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Intelligent optimal dispatching of active distribution network using modified flower pollination algorithm

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Abstract: In order to solve the problem of harmonic waves caused by battery energy storage (BES) and distributed generation (DG) inverters in an active distribution network, an intelligent optimal dispatching method based on a modified flower pollination algorithm (MFPA) is proposed. Firstly, the active distribution network dispatching model considering the power quality (PQ) problem caused by BES and DG is proposed. In this model, the objective function considers the additional network loss caused by a harmonic wave, as well as the constraints of the harmonic wave and voltage unbalance. Then, the MFPA is an improvement of a flower pollination algorithm (FPA). Because the MFPA has the characteristics of higher solution accuracy and better convergence than the FPA and it is not easy to fall into local optimal, the MFPA is used to solve the proposed model. Finally, simulation experiments are carried out on IEEE 37 bus and IEEE 123 bus systems, respectively. The experimental results show that this method can achieve satisfactory power quality while optimizing the total active power loss of the branch. The comparative experimental results show that the developed algorithm has better convergence than the FPA.

Key words: active distribution network, flower pollination, optimal dispatching, power quality

1. Introduction

With the rapid development of human society and economy, the problems of energy consumption and environmental pollution is becoming more and more serious. By the end of 2009, 44 cities in China have been listed as resource-exhausted cities, as described in Zhang Y., Meng K., Luo F., *et al.* [1]. In recent years, the development of new energy has higher requirements for the construction of the distribution network and the access of distributed energy resources (DERs) introduces new power points to the distribution network. Large-scale wind and solar energy connected to the distribution network, can help improve the energy structure, but it also brings a lot of problems to the distribution network. An active distribution network (ADN) can reasonably plan distributed generation (DG), enhance the acceptance ability of the distribution network for the DG and solve the above problems brought by the DER access, as described in Itaya N. [2]. With the increase of the DER penetration in the new environment, distribution system operators (DSOs) can play a more active role in command and control, thus potentially bring better economic benefits and energy service quality to customers, as described in Hadush S., Meeus L. [3], and improve the reliability of the distribution system.

Some papers realize optimal scheduling of the ADN by optimizing a battery, as described in Yang Jiaran, Wang Xingcheng, *et al.* [4]. Yang Jiaran, Wang Xingcheng, *et al.* [4] further improve the disadvantage of fixed cycle length of charge and discharge, and begin to study a flexible battery management system, so as to ensure higher economic benefits. Si Jingjing [5] considers wind power generation and battery devices into the calculation of the optimal active and reactive power flow of distribution network. The battery device has a fixed daily charging and discharging cycle length. Dong Lei, Gong Chengxiao, *et al.* [6] introduce four variables to define forward and reverse active and reactive power flows. The papers above adopt traditional mathematical programming methods. Although the obtained solutions can guarantee the optimality and calculation rate, certain model accuracy needs to be sacrificed in the process of simplification.

Gabash A. and Li P. [7] put forward a new model of environmental and economic dispatch for a wind power generation system including operation risk and standby cost. Based on a flower pollination algorithm and differential evolution algorithm, an optimization algorithm with a time-varying fuzzy selection mechanism is proposed. As described in Urvinder Singh and Rohit Salgotra [8], a new flower pollination algorithm (FPA), namely an enhanced flower pollination algorithm (EFPA), is proposed. This algorithm makes use of the Cauchy mutation concept in global pollination to enhance local search and improve the exploration and development trend of the FPA. It also uses dynamic switching to control the speed of exploration and development. Although the above methods do not need to linearize the model and convex programming, it can ensure a certain computing speed, but the results obtained cannot guarantee the global optimality. Rohit Salgotra and Urvinder Singh [9] propose a new FPA variant named an adaptive levy flower pollination algorithm (ALFPA), it uses a new mutation operator, dynamic switching, and an improved local search algorithm. However, in the ALFPA with a low population size, there is less diversity of possible solutions, so its exploration effect is poor. Ong Kok Meng, Ong Pauline, Sia Chee Kiong and Low Ee Soong [10] propose a moving target tracking algorithm based on a modified flower pollination algorithm (MFPA). Experimental results show that this algorithm is superior to other algorithms in efficiency and accuracy.

Most of the existing research results only focus on the impact of an energy storage battery in an active distribution network, and seldom consider the coordination between a wind farm and an energy storage battery. In addition, there are some defects in the solution methods of the optimization problems. For example, due to the inherent precocity of a particle swarm optimization algorithm, it is easy to fall into local optimization, resulting in randomness of each optimization result. Based on the existing researches, this paper proposes an active distribution network optimal scheduling strategy based on an MFPA. The strategy considers the power quality problem caused by the harmonics generated by the inverters of battery energy storage and distributed generation in the active distribution network. Because the MFPA has higher solution accuracy and better convergence than the FPA, it can achieve a better global optimization ability, so it can achieve a better scheduling effect.

2. Optimization dispatching model of active distribution network

The main task of active distribution network scheduling is to dispatch each generation unit to control the power supply and energy consumption in the active distribution network (ADN). The optimization goal of the scheduling model is to minimize the energy consumption of the ADN to ensure power quality by controlling energy storage and controllable distributed generation, such as a wind-driven generator and photovoltaic generator.

2.1. Dispatching control strategy of active distribution network

Active distribution network optimal scheduling involves a wide range of contents, including the acquisition of the system external information, structure information and operation information, the design of the optimal scheduling program and the transmission of the scheduling control information. The external information mainly includes the weather information and the external power purchase price that influences the output of distributed energy such as the wind energy and photovoltaic in an active distribution network (ADN). The optimal scheduler is the core of the whole system. It means to integrate all the obtained internal and external information, calculate the optimal scheduling control information of each component involved in the active distribution network scheduling, and make the output plan for it accordingly. Dispatch control information, as the precondition of operation scheduling, is issued by the optimal operation management system of the active distribution network and transmitted to all scheduling resources within the jurisdiction of the system.

The control contents of the active distribution network include generation control, a voltage source converter (VSC), load control and so on, including the output power control of controllable distributed generation (DG), the charging and discharging control of a centralized energy storage system (ESS) and flexible load control that can be adjusted to a certain extent according to the actual operating load. Generally, the owner of the controlled distributed energy resource (DER) needs to sign a contract with the grid operator, accepts the dispatch instructions from the grid operator and obtains benefits from the grid operator.

Fig. 1 shows the structure diagram of active distribution network optimal scheduling operation. From Fig. 1, it can be seen that the various components of the ADN, the required internal and external information, and the coordination relationship between the various components are involved in the ADN scheduling. In general, the acquisition and delivery of the internal and external information can be accomplished through advanced information and communication technology (ICT).

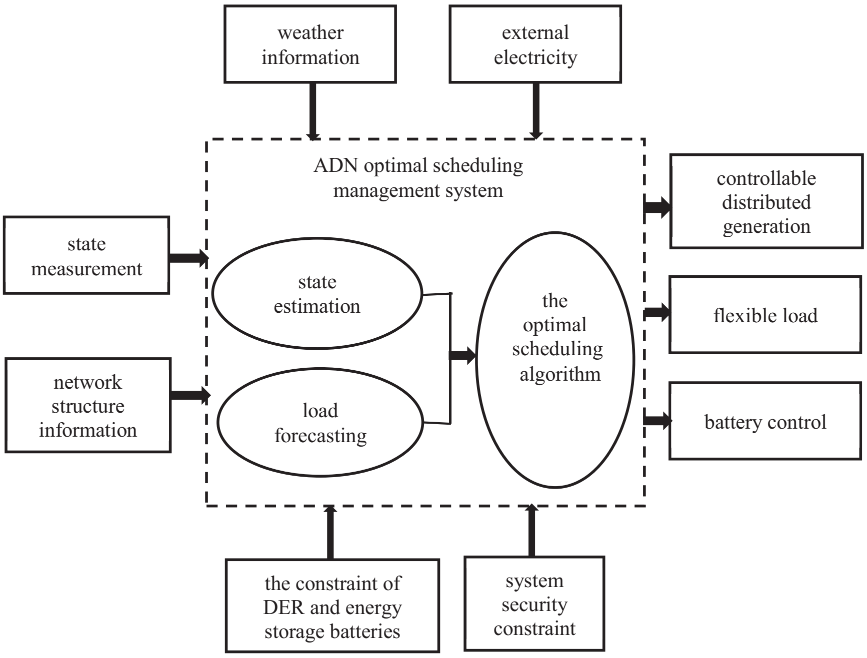

Fig. 1. ADN optimal scheduling management system structure diagram

2.2. Active distribution network scheduling model

2.2.1. Objective function

Battery energy storage (BES) and distributed generation (DG) are introduced into the active distribution network (ADN), and the harmonic wave problem caused by the inverter will lead to more active power loss in the network. Therefore, the power loss of the network with all related frequencies is taken into account, as shown in Equation (1):

$$F = \sum_{t=1}^{T} \left(P_{\text{loss}}^{t} + \sum_{h \in \Omega} P_{\text{loss}}^{t,h} \right), \tag{1}$$

where: P_{loss}^{t} is the network active power loss of base frequency under time t, $P_{\text{loss}}^{t,h}$ is the network active power loss under time t when the harmonic frequency is h, and Ω is the collection of related harmonic frequencies.

2.2.2. Constraint condition

a. Power quality constraint

1. Total harmonic distortion (THD) constraint

In this paper, THD is used to recalculate the total harmonic level at bus i:

$$\frac{\sum_{h \in \Omega} \left(v_{i,h}^{p,t} \right)^2}{v_i^{p,t}} \le \text{THD}_{i,\max}, \qquad p = a, b, c, \tag{2}$$

where: $v_i^{p,t}$ and $v_{i,h}^{p,t}$ are the base frequency voltage and the voltage when harmonic frequency is h of p phase at bus i under time t, respectively. $\mathrm{THD}_{i,\max}$ is the upper limit of THD.

2. Voltage unbalance factor (VUF) constraint

A voltage unbalance factor (VUF) can be used to reflect voltage unbalance levels, so the following constraint is used to ensure a good voltage unbalance level:

$$\frac{v_i^{2,t}}{v_i^{1,t}} \times 100 \leq UM\%, \tag{3}$$

where: $v_i^{1,t}$ and $v_i^{2,t}$, respectively, represent the positive and negative sequence voltages of bus i at time t. $UM\%$ refers to the upper limit of the VUF. Here, the VUF is calculated only with voltage at base frequency, because only the voltage at the base frequency is the sine wave.

b. System security constraints

1. Root mean square (RMS) voltage constraint

$$v_{i,\min}^{p} \leq v_{i,\mathrm{rms}}^{p,t} \leq v_{i,\max}^{p}, \qquad p = a, b, c, \tag{4}$$

$$v_{i,\mathrm{rms}}^{p,t} = \sqrt{\left(v_i^{p,t}\right)^2 + \sum_{h\in\Omega}\left(v_{i,h}^{p,t}\right)^2}, \tag{5}$$

where: $v_{i,\mathrm{rms}}^{p,t}$ is the RMS voltage of bus i at time t and phase p, $v_{i,\min}^{p}$ and $v_{i,\max}^{p}$ are, respectively, the lower and upper limits of $v_{i,\mathrm{rms}}^{p,t}$.

2. Root mean square (RMS) current constraint

$$I_{ij,\min}^{p} \leq I_{ij,\mathrm{rms}}^{p,t} \leq I_{ij,\max}^{p}, \qquad p = a, b, c, \tag{6}$$

where: $I_{ij,\mathrm{rms}}^{p,t}$ is the RMS current between bus i and j, $I_{ij,\min}^{p}$ and $I_{ij,\max}^{p}$ are the lower and upper limits of $I_{ij,\mathrm{rms}}^{p,t}$, respectively. The calculation method of $I_{ij,\mathrm{rms}}^{p,t}$ is as follows:

$$I_{ij,\mathrm{rms}}^{p,t} = \sqrt{\left(I_{ij}^{p,t}\right)^2 + \sum_{h\in\Omega}\left(I_{ij,h}^{p,t}\right)^2}, \tag{7}$$

where: $I_{ij}^{p,t}$ and $I_{ij,h}^{p,t}$, respectively, represent the base frequency current and the current when the harmonic frequency is equal to h between bus i and j at time t.

c. Battery energy storage (BES) constraints

As described by Wang W., He W., Cheng J., *et al.* [11], the energy constraint, power constraint and charge/discharge cycle constraint of the BES are listed as follows:

1. Energy constraint

$$E_i^t = E_i^{t-1} - \varepsilon P_i^{ES,t}\Delta t, \tag{8}$$

$$\varepsilon = \begin{cases} \varepsilon_{\mathrm{in}} & P_i^{ES,t} < 0 \\ 1/\varepsilon_{\mathrm{out}} & P_i^{ES,t} \geq 0 \end{cases}, \tag{9}$$

$$E_i^{24} = E_i^0, \tag{10}$$

$$E_{i,\min} \le E_i^t \le E_{i,\max}, \tag{11}$$

where: E_i^t is the energy stored in i-th BES under time t, $E_{i,\min}$ is the lower limit and $E_{i,\max}$ is the upper limit of E_i^t, $P_i^{ES,t}$ is the active power of the BES, ε_{in} and $1/\varepsilon_{\text{out}}$ are the charge and discharge factor of the BES, respectively.

In the above four formulas, Equation (8) represents the relationship between the energy levels in two consecutive time periods, Equation (10) indicates that the final value of the energy needed to be stored is equal to the initial value, and Equation (11) limits the upper and lower bounds of the stored energy.

2. Power constraint

In order to ensure that the active power, reactive power and apparent power are within the limits, the following constraints are applied:

$$-P_{i,\text{rated}}^{ES} \le P_i^{ES,t} \le P_{i,\text{rated}}^{ES}, \tag{12}$$

$$Q_{i,\min}^{ES} \le Q_i^{ES,t} \le Q_{i,\max}^{ES}, \tag{13}$$

$$\sqrt{\left(P_i^{ES,t}\right)^2 + \left(Q_i^{ES,t}\right)^2} \le S_{i,\max}^{ES}, \tag{14}$$

where: $P_{i,\text{rated}}^{ES}$ is the rated active power of the BES, $Q_i^{ES,t}$ is the reactive power of the BES, $Q_{i,\min}^{ES}$ and $Q_{i,\max}^{ES}$ are the lower and upper limits of $Q_i^{ES,t}$, $S_{i,\max}^{ES}$ is the apparent power limit of the BES.

3. Charge/discharge cycle constraint

The battery energy storage only allows one cycle of charge and discharge in one day due to the limitation of the battery life. The restriction is as follows:

$$N_i^{BES} \le 1, \tag{15}$$

where: N_i^{BES} is the cycle of charge and discharge of i-th BES.

4. Distributed generation (DG) limits

$$P_{i,\min}^{DG} \le P_i^{DG,t} \le P_{i,\max}^{DG}, \tag{16}$$

$$\phi_{i,\min}^{DG} \le \phi_i^{DG,t} \le \phi_{i,\max}^{DG}, \tag{17}$$

where: $P_i^{DG,t}$ represents the active power generated by distributed generator i of non-renewable resources at time t, $P_{i,\min}^{DG}$ and $P_{i,\max}^{DG}$, respectively, represent the lower limit and upper limit of $P_i^{DG,t}$. Equation (16) is used to describe the active power control of a micro turbine, etc. $\phi_i^{DG,t}$ represents the power factor angle of the distributed generator, $\phi_{i,\min}^{DG}$ and $\phi_{i,\max}^{DG}$ represent the lower limit and upper limit, respectively. Equation (17) is used to represent the reactive power control of distributed generators.

3. Active distribution network scheduling model based on modified flower pollination algorithm

3.1. Flower pollination algorithm

A flower pollination algorithm (FPA) is a meta-heuristic algorithm proposed by Yang according to the flower pollination process, as descriped in Rathasamuth W., Nootyaskool S. [12]. Yang discovered the following characteristics of the flower pollination algorithm through research:

1. Biological cross-pollination can be regarded as a global pollination process, which is carried out by pollinators carrying pollen particles in a Lévy flight.
2. Non-biological self-pollination can be regarded as a process of local pollination.
3. Flower constancy can be considered as reproductive probability, which is directly proportional to the similarity of two flowers.
4. The global pollination and local pollination of flowers are regulated by the conversion probability $p \in [0, 1]$. According to the experimental study on this parameter in Rathasamuth W., Nootyaskool S. [12], $p = 0.8$ is more conducive to the optimization of the algorithm.

The global update formula:

$$x_i(t+1) = x_i(t) + L\left(x_i(t) - x_{\text{best}}(t)\right), \tag{18}$$

Since insects can fly long distances at various steps, a Lévy flight can simulate such flight, so L follows the Lévy distribution.

The local update formula:

$$x_i(t+1) = x_i(t) + m\left(x_j(t) - x_k(t)\right), \tag{19}$$

where m is a random number subject to uniform distribution on [0, 1]. $x_i(t)$ and $x_k(t)$ are the pollens for different flowers of the same species.

A flower pollination algorithm (FPA) requires fewer tuning parameters and lower computational cost, but it uses a typical random method to select the initial solutions. Due to the low diversity of the population, there are problems such as slow convergence rate and prematurity. Therefore, applying the FPA in the case of random initial population will cause the search process to be conducted in an inappropriate search space, which may lead to a poor solution or local optimization. In the FPA development process, the lack of information shared between good solutions leads to a poor convergence rate. On the other hand, the random walking behavior of the FPA during the whole detection process may slow down the convergence rate.

3.2. Modified flower pollination algorithm

In view of the defects of the FPA, an MFPA is proposed in this paper and modified from three aspects: (i) initializing the initial population based on chaos theory, (ii) adaptive step-size strategy is adopted in the search process, and (iii) on this basis, the information sharing method based on a leaping algorithm is proposed. Algorithm 3-2 shows the flow chart of the MFPA and the steps are explained as follows:

Step 1. Parameter initialization

Step 2. Generate initial population

The initial population of d-dimensional n flowers is shown in Equation (22):

$$x_{n+1} = (x) - floor(x), \tag{20}$$

where:

$$x = x_n + 0.2 - (0.5/2\pi)\sin(2\pi\, x_n), \tag{21}$$

$$x_{i,j} = x_{\min,j} + (x_{\max,j} - x_{\min,j})x_n\,, \tag{22}$$

where: $x_{\min,j}$ and $x_{\max,j}$ are the lower bound and upper bound for the dimension j, with $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, d$. x_n is a chaotic sequence generated by circular mapping, as shown in Equation (20).

Step 3. Information sharing based on frog leaping algorithm

According to a frog leaping algorithm, the local search of the MFPA algorithm contains information exchanged between different information solutions. Therefore, the population of n flowers is divided into m tribal groups, and each tribe group has p flowers. For each tribal group, the flower with the lowest fitness value will conduct local search within the maximum stride range $s_{\max}$, according to:

$$x_{wi}(t+1) = x_{wi}(t) + rand\,(x_{bi}(t) - x_{wi}(t)) - s_{\max}\,, \tag{23}$$

where: *rand* is a random value from a uniform distribution over the interval [0, 1], while x_{wi} and x_{bi} denote the worst flower and best flower in the tribal group i, respectively. In the study, each tribe always has three flowers.

Step 4. Perform Lévy flight random-walk with adaptive step size strategy

For each solution, $x_i(t)$, an evenly distributed number, *rand*, is generated from the uniform distribution [0, 1]. If $rand > switching\ probability$, the Lévy flight random walk is performed from the position of $x_i(t)$, in order to generate a new potential better solution $x_i(t+1)$, which is characterized by:

$$x_i(t+1) = x_i(t) + \alpha L\,(x_i(t) - x_{\text{best}}(t))\,, \tag{24}$$

where t denotes the current generation number, L is the Lévy distribution, and $x_{\text{best}}(t)$ is the best solution. The α is the step size control parameter proposed by Ong Kok Meng, Ong Pauline, Sia Chee Kiong and Low Ee Soong [10], according to:

$$\alpha = \alpha_L\left(1 + \frac{\alpha_U}{\sqrt{t}}\tan h\left(\frac{x_i(1)}{x_{\text{best}}(t)}\right)\right), \tag{25}$$

where: α_L and α_U are the predefined minimum and maximum step sizes, respectively. T denotes the t-th iteration number, $\tan h(\cdot)$ is the hyperbolic tangent, $x_i(1)$ is the best fitness value in the initial population.

Step 5. Update the new solution

If a new solution is found that is better, it will replace the previous generation of solutions. Then, the optimal solution $x_{\text{best}}(t)$ is updated.

Step 6. Termination criteria terminate when the algorithm reaches a predetermined maximum number of iterations.

Algorithm 3-2 modified flower pollination algorithm

Establish objective function and constraint conditions
Input parameters: n (number of candidate solutions), p (switch probability), a minimum Lévy flight step size, maximum Lévy flight step size, it (maximum number of iterations)
Generate initial population of n flower $x_i(1)$, $i = 1, 2, \ldots, n$ using a circle map:
Set $i = 0$
while $i < n$
    $i = i + 1$
    Evaluate the fitness function, $F_i(1) = f(x_i(1)$
end while
Find the minimum fitness value among all flowers
Set $t = 1$
while $t < it$
    $t = t + 1$
    For all flowers, perform a Lévy flight random walk with adaptive step size strategy:
    Divide n flowers into m tribal groups
    set $group = 0$
    while $group < m$
    $group = group + 1$
    Identify the worst flower in a tribal group
    The worst flower, $x_{w(i)}(t-1)$ is updated using Equation (22)
        if $F_{w(i)}(t) < F_{w(i)}(t-1)$
            Maintain $x_{w(i)}(t)$
        else
            Replaced $x_{w(i)}(t)$ with a random number within limits
        end if
    end while
    Remix all tribal groups
    while $i < n + 1$
        Generate a random number, $rand$
        if $rand < p$
            Generate a new flower, $x_i(t)$ using Equation (23)
        else
            The new flower, $x_i(t)$ is equal to the previous generation flower, $x_i(t-1)$
        end if
        $i = i + 1$
    end while
    Evaluate New Solutions
    Update the current global best solution
end while
Output the optimal solution

In Equation (25), the adaptive step size α is formulated in such a way that α_U is assigned as 10, initially. Then, a parametric study is carried out to identify the most appropriate value for α_U. From some studies, it has been observed that $\alpha_U = 8$ works more effectively for the optimal dispatching of an active distribution network. Notice that since $0 \leq \tan h(\cdot) \leq 1$, the term α_L is assigned as 1 and is imposed on Equation (25) such that the step size will not equal to zero. In addition, the inclusion of $\sqrt{t}$ ensures that the global searching of the MFPA is focused on exploration at the outset. As the number of iterations increases, the value of α decreases, so the MFPA search moves in the utilization direction at the end of the search.

3.3. Optimization scheduling of active distribution network based on modified flower pollination algorithm

Fig. 2 shows the MFPA-based scheduling flow chart of active distribution network.

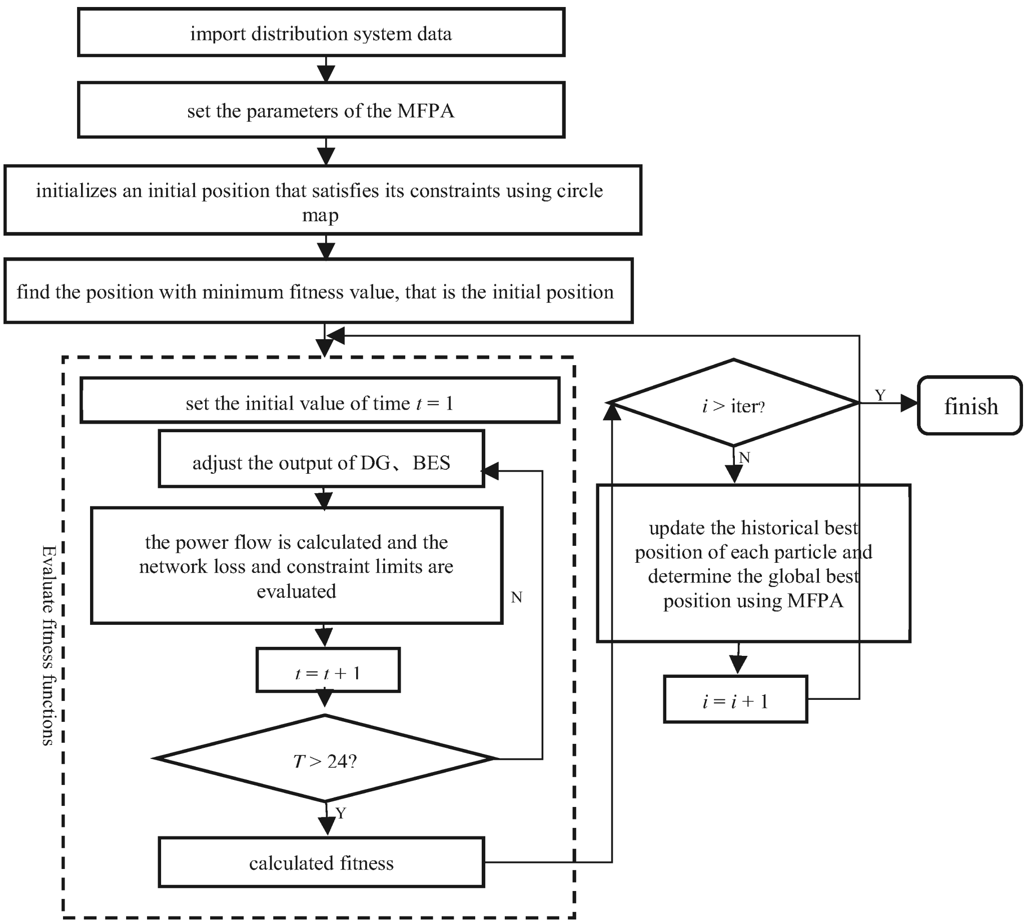

Fig. 2. Flowchart of active distribution network scheduling based on MFPA

4. Simulation verification and analysis

4.1. Experimental environment

This paper adopts the method proposed by IEEE 37 bus and IEEE 123 bus system verification. Guo Qing, Hui Xiaobin, Zhang Jiakui, Li Zhengxin [13] set the total load of the system and the active power generated by wind power generation per hour. The current extreme value of each phase of the distribution line is set as 600 A, and the rated current of the three-phase transformer is increased to $\sqrt{3}$ times of the original value. The generator object of OpenDSS was used to add and model the wind generator (WG) and battery energy storage system (BES). The BES charging-discharging efficiency is set as 0.9, and the initial, upper and lower limits of the BES were set as 50%, 90% and 20% of the rated energy, respectively. Table 1 and Table 2 show the parameter settings of the test system. Other parameters use the default values set in OpenDSS. It is assumed that the capacitor is switchable and its adjustable size is 1~5.

Table 1. Related parameters of battery energy storage system

	node	**Apparent power (kVA)**	**Rated active power (kW)**	**Maximum reactive power (kvar)**	**Rated storage capacity (kWh)**
IEEE 37 node system	709	100	100	100	850
IEEE 123 node system	76	100	100	100	850
	68	100	100	100	850

Table 2. Related parameters of simple harmonic load

	IEEE 37 node system	**IEEE 123 node system**
Harmonic load busand phase	Bus 742 (B phase)	
	Bus 723 (C phase)	Bus 76
	Bus 715 (A phase)	Bus 73
	Bus 736	

In all of the following simulations, the upper and lower limits of voltage are set to 1.10 and 0.90, respectively. The limits for the total harmonic distortion of voltage and the single harmonic distortion of voltage are set to 5% and 3%, respectively. In this paper, the method without considering power quality (NPQ) is compared with the power quality (PQ) method proposed, and we analyze the operation results of 30 iterations.

4.2. Results analysis

1. Analysis of optimal scheduling results

For the IEEE 37 bus system, it is assumed that two capacitor Banks (0, 400) kvar with a distance of 80 kvar are installed on 737 and 706 buses, respectively. The results are shown in Fig. 3, Fig. 4 and Fig. 5.

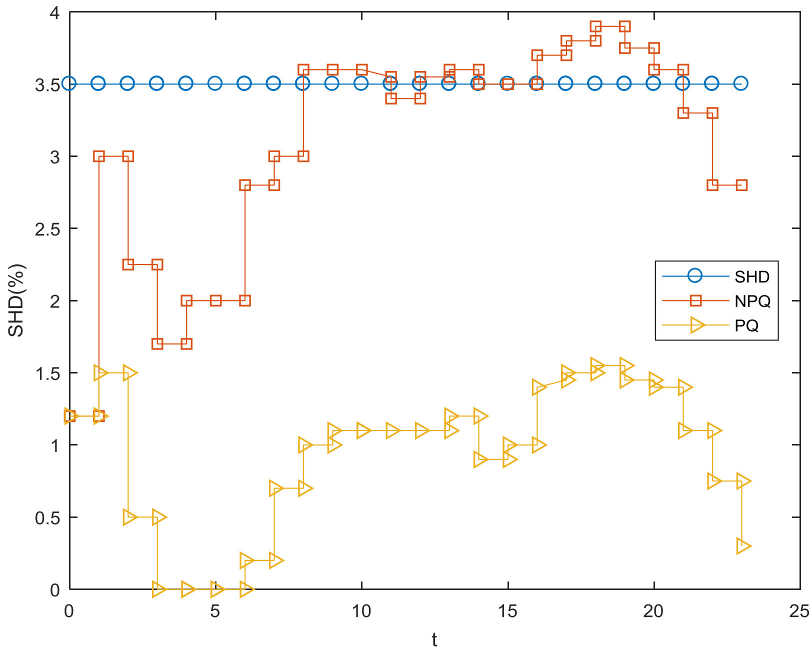

Fig. 3. Maximum single harmonic distortion value per hour in the IEEE 37-node system

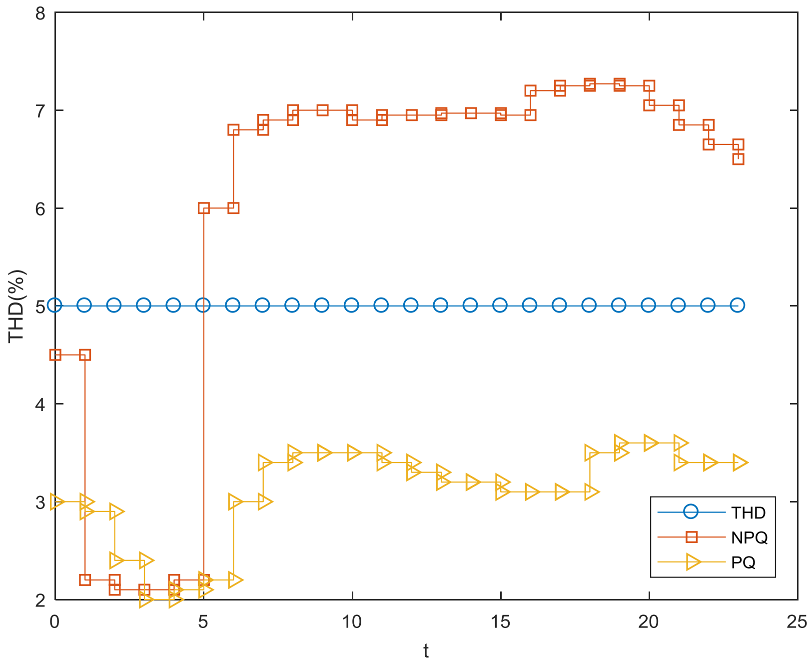

Fig. 4. Total harmonic distortion value of maximum voltage per hour under the IEEE 123 node system

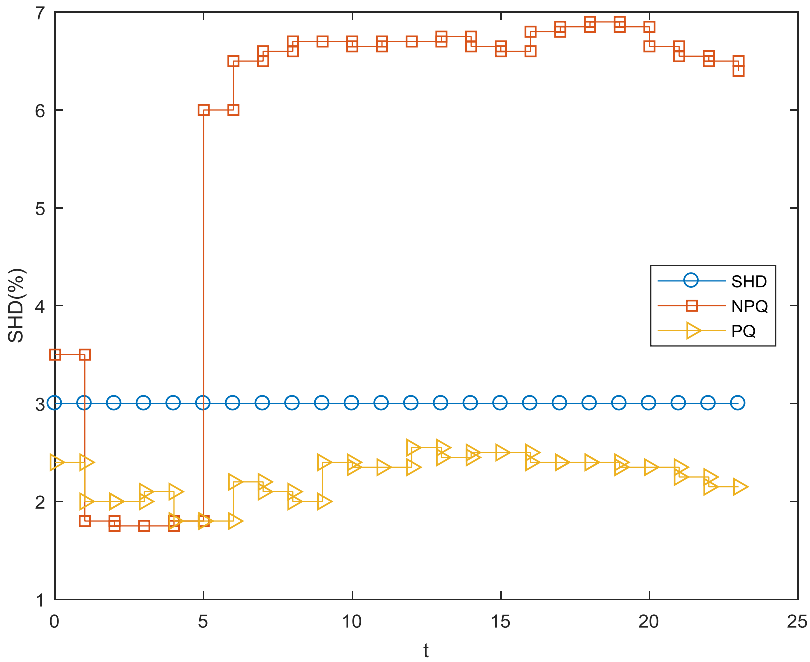

Fig. 5. The maximum single harmonic distortion value per hour under the IEEE 123 node system

As shown in Fig. 3, Fig. 4 and Fig. 5, the NPQ method violates a single harmonic distortion (SHD) constraint for nearly half a day in the IEEE 37 bus system, and for more than half a day violates total harmonic distortion (THD) and IHD constraints in the IEEE 123 bus system. This result indicates that the NPQ cannot reach a satisfactory harmonic level. By contrast, the strategy proposed in this paper does not violate the PQ constraint, so it can better guarantee the power quality. As shown in Table 3, power losses in the IEEE 37 bus system and IEEE 123 bus system are further compared. Compared with the method NPQ, the method proposed in this paper has higher base frequency power loss and lower harmonic power loss, and achieves a satisfactory PQ level on the premise of reducing economic cost. Meanwhile, it can be seen from Table 3 that

Table 3. Comparison of network loss of PQ and NPQ methods in IEEE 37 and 123 node systems

		Network loss of base frequency (kW)	**Harmonic network loss (kW)**	**The total network loss (kW)**
IEEE 37 node system	NPQ	1276.855	9.779	1288.400
	PQ	1303.998	5.569	1310.509
IEEE 123 node system	NPQ	1173.940	23.190	1194.135
	PQ	1233.209	7.821	1242.104

in the IEEE 37 bus and IEEE 123 bus systems, the harmonic power loss decreases by 41.52% and 66.12%, respectively, while the base frequency power loss increases by 3.12% and 5.31%, respectively. Therefore, in the two test systems, the reduction rate of harmonic power loss is much higher than the increase rate of base frequency power loss.

2. Calculation performance analysis

This section mainly studies the computational performance of using a modified flower pollination algorithm (MFPA) to solve the optimal scheduling problem of an active distribution network (ADN). First, we compare the convergence characteristics of the FPA and MFPA in the IEEE 37 bus system and IEEE 123 bus system, respectively, as shown in Fig. 6 and Fig. 7. It can be seen from the figures that the proposed method has good convergence in both test systems. The MFPA has better convergence characteristics than the FPA. In Table 4, the minimum, average and standard deviation of the fitness function of the proposed optimization problem are studied. In Table 4, Case 3.4 represents the research situation of the original IEEE 123 bus system, and the load levels of Cases 3.1, 3.2 and 3.3 are 70%, 80% and 90% of Case 3.4, respectively. As can be seen from Table 4, the proposed method is robust because the standard deviation is very small compared to the mean, and in most cases the difference between the minimum and the mean is small (see Case 3.1, Case 3.2, Case 3.3). In addition, no infeasible solutions were found in Case 3.1 to 3.3. By contrast, in Case 3.4, because many infeasible solutions are found through the MFPA-based method, a very large average value is obtained, which is because the load level in this case is very heavy and the constraints are much stricter than in other cases, resulting in a more complex and difficult optimization problem. However, the proposed method is still satisfactory in 30 runs. Therefore, the proposed active distribution network scheduling method based

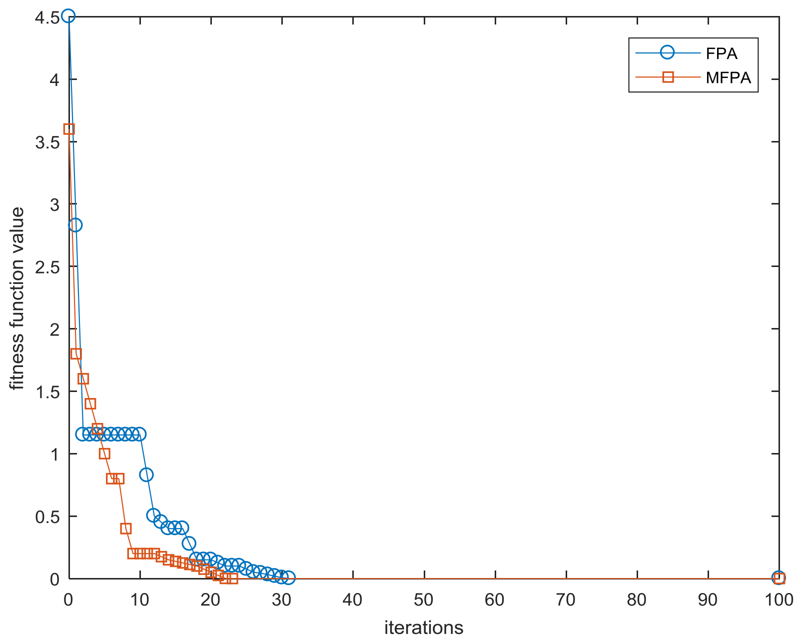

Fig. 6. Convergence curve of the FPA and MFPA under the IEEE 37 node system

on the modified flower pollination algorithm can well solve the power quality problem caused by harmonics when considering the PQ.

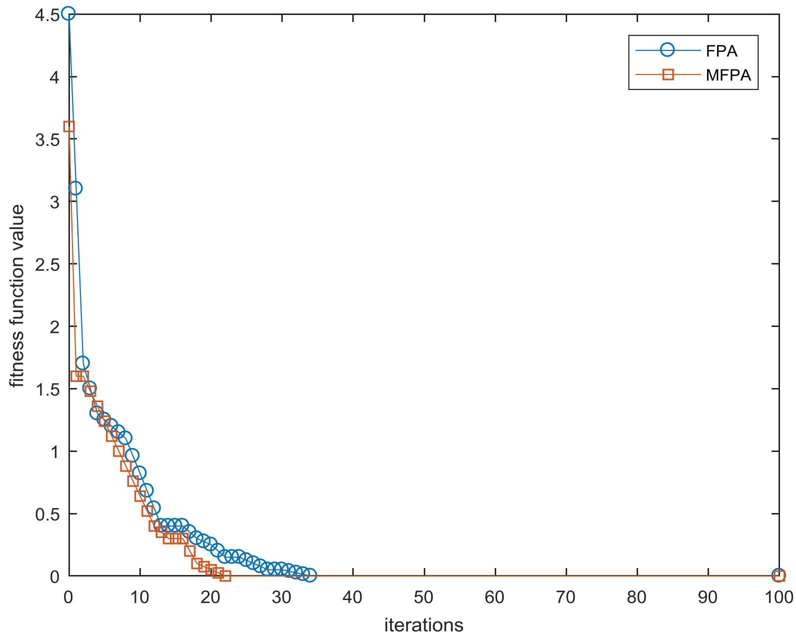

Fig. 7. Convergence curve of the FPA and MFPA under the IEEE 123 node system

Table 4. Algorithm performance analysis of IEEE 123 node system

	Fitness value		
	The minimum value ($\times 10^3$)	**The standard deviation** ($\times 10^3$)	**The mean**($\times 10^3$)
Case 3.1	498.135	11.758	510.208
Case 3.2	700.524	26.306	735.098
Case 3.3	934.890	31.774	1000.559
Case 3.4	1241.111	74379560.180	271510304.217

5. Conclusion

In this paper, an optimal dispatching model of an active distribution network (ADN) is proposed, which mainly considers the power quality problems caused by distributed generation (DG) and battery energy storage (BES) when making scheduling plans. It introduces a harmonic constraint and voltage unbalance constraint into simulation calculation, and adds harmonic loss into the objective function. The simulation results show that this method can get satisfactory power quality (PQ) compared with an NPQ method. Therefore, this method has a broad application prospect in ensuring the supply of high quality electric energy in the operation of an active distribution network. In addition, the simulation results also show that satisfactory power quality and good operation economy are contradictory, and if the PQ constraint needs to be satisfied, more total power loss will be caused, and the uncertainty of wind power generation is not considered in this paper. The comparison experiments between an FPA and an MFPA show that the MFPA has better convergence characteristics than the FPA and can achieve better global optimization. In the next study, we will focus on the stochastic operation model considering both PQ and wind uncertainty.

References

[1] Zhang Y., Meng K., Luo F., *et al.*, *Optimal Allocation of Battery Energy Storage Systems in Distribution Networks with High Wind Power Penetration*, IET Renewable Power Generation, vol. 10, no. 8, pp. 1105–1113 (2016).

[2] Itaya N., *Power-distribution-system voltage control system, power distribution system voltage control method, and centralized voltage control apparatus* (2014).

[3] Hadush S., Meeus L., *DSO-TSO cooperation issues and solutions for distribution grid congestion management*, Energy Policy, vol. 120, pp. 610–621 (2017).

[4] Yang Jiaran, Wang Xingcheng, *et al.*, *Multi-objective optimal dispatching of wind power system based on hybrid intelligent algorithm*, Power System Protection and Control (2017).

[5] Si Jingjing, *Research on optimal scheduling strategy of active distribution network based on PSO-BFO algorithm*, Lanzhou Jiaotong University (2016).

[6] Dong Lei, Gong Chengxiao, *et al.*, *Distributed multi-objective optimal scheduling of active distribution network based on alternating direction multiplier method*, Electric Power Construction (2017).

[7] Gabash A., Li P., *Reverse active-reactive optimal power flow in ADNs: Technical and economical aspects*, in Proc. 3rd IEEE Energy Conf., Dubrovnik, Croatia, pp. 1115–1120 (2014).

[8] Urvinder Singh, Rohit Salgotra, *Pattern Synthesis of Linear Antenna Arrays Using Enhanced Flower Pollination Algorithm*, International Journal of Antennas and Propagation (2017).

[9] Rohit Salgotra, Urvinder Singh, *Application of mutation operators to flower pollination algorithm*, Expert Systems with Applications, vol. 79, 15, pp. 112–129 (2017).

[10] Ong Kok Meng, Ong Pauline, Sia Chee Kiong, Low Ee Soong, *Effective moving object tracking using modified flower pollination algorithm for visible image sequences under complicated background*, Applied Soft Computing Journal (2019).

[11] Wang W., He W., Cheng J., *et al.*, *Active and reactive power coordinated control strategy of battery energy storage system in active distribution network*, Automation, IEEE (2017).

[12] Rathasamuth W., Nootyaskool S., *Comparison solving discrete space on flower pollination algorithm, PSO and GA*, International Conference on Knowledge and Smart Technology, IEEE (2016).

[13] Guo Qing, Hui Xiaobin, Zhang Jiakui, Li Zhengxin, *Improved flower pollination algorithm with multi-mode function optimization*, Journal of Beijing University of Aeronautics and Astronautics [J], vol. 44, no. 4, pp. 828–840 (2018).