of the active power decrement of the distribution network is 47.3%. The refined ant lion algorithm has better reactive power majorization effect on the distribution network connected with region power sources. By comparison, we can know that both algorithms can meet the requirements of objective function and reduce the active power decrement and Loss of related parameters of region network, but compared with the final optimization results of the two algorithms, the optimization results of the refined ant algorithm are better than those of the standard ant lion algorithm.

Table 1. Comparison Table of Active Power Loss under Different Conditions

Program	Initial state	ALO	IALO
Active power loss	238.5	148.7	125.8
Reduce percentage	0	37.7%	47.3%

6. Conclusion

In this paper, a refined ant lion algorithm is proposed to deal with the reactive power majorization scheme of distributed generation connected to region network system. Firstly, the equivalent model of distributed generation is established, and the repercussion of region generation interlinkaged to distribution network on power flow is further studied. The objective function and constraint conditions of region generation connected to distribution network are analyzed. According to the shortcomings of standard ant lion algorithm, the refined ant lion algorithm is studied. Finally, the simulation analysis is applied to the IEEE33-bus system, with two region electric loads and two reactive power offset equipment connected. A multi-objective optimization function with minimum active power decrement and minimum voltage deviation is established by using the weighting method. At the same time, for the sake of preventing the system node voltage from crossing the line, the voltage amplitude of the constrained node is added to the objective function in the form of a penalty function. By using the improved ant lion algorithm and the standard ant lion algorithm to solve the problem, the majorization results of the two algorithms are compared, which proves the effectiveness of the improved ant lion algorithm in solving the reactive power optimization problem. In terms of algorithm, this paper improves the ant lion algorithm, but in the case of a large number of different types of distributed power provision access, the model solution is more complicated, and its optimization and convergence effect need further study.

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