Evaluation of Distribution Power Supply Capability Based on Reconstruction Strategy

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Abstract. In order to further improve the power supply capacity of the distribution network and deeply excavate the power supply potential, a method of calculating the power supply capacity of the distribution network is proposed. The fastness and stability of network reconfiguration is improved by using invalid solution and improved harmony algorithm. The objective function of the mathematical model can be established by using the maximum load available from the distribution network. The growth mode of the traditional repetitive trend algorithm is changed, and the growth step of the load is corrected by the sensitivity of the node load to the voltage. The simulation results of IEEE 33-node system show that the proposed method has the feasibility and some guiding significance to the power system planning.

1. Introduction

As an important link between the customer and the generation & transmission system, distribution network is the important infrastructure equipment to ensure the city's economic construction and has the responsibility of providing users with the power. With the increasing scale of the distribution network and the growing load demand, the scientific assessment of the maximum power supply capacity of the distribution network will provide an important reference for the growth of electricity load, the post-fault load transfer and the reasonable utilization of equipment resources. It will be critical to optimize the system grid structure and guide the urban power grid planning[1].

At present, the methods of calculating the power supply capacity of the distribution network mainly include the maximum load multiple method [2], the linear programming model and the power flow calculation model based on the N-1 safety criterion [3, 4], and the new strategies of active reconstruction on distribution network [5, 6]. The reconstruction strategy can improve the utilization efficiency of the equipment and the overall utilization level of the distribution network. In [5], the method of active reconstruction of the distribution network was proposed. This method is based on the same load multiple, and the maximum load capacity of the network is used as the objective function. The binary particle swarm optimization is used to search network topology of the largest load power capacity. However, this method may generate a large number of solutions that do not satisfy the topological constraints in the process of optimization, which will greatly reduce the searching speed and make the algorithm cannot search the global optimal value. Meanwhile, the same load multiplier growth limits the potential for further excavation of power supply. A coding method to avoid the infeasible solution was proposed in [7] by using the basic ring matrix, which can accelerate the network reconstruction. In [8], the
sensitivity analysis method is proposed by the trend of the step-by-step flow algorithm to deeply explore the potential of the power supply capacity of the distribution network and evaluate the power supply capacity of the distribution network more accurately. In [9], a method of reconstruction using branch loops was proposed. The branch loop matrix contains all the loops that exist in the system network. Therefore, the iterative evolution of the intelligent algorithm becomes a process of finding which switches need to be disconnected from all loops, and all the solutions generated in this process are feasible.

This paper proposes a method to calculate the maximum power supply capacity by using network reconstruction strategy. Introducing the branch loop and the coding method of avoiding inefficient solution can effectively prevent the generation and repetitive calculation of invalid solution, which can narrow the search space and accelerate the search speed. At the same time, the maximum power supply capacity is obtained by using variable power flow and improved harmony algorithm. Finally, the simulation results of 33-node system verified that the algorithm is better and faster.

2. Evaluation model of maximum power supply capacity of distribution network
The maximum power supply capacity of the distribution network (PSCI) [5] is determined by the topology of the distribution network, the mode of operation and the growth pattern of the load. The mathematical model is expressed as

$$PSCI = \max S = \sum_{i\in S_n} S_{li} + \sum_{j\in D} k_j S_{dj}$$

(1)

where $PSCI$ is the maximum power supply capacity of the network, $S_{li}$ is the current actual load of node $i$, $n$ is the number of load nodes, $k_i$ is the growth factor of node $j$ load, $D$ is the area where power supply is calculated, and $S_{dj}$ is load node $j$ growth base. The first term in the objective function is to evaluate the current load level of the network, and the second one is to evaluate the power supply margin of the network.

Different from the transmission system, the power distribution capacity of the distribution network does not need to consider the system stability limit constraints, but it needs to consider the node voltage limit, equipment capacity constraints and system power flow restrictions. The constraints are:

$$Ai = I$$

(2)

$$V_{\text{min}} \leq V \leq V_{\text{max}}$$

(3)

$$i_i \leq i_{\text{max}}$$

(4)

where $A$ is the branch node association matrix of the assessment network. $i$ is the current of all branches, and the equation constraint is the fundamental flow constraint of the system. $V_{\text{min}}$ is minimum of node voltage. $V_{\text{max}}$ is maximum of node voltage. $i_i$ is for the current of the branch and $i_{\text{max}}$ is the allowed maximum current.

3. Avoiding invalid coding strategy
When the intelligent optimization algorithm is used to reconstruct the system network, the candidate solution formed by the algorithm has great randomness. In the process of initialization and iteration, a
large number of infeasible solutions are generated, which causes the ring and isolated load nodes. Moreover, due to the uncertainty of the algorithm in the iterative process, it may produce a large number of repeated solutions. Meaningless repetitive solution will waste computing time. So reducing the computational space can effectively improve the calculation speed.

3.1. Euclidean distance
The intelligent algorithm has a lot of randomness in the iterative process and produces a lot of repetition. Due to the real variable being used in this paper, the value of each candidate solution is a different positive integer, which represents a discrete point in the Euclidean space. Therefore, it can be determined whether is repeated the solution by the condition that the candidate solutions with the difference distances are not the same candidate solutions.

The Euclidean distance of the two variables $X_1 = [x_1, x_2, \ldots, x_n]$ and $Y_1 = [y_1, y_2, \ldots, y_n]$ in the n-dimensional space can be expressed as:

$$D(X,Y) = \sqrt{(x_1 - y_1)^2 + (x_2 - y_2)^2 + \cdots + (x_n - y_n)^2}$$  \hspace{1cm} (5)

Using the current distance between the candidate solution vector and the $x_0 = [0,0,0,0,0]$ vector, it can determine whether the new solution is a candidate for the repeated the solution. Avoiding the repeated solution to the meaningless power flow calculation can effectively reduce the calculation time.

3.2. Improved harmony algorithm
Harmony algorithm is a kind of intelligent optimization algorithm, inspired by the band playing music in the process of adjusting the notes to achieve the optimal state [10]. It has the characteristics of simple calculation process and fast searching speed. But its optimization process is quietly random, and the solution variable update is not directional and easy to fall into the local extreme value in the later period of the calculation process. In this paper, we make contribution to the improvement which is aimed at shortcomings of harmony algorithm as follows:

1) When the selected solution need to be disturbed, by using the fish foraging behaviour, if the fitness function of the candidate solution is better than the current position within the scope, the solution moves to the optimal value with one step [11]. The mathematical expression of the disturbance

$$x_i^{t+1} = \begin{cases} x_i^{t} + c_1 \times \bar{d}_i \times r, & r < 0.5 \\ x_i^{t} + c_1 \times bw, & r \geq 0.5 \end{cases}$$  \hspace{1cm} (6)

where $c_1$ is a random number, $\bar{d}_i$ is the direction vector of the variable $x_i$ pointing to the current optimal value. $bw$ is the random direction disturbance vector. Therefore, each time a disturbance occurred makes the candidate solution move to the current optimal value of the direction with a certain probability.

2) When the algorithm falls into the local extremum and the population diversity is worse, the algorithm is difficult to jump out of the local minimum. To deal with this problem, the Logistic chaos operator is introduced in this paper. The mathematical expression is:

$$x_{i,t+1} = \frac{\mu x_i (1 - x_i)}{1}$$  \hspace{1cm} (7)
where $x_i \in (0,1)$ is a chaotic variable, if the attractor $\mu=4$, the system will be in complete chaotic state. The chaotic variables are randomly generated and mapped to the solution space to disturb the non-optimal solutions in the harmony memory. It can keep the diversity of the population and help the algorithm jump out of the local extremum. The flowchart of the improved algorithm is shown in Fig. 2.

4. Improved repetitive power flow algorithm

The repetitive power flow algorithm increases the load power of each node by a certain proportion until the calculation accuracy is achieved and do not satisfy an inequality constraint condition [12]. Compared with the continuous power flow method, the repetitive power flow algorithm has higher reliability and fewer parameter settings [13].

4.1. Variable step size method based on node load-voltage sensitivity analysis

For the calculation of power flow, conventional repetitive power flow algorithm adopts the strategy that the loads of all the nodes are increased by the same proportion step size in the process of calculation. In our method, the loads of different nodes are increased by different step size, which can more deeply tap system power supply potential. The constraints of the distribution capacity of the distribution network node voltage and branch capacity. The step size of each node load is based on the sensitivity to the corresponding node voltage. The iterative equation for the Newton flow calculation:

$$
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix} =
\begin{bmatrix}
H & N \\
J & L
\end{bmatrix}
\begin{bmatrix}
\Delta \theta \\
U^{-1}\Delta U
\end{bmatrix}
$$

where $H, N, J, L$ are the block matrix in the Jacobian matrix, $\Delta P, \Delta Q, \Delta \theta, \Delta U$ are the change of active power, reactive power, voltage phase angle and voltage amplitude, respectively. Eliminating the $\Delta \theta$, the above equation is developed as

$$
\Delta U =
\begin{bmatrix}
S_P \\
S_Q
\end{bmatrix}
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix}
$$

where $S_P = (L - JH^{-1}N)^{-1}JH^{-1}$, $S_Q = (L - JH^{-1}N)^{-1}$ respect for the active power, reactive power on the voltage amplitude sensitivity.

Herein, we define the node voltage residual margin to reflect the approximation of the node voltage to the limit voltage. The expression is

$$
U_{bi} = \frac{U_i - U_b}{U_b}
$$

where $U_i$ is the voltage amplitude of node $i$ and $U_b$ is the reference value of the node voltage.

For each repetitive trend, it is necessary to recalculate the step size. First, the minimum voltage node is found by using the residual margin of the node voltage. The influence of the load on the node voltage is obtained by the sensitivity analysis results. Following the principle of "the greater the influence and the smaller the step size", The growth step of each node is determine by the sensitivity coefficient.
5. Example analysis
In this paper, distribution system of a single feed IEEE 33-node is simulated to verify our method. The wiring diagram of IEEE 33-node system is shown in Fig. 1. It includes 33 lines, 5 contact lines, bus reference voltage of 12.66 kv, and the total load of 3715 + j2300 kVA. The specific line parameters can be seen in [14]. The distribution system is divided into four regions, and we use the same load limiting parameters as [14]. The improved harmonic algorithm parameters are set as follows: HMS = 8; memory probability $HMCR_{min} = 0.8$, $HMCR_{max} = 0.95$; fine-tuning probability $PAR = 0.2$; maximum iteration $itermax = 100$.

![Wiring diagram of a 33-node distribution system](image)

5.1. Algorithm performance verification
Due to the randomness of the harmony algorithm, the size of the probability of each iteration to produce new solutions in different ways and the number of iterations each time is different, and it will cause the time of each calculation volatile. In order to reflect the superiority of the improved algorithm in time calculation and optimization accuracy, the improvement method and the unmodified method with 50 simulation calculations were compared. The results are shown in Table 1. Since the improved harmony algorithm can avoid the calculation of the repeated solution, the calculation time can be greatly shortened. In addition, the direction of the algorithm is helpful to the algorithm to proceed to the optimal solution. When the algorithm falls into the local extremum, it is possible to use the catastrophic operator to jump out of the local extremum and to search for the global optimal solution.

| Calculation method  | 50 times simulation average time (S) | Optimization rate (%) |
|---------------------|-------------------------------------|-----------------------|
| harmony algorithm   | 125.52                              | 27%                   |
| Improved Harmony Algorithm | 72.45                              | 41%                   |

5.2. Algorithm comparison analysis
According to the proposed method, the improved harmony algorithm is used to optimize with the objective function of power supply capacity. The simulation results are shown in Table 2 and the corresponding reconfiguration scheme diagram is shown in Fig. 4. It can be seen that the method of this paper has a great improvement compared with the results in [5]. Compared with the variable-step method of the same proportion, the proposed method can fully consider the node load with large influence on the constraint in a small proportion of growth and the node load with small influence on the constraint to in a larger proportion of growth, which can be more deeply excavate power distribution network potential.
Table 2. Maximum power supply capacity optimization comparison results

| The entire distribution network | Original load | PSCI (KVA) | Limit the constraint | Switch off the situation |
|---------------------------------|---------------|------------|----------------------|-------------------------|
|                                 | Active load(KW) | Reactive load(Kvar) | Active load(KW) | Reactive load(Kvar) |                          |
| Before reorganization           | 3715          | 2300       | 4220                | 2613                    | Node 18                  | —                       |
| This article method             | 5836          | 3613       | 6179                | 3613                    | Line 1                   | 11 14 20 36 37          |
| Literature [5] method           |               |            |                     |                         | Node 32                  | 10 14 28 32 33          |

6. Conclusion
In this paper, a method of calculating the power supply capacity of the distribution network using the reconstruction strategy is proposed. The step size of the traditional repetitive power flow calculation is modified by the variable step size method based on the node load-voltage sensitivity analysis. Meanwhile, Branch loop matrix and Euclidean distance is used to narrow the search space, which can shorten the calculation time. Improved harmony algorithm can maintain good stability. The validity and feasibility of the method proposed in this paper are confirmed by the simulation of IEEE 33-node system.

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