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Calculation of maximum permitted capacity of photovoltaic based on flower pollination algorithm combined with genetic algorithm (GA-FPA) in distribution network

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Abstract. The interconnection of distributed photovoltaic (PV) power in the distribution network will bring plenty of adverse effects. It is critical of researching on maximum permitted capacity (MPC) of distribution network to maintain the safe operation of distribution network. A mathematical optimization model was constructed for the MPC of distributed PV with the objective of maximizing the difference between the sum of distributed PV introduction and the network loss, and the constraints of system power flow, node voltage, feeder current, and short-circuit current. At the same time, an improved Flower Pollination Algorithm (FPA) that is Flower Pollination Algorithm combined with Genetic Algorithm (GA-FPA) was proposed to analyse IEEE 33-bus system. Further, by comparing with other optimization algorithms in terms of convergence speed and convergence accuracy, like original FPA and Genetic Algorithm (GA), the correctness of the model and the effectiveness of the algorithm are verified.

1. Introduction

In recent years, with the widespread development and utilization of PV power generation, the issue of PV MPC has become the focus of discussion. The MPC of PV refers to the maximum PV capacity that the system can withstand under the condition that the system operation constraints are met. Distributed PV power generation has become an important direction in PV power generation research, because of its advantages of small footprint and close to the local load center [1].

Many researchers have engaged in the impact of distributed photovoltaics (PVs) on the power quality, relay protection, voltage control, and reliability of distribution networks [2], in the past years. Domestic and foreign scholars have also theoretically analyzed the maximum PV penetration level of distribution networks. Numerous methods of simulation and intelligent algorithms have been adopted to optimize the MPC of PV. For example, references [3,4] set out from the correlation between the distributed PV power supply and the load distribution, established a mathematical model with voltage deviation, voltage fluctuation and distribution network flow as the main constraints, and determined the maximum penetration level of the distributed PV power supply. Cuckoo optimization algorithm (COA) [5] and the improved particle swarm optimization (IPSO) [6] have been used to solve the PV introduction capacity under the timing analysis framework through the method of time series simulation. In [7], a planning method of PV permitted penetration based on the voltage deviation opportunity constraint is proposed and the improved random weight particle swarm optimization (PSO) is used to solve the planning model. Reference [8] used the power flow simulation method to calculate the steady-state operation of the system. A simulation evaluation method was also used to obtain the maximum PV introduction capacity of Hainan Power Grid in [9]. Huang *et al* [10] calculate the steady state voltage and voltage harmonic distortion with power flow program and various levels of PV penetration are presented under the voltage constraints the voltage harmonic distortion constraints.

Based on the existing researches, the impact of grid-connected PVs on distribution network voltage, feeder current capacity, and short-circuit current from the perspective of safe operation of distribution networks is considered comprehensively in the paper. It also takes the limitation of PV generation capacity into account and builds a mathematical model of the MPC of PV. At the same time an improved FPA is put forward to solve the model. FPA has been proposed by [11] and is especially suitable for solving engineering problems. Recently, many variants of FPA have been developed by modification, hybridization, and parameter-tuning to cope with the complex nature of optimization problems [12]. Benkercha *et al* [13] combined the artificial neural network and flower pollination algorithm to model fuzzy logic MPPT controller for PV systems. A hybrid flower pollination algorithm is used for parameter estimation of PV modules in [14,15]. Finally, IEEE33 bus distribution network is used to verify the correctness of the model and the effectiveness of the proposed algorithm.

2. MPC model of distributed PV

The MPC model of distributed PVs established in this paper is the maximum of the sum of the PV capacity that can be connected in the distribution network under the premise that the system voltage, feeder current and short-circuit current are not exceeded.

2.1. Objective function

Distributed PVs usually operate in a constant power factor control mode and operate at a unity power factor [16]. This paper regards it as a PQ node with constant power factor. With the grid-connection of the distributed PV power supply, the power flow may be changed, so as the network loss. The excessive network loss is not conducive to the economic operation of the distribution network. Based on this, this paper regards the difference between the total PV power supply introduction and the network loss as the PV's effective hosting capacity. The expression is:

$$\max f = \sum_{m=1}^{N_{pv}} P_{pv,m} - \sum_{i,j\in\{N_B\}} \frac{P_{ij}^2 + Q_{ij}^2}{U_i^2} R_{ij} \tag{1}$$

In equation (1), N_{PV} is the total number of nodes connected to the PV in the system. $P_{PV,m}$ is the PV introduction of the node m. $\{ N_B \}$ is the set of all nodes in the system. P_{ij} and Q_{ij} are the active power and reactive power flowing through the branch ij respectively. The value U_i is the voltage value of the node i. R_{ij} is the line resistance value between the node i and the node j.

2.2. Constraints

Constraints include power flow constraints, node voltage constraints, feeder current constraints, short-circuit current constraints, and distributed PV power output constraints, which are formulated as follows:

$$\begin{cases} P_{s,i} = V_i \sum_{j=1}^{N} V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) \\ Q_{s,i} = V_i \sum_{j=1}^{N} V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) \end{cases} \tag{2}$$

$$V_{i\min} \le V_i \le V_{i\max} \tag{3}$$

$$S_{l,i} \le S_{l,i\max} i = 1,2,\cdots,N_l \tag{4}$$

$$I_{sc} \le I_{sc\max} \tag{5}$$

$$0 \le S_{PV,i} \le S_{PV,\max} \tag{6}$$

In the formulas, $P_{s,i}$ and $Q_{s,i}$ are the active and reactive powers of node i and j respectively. V_i and V_j are the voltage amplitudes of node i and j respectively. G_{ij} and B_{ij} are the real and imaginary parts of the system admittance matrix respectively. θ_{ij} is the voltage phase difference between nodes i and j. V_{imin} and V_{imax} are the voltage upper and lower limits allowed by node i. $S_{l,i}$ and $S_{l,imax}$ are the current capacity and the maximum allowable ampacity of branch i. N_l is the total number of branches. I_{sc} and I_{scmax} are the branch short-circuit current and the maximum allowable short-circuit current, respectively. $S_{PV,i}$ and $S_{PV,max}$ are the PV power generation and maximum capacity, respectively.

3. Improved FPA optimization model

3.1. Basic FPA

The FPA is a new type of meta-heuristic cluster intelligent optimization algorithm proposed by the British Cambridge scholar Yang in 2012 [17]. The algorithm is a simulation of cross-pollination and non-biological self-pollination of pollen plants in nature to solve the optimization problem. Based on the characteristics of pollination, the following PFA rules were established [18].

- Biological cross-pollination can be considered as a global pollination process, and the pollinator's movement is subject to Levy flight (Rule 1).
- Non-biological and self-pollination are considered as local pollination (Rule 2).
- The regularity of flowers can be considered as the probability of reproduction. The probability of reproduction is proportional to the similarity of the two flowers participating in the pollination process (Rule 3).
- The probability of conversion $p \in [0,1]$ controls the conversion between global pollination and local pollination. Assume that each flower is a solution to the optimization problem, and that each flower controls the cross pollination probability or propagates the progeny by probabilistic self-pollination (Rule 4). Research shows that $p=0.8$ is more effective.

For global pollination, rule (1) and rule (3) can be expressed as:

$$x_i^{t+1} = x_i^t + \gamma L(\lambda)(g_* - x_i^t) \tag{7}$$

where x_i^t is the pollen of i in iteration t and g_* is the best iterative solution currently found in all solutions. γ is a scale factor that controls the step size. $L(\lambda)$ is based on Levy flight as the main step, and is also a parameter related to pollination intensity. The formula of $L(\lambda)$ is shown in (8):

$$L(\lambda): \frac{\lambda\Gamma(\lambda)\sin(\pi\lambda/2)}{\pi}\frac{1}{s^{1+\lambda}}(s ? \quad s_0 > 0) \tag{8}$$

where λ is a value of 1.5 and $\Gamma(\lambda)$ is a standard gamma function. s is a moving step size and FPA uses Mantenia algorithm to generate the most effective step size s, the formula is:

$$s = \frac{U}{|V|^{1/\lambda}}, U \sim N(0,\sigma^2), V \sim N(0,1) \tag{9}$$

where U follows a Gaussian distribution with a mean of 0 and a standard deviation of σ^2, and V

follows a standard normal distribution.

For local pollination, rule (2) and rule (3) can be expressed as:

$$x_i^{t+1} = x_i^t + \varepsilon(x_j^t - x_k^t) \tag{10}$$

In the formula (10), x_j^t and x_k^t are pollens from different flowers of the same species. E is a uniform distribution between 0 and 1.

3.2. Improved FPA

From the principle of FPA in Section 2.1, it can be observed that the population of flowers (pollen) mainly relies on formula (7) or formula (10) to update the position of individuals. With the increase in the number of iterations, pollen gametes tend to be homogenized, and are easily trapped in Local optimal and unable to jump out. The GA mutation idea is used to make the following improvements for the FPA as follows.

In the iterative optimization process of the FPA, a threshold is set. When the obtained optimal solution does not change during continuous Q iterations or the variation μ is small, it can be considered that the algorithm is trapped in the local optimal solution. At this point, the optimal solution obtained by the FPA is used as the initial point of the genetic algorithm, and operations such as selection, crossover, and mutation are performed on the population to obtain a group of new solutions and update the entire population. By introducing mutation strategy, the diversity of population is increased and the optimization ability of the algorithm is improved.

GA-FPA (Flower Pollination Algorithm combined with Genetic Algorithm) implementation steps are as follows:

- Step 1 Initialize the algorithm parameters

Pollen population *n* is taken as 25 while the probability of conversion *p* is 0.8. The maximum iteration number *N_iter* is 50 and population size *sizepop* of GA is 25. Initialize crossover probability P_{cross} to 0.6 and mutation probability $P_{mutation}$ to 0.01 and iteration number *Maxgen* to 30. Set initial iteration number to *t*=0. The threshold parameter is set to $Q = 4$, μ=0.001.

Determine the upper and lower limit values of branch current, short-circuit current, and node voltage according to the grid parameters.

Rewrite the target function to:

$$\min g = \frac{1}{f} + \lambda_1 |U_i - V_b| + \lambda_2 |S_{li} - S_{\lim ax}| + \lambda_3 |I_{sc} - I_{sc\max}| \tag{11}$$

where λ_1, λ_2, and λ_3 are the penalty factors corresponding to equations (3), (4), and (5), respectively. V_b is the allowable voltage amplitude of the node.

- Step 2 Form the initial population

Each flower corresponds to a scheme of PV introduction, the number of which is *d*. Set the PV grid connection point to *d*. The pollen in each flower is a vector with dimension *d*, the value of which is the PV introduction capacity corresponding to each PV grid connection point. According to the power flow, the objective function value of each pollen is obtained, and the position of the optimal pollen is get.

- Step 3 Population iteration

The number of iterations increases by one. Generate a random number *rand*. If *rand* is larger than *p* (transition probability), a global position update is performed according to formula (7) and cross-boundary processing is performed too; otherwise local-area update and cross-boundary processing is performed according to equation (10).

- Step 4 Update the global optimum

Calculate the objective function value of the updated flower of the population. If the updated flower objective function value is better than the current flower objective function value, the current flower and the current objective function value will be replaced with the new flower and its corresponding objective function value, respectively. Otherwise it will not be updated.

- Step 5 It is judged whether the objective function value is trapped in a local optimum. If the judgement is true, the process (loop) will continue; otherwise, the process is transferred to step 7.
- Step 6 Use Genetic Algorithm to perform mutation and other operations

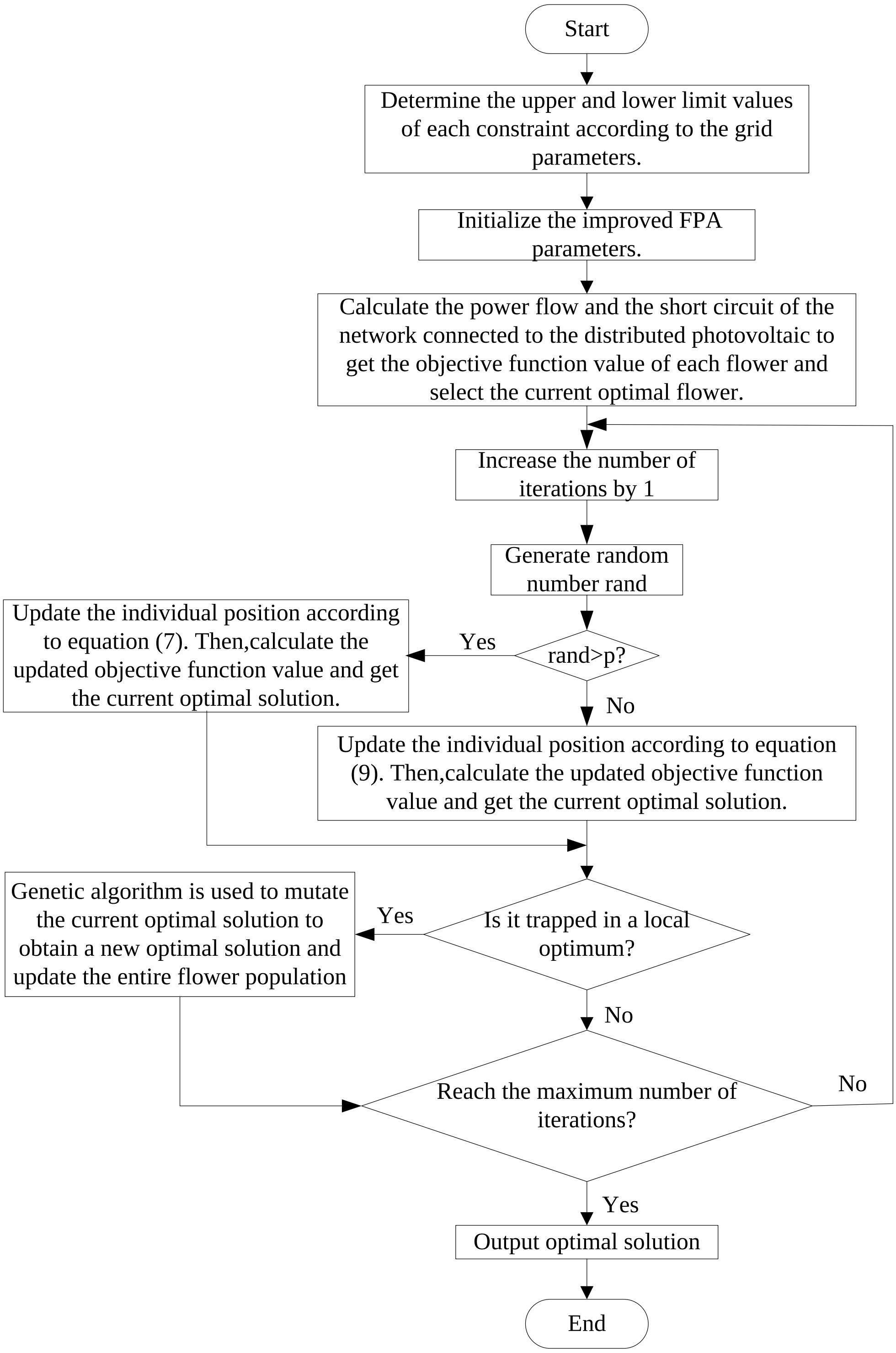

Figure 1. Flow chart of the improved FPA.

The solution generated in step 4 is used as the initial point of the genetic algorithm to select, crossover, and mutate the population which aims to obtain a new set of solutions. If the new solution is better than the current optimal solution, the new solution is used as replacement of the current optimal solution and the population is updated; otherwise it is not updated.

- Step 7 It is judged whether the end condition is satisfied. If the condition is satisfied, the iterative process is stopped and the optimal solution is output; otherwise, the process goes back to step 3.

Specific flow chart is shown in figure 1.

4. Analysis of examples

Taking the IEEE33-bus system as an example, the GA-FPA proposed in this paper is used to solve the MPC of PV in the distribution network. The rated voltage of the system is 12.66 kV, and the system load is 3.715+*j*2.3MVA. The specific network topology is shown in figure 2.

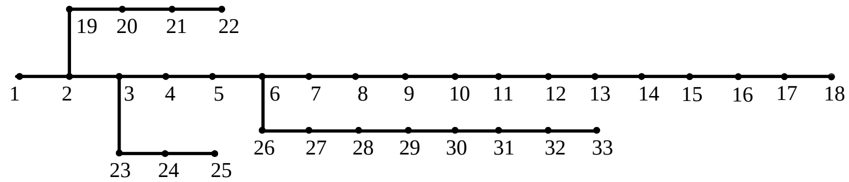

Figure 2. IEEE 33-bus test system.

Assume that nodes 4, 7, 8, 14, 15, 16, 17, 18, 21, 22, 24, 25, 29, 30, 31, 32 are planned PV introduction points. The upper limit of the access capacity of each PV is 1 MW, and the PV power supply operates at the unit power factor. The allowable node voltage range after PV introduction is 0.95-1.05 pu. The line ampacity is 5.5 MVA. The maximum short-circuit current value is determined with reference to the stipulated values in the "10kV Distribution Engineering Typical Design Technical Guidelines" formulated by the State Grid Corporation of China: The maximum three-phase short-circuit current cannot exceed 20 kA.

The MPC of the distributed PVs optimized by the improved FPA is 4.6 MW, and the corresponding capacity of each PV node is shown in figure 3.

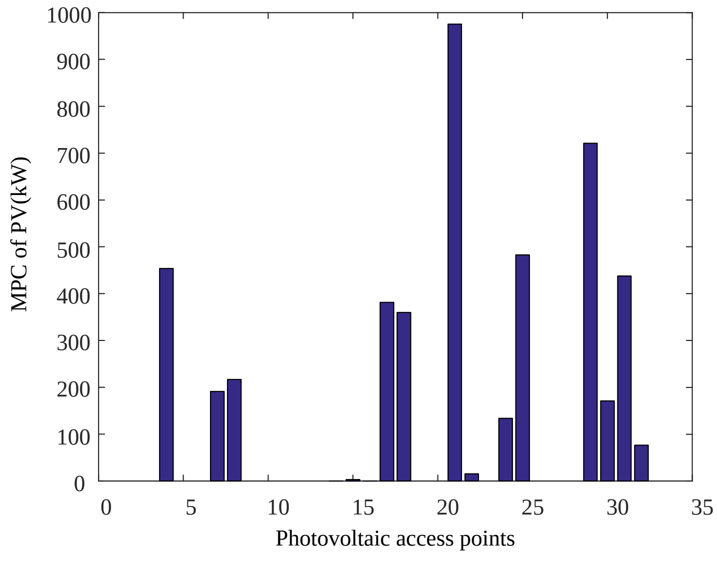

Figure 3. MPC of each PV access point.

To further illustrate the optimization speed and accuracy of the improved algorithm, the original FPA and GA were used to calculate the MPC of distributed PVs. The calculation results are shown in table 1.

Table 1. MPC of PV optimized by different algorithms.

Algorithm	MPC of PV(kW)	Network loss (kW)
GA	4443.77	178.55
FPA	4608.04	87.30
GA-FPA	4619.61	84.02

By analyzing the data in table 1, we can see that there is a difference in the maximum PV introduction capacity obtained by the optimization of different algorithms. Among them, the GA optimization results are the worst, that is, the PV MPC is the smallest, and the network loss is the largest. PV MPC results obtained by the two FPA algorithms are comparable. Figure 4 shows the evolution of several algorithms in optimizing PV MPC. Figure 4 has shown that the optimization speed of GA algorithm is the slowest, that is, this method can converge about 30 iterations. GA-FPA converged about 10 iterations which has the fastest optimization speed. The optimization speed of the FPA is between the above two, and it can be converged around 15 iterations.

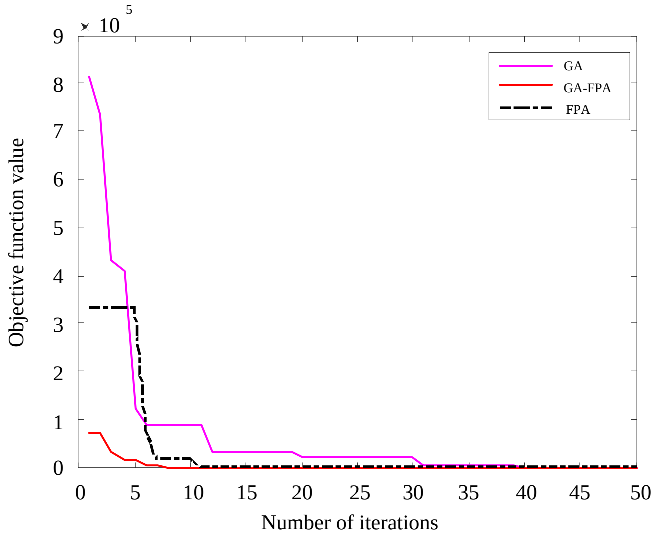

Figure 4. Comparison of different algorithms for optimization.

Through the above analysis, the optimization speed and solution accuracy of the GA-PFA are better than the FPA and GA, which ensures the diversity of the population and makes the algorithm not easy to fall into a local optimum. The example proves the correctness and effectiveness of the model and algorithm, and the applicability of the improved algorithm to the model.

5. Conclusion

Based on the safe operation of distribution network, this paper constructed the mathematical model of permitted capacity with the objective function which maximizes the difference between the sum of distributed PV introduction and the network loss, and considers the restrictions where the system current, node voltage, feeder current, and short-circuit current are taken into account.

The improved FPA was used to solve the MPC of distributed PV of the IEEE33 node system model, and the results were compared with the original FPA and GA. GA-FPA shows more effective because of maximum PV integration, minimum network loss and reasonable convergence speed.

In future, the stochastic and uncertainty of PV can be considered in solving MPC problem to demonstrate the effectiveness of GA-FPA. In addition, an advanced GA-FPA with better performance will be presented in future.

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