Research on Artificial Intelligence Algorithm for Reactive Power Optimization of Distribution Network

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Abstract. Reactive power optimization of power system is a complex problem with many variables. Its variable type from the continuous variable, namely, have discrete variable again. In this paper, genetic algorithm is adopted as the reactive power optimization algorithm, and the minimum loss of active power network is selected as the objective function to discuss the reactive power optimization method of distribution network.

1. Introduction
Power quality is the lifeline of power system, and unstable power quality will bring a lot of inconvenience to users [1]. From the perspective of power system operation, reactive power deficiency may lead to power system voltage collapse, large-scale blackout and other major accidents. Failure to deal with the problem of reactive power optimization will not only increase the cost of power supply investment and generation, but also bring immeasurable losses.

2. Reactive power optimization method for urban distribution network
Traditional optimization methods include analytical method, linear programming method, nonlinear programming method, mixed integer programming method, etc. [2]. With the improvement of computer technology, artificial intelligence optimization methods have appeared: sensitivity analysis method, ant colony algorithm, genetic algorithm, etc. [3].

2.1. Analytical method
The essence of analytic method is to use calculus as solving tool to get the final optimal solution. The disadvantage of the analytical method is that the calculation result has a large error with the actual situation, which is mainly reflected in that the compensation capacity and compensation position of the capacitor are discrete variables, and the calculated optimal capacity and the installation position of the compensation capacitor are not consistent with the actual situation.

2.2. Inductive method
Induction includes: linear programming, nonlinear programming and dynamic programming, etc. [4]. Linear programming method is characterized by simple processing of constraints, easy convergence and fast computation. However, the simplification of the linear programming method often makes the optimization results inconsistent with the reality. Nonlinear programming method was first applied to the problem of reactive power optimization, but due to the complexity of reactive power optimization
problem, there is still no mature nonlinear programming algorithm to solve the problem of reactive power optimization. The dynamic programming method adopts the method of resolving the problem into several related stages, making a decision for each stage in the solving process, and finally seeking the optimal solution for the whole.

2.3. Artificial intelligence algorithm
Common artificial intelligence algorithms include: artificial neural network algorithm, particle swarm optimization algorithm, genetic algorithm, etc. Artificial intelligence algorithm is an expert in dealing with discrete variables and nonlinear problems, and its convergence and speed of calculation are obviously better than traditional optimization algorithm, so it has been widely used in the field of reactive power optimization.

Neural network algorithm has strong learning ability, learning process is simple, easy to realize through programming. However, the correctness of the solution cannot be guaranteed, and it is difficult to obtain the global optimal solution if the learning method is not selected properly. Genetic algorithm has strong global search ability and can search global optimal solution with large probability. Particle swarm optimization is simple and easy to understand and widely used in reactive power optimization. However, the parameter setting process of particle swarm optimization is very critical. If the acceleration constant and inertia weight coefficient are set irrationally, the algorithm will fall into local optimization. Artificial intelligence algorithm has unique advantages in dealing with nonlinear problems and discrete variables. In terms of variables and constraints, it is not as harsh as conventional optimization algorithm, which is unmatched by traditional optimization algorithm.

3. Overview of research on reactive power optimization of distribution network

3.1. Loss reduction of distribution network
Common loss reduction measures in the power network include shortening the length of low-voltage power supply line, reactive power compensation, balancing three-phase load, adopting energy-saving transformer, reasonably configuring transformer capacity and adopting loss reduction technical measures of distribution network with large-diameter line [5]. Among them, the most important is reactive power compensation. The purpose of reactive power compensation is to optimize the operation of distribution network.

3.2. Reactive power optimization scheme
Based on the characteristics of closed-loop design and open-loop operation of distribution network, centralized compensation is adopted to compensate reactive power in the study of reactive power optimization. 2~3 fixed points are set at the compensation location in the distribution network. Generally, the compensation location is set at the node with low power factor, and the effect is more obvious when reactive power compensation is carried out at this point. Reactive power compensation capacity is obtained by genetic algorithm. The generator node voltage and the voltage of the adjustable transformer are also considered as control variables when the genetic algorithm control variables are set.

3.3. Power flow calculation overview of distribution network
Power flow calculation of distribution network is a process of solving the voltage and power of each node and the active power loss of the entire network according to the given network structure of distribution network and its related parameters [6]. Power flow calculation of distribution network is the basis of reactive power optimization analysis and calculation. Improved newton-rapson method is an excellent tool to solve the nonlinear problem of distribution network [7].

As a connection channel, distribution network is characterized by radial structure, multiple branches, complex structure and large resistance and reactance. In the distribution system, the distance between adjacent nodes is relatively close and the client generally has no grounding branch. Therefore, the
voltage difference between the nodes is not significant. For distribution systems without grounding branches, the jacobian matrix can be improved into the form of equation (1).

$$H_{ij} \approx U_i U_j B_{ij} \cos \theta_{ij} \quad i \neq j$$

$$H_{ij} \approx -U_i \sum_{j \neq i} U_j B_{ij} \theta_{ij} \quad i = j$$

$$N_{ij} \approx -U_i U_j G_{ij} \cos \theta_{ij} \quad i \neq j$$

$$N_{ij} \approx U_i \sum_{j \neq i} U_j G_{ij} \cos \theta_{ij} \quad i = j$$

$$J_{ij} \approx U_i U_j G_{ij} \cos \theta_{ij} \quad i \neq j$$

$$J_{ij} \approx U_i \sum_{j \neq i} U_j G_{ij} \cos \theta_{ij} \quad i = j$$

$$L_{ij} \approx U_i U_j B_{ij} \cos \theta_{ij} \quad i \neq j$$

$$L_{ij} \approx -U_i \sum_{j \neq i} U_j G_{ij} \cos \theta_{ij} \quad i = j$$

4. Genetic algorithm reactive power optimization solution

4.1. basic theory of genetic algorithm
Genetic algorithm (ga) is a global stochastic search optimization algorithm based on genetic theory. Genetic algorithm encodes the operating objects, and the operation of the algorithm is aimed at the genetic individuals formed after coding without auxiliary information. The evaluation standard for individuals is the fitness function, and the evaluation of selection, crossover, variation and other operations is also inseparable from the fitness function.

4.2. operation process of genetic algorithm
Reactive power optimization using genetic algorithm to process roughly as follows: first, to produce a set of random Numbers as the initial population, controlled variable coding in the heart of the reactive power optimization problem of control variables are involved in chromosome coding, then execute the select operation, selection is based on the fitness function, the selected individuals in the matrix, to prepare for the next genetic operations, after respectively carry out the crossover operation and mutation operation to generate new individuals to enrich the population, after many genetic operation, after reaching a certain number of iterations, if set of genetic algebra is reasonable, can always seek out the reactive power optimization problem of the optimal solution.

1) Genetic algorithm coding
   The coding of genetic algorithm is a bridge from the problem space to the genetic algorithm space.

2) Individual evaluation
   The fitness function as the standard of individual evaluation is always non-negative. The larger the value is, the closer the corresponding solution is to the optimal solution. If the objective function is the maximum value, the objective function can be directly used as the fitness function. If the objective function is minimized, its inverse is the fitness function. The fitness function indicates the direction for the selection of the optimal solution, and the individuals with higher fitness value will obtain a greater probability to inherit to the next generation and carry out the next genetic operation.
In the process of reactive power optimization, the minimum loss of active power network is taken as the objective function. Considerations include the transformer tap position, shunt capacitor compensation capacity, and generator terminal voltage. The mathematical model is as follows:

\[
\min F = P_L + \lambda_1 \sum \left( \frac{\Delta V_i}{v_{\text{imax}} - v_{\text{imin}}} \right)^2 + \lambda_2 \sum \left( \frac{\Delta Q_i}{q_{\text{imax}} - q_{\text{imin}}} \right)^2 \tag{2}
\]

Where, \(P_L\) is the active network loss; Lambda \(\lambda_1 \sum \left( \frac{\Delta V_i}{v_{\text{imax}} - v_{\text{imin}}} \right)^2\) of each node voltage, the more limited penalty function; Lambda \(\lambda_2 \sum \left( \frac{\Delta Q_i}{q_{\text{imax}} - q_{\text{imin}}} \right)^2\) for generator reactive power is limited to punish function item;

Constraints include equality constraints and inequality constraints. Where, the equality constraint condition is the active power flow constraint; the inequality constraint condition is the running limit constraint. The details are as follows:

\[
\Delta V_i = \begin{cases} 
V_i - V_{\text{imax}} & V_i > V_{\text{imax}} \\
0 & V_{\text{imin}} \leq V_i \leq V_{\text{imax}} \\
V_{\text{imin}} - V_i & V_i < V_{\text{imin}} 
\end{cases} \tag{3}
\]

\[
\Delta Q_i = \begin{cases} 
Q_i - Q_{\text{imax}} & Q_i > Q_{\text{imax}} \\
0 & Q_{\text{imin}} \leq Q_i \leq Q_{\text{imax}} \\
Q_{\text{imin}} - Q_i & Q_i < Q_{\text{imin}} 
\end{cases} \tag{4}
\]

Constraints of power flow equation:

\[
\begin{align*}
P_{ig} &= P_{id} + V_i \sum_{j=1}^{n} V_j (G_{ij} \cos \delta_{ij} + B_{ij} \cos \delta_{ij}) \\
Q_{ig} &= Q_{id} + V_i \sum_{j=1}^{n} V_j (G_{ij} \cos \delta_{ij} - B_{ij} \cos \delta_{ij})
\end{align*} \tag{5}
\]

\(P_{ig}\) represents the active power injected by node \(i\); \(Q_{ig}\) represents the active power injected by node \(i\); \(P_{id}\) represents the active power of node \(i\); \(Q_{id}\) represents the active power of node \(i\); \(V\) represents the node voltage of node \(i\). \(G_{ij}\) represents the conductance between nodes \(i, j\); \(B_{ij}\) represents the susceptance between nodes \(i, j\); \(\delta_{ij}\) represents the difference Angle between the voltage of node \(i, j\).

Inequality constraint:

\[
\begin{align*}
V_{\text{imin}} &< V_i < V_{\text{imax}} \\
Q_{\text{gimin}} &< Q_{gi} < Q_{\text{gimax}} \\
T_{\text{imin}} &< T_i < T_{\text{imax}} \\
C_{\text{imin}} &< C_i < C_{\text{imax}} \\
V_{\text{gimin}} &< V_{gi} < V_{\text{gimax}}
\end{align*} \tag{6}
\]

\(V_{\text{imin}}, V_{\text{imax}}\) represent the upper and lower limits of node \(i\) voltage; \(Q_{\text{gimin}}, Q_{\text{gimax}}\) represents the upper and lower limits of reactive power output of the generator; \(T_{\text{imin}}, T_{\text{imax}}\) represent the upper and lower limits of transformer ratio; \(C_{\text{imin}}, C_{\text{imax}}\) represent the upper and lower limits of parallel compensation capacitance; \(V_{\text{gimin}}, V_{\text{gimax}}\) represent the upper and lower limits of generator terminal voltage.
1) Selection: the selection operation is to screen in the population according to the fitness value. The larger the fitness value, the closer the individual is to the optimal solution and the greater the probability of inheritance to the next generation. Individuals with smaller fitness values have lower probability of inheritance and may be eliminated.

2) Cross: crossover operation simulation is in the process of biological genetic evolution of genetic recombination link, it is the unique genetic algorithm to generate new individual, is an important means of genetic algorithm to find the optimal individual, specific operation is: according to determine the cross selection probability of select two individuals in the population, according to the different ways of cross exchange of two individual genes somewhere or some bits.

3) Variation: variation is also a way of generating new individuals in genetic algorithms. In practice there is a small chance of changing one or more bits of an individual's genes. In binary coding, the mutation operation reverses a gene value at random.

4) Termination criterion: the convergence criterion of genetic algorithm is basically heuristic, and it does not need gradient information. The commonly used convergence criteria are as follows: the algorithm converges after the maximum number of iterations is reached; The algorithm is considered to be convergent if the optimal solution obtained through multiple iterations is the same. If the difference between the fitness value of the optimal solution and the average fitness value is less than a given constant, the algorithm can be considered to be convergent. In this paper, a simple genetic algorithm is used as the criterion of convergence.

5. The example analysis

5.1. Power grid information before system optimization
In order to verify the calculation effect of reactive power optimization using genetic algorithm, this chapter USES the example of IEE 30-node distribution network for reactive power optimization calculation, and analyzes the results of reactive power optimization. The grid diagram before system optimization is shown in figure 1. The IEEE 30-node system consists of 6 generator nodes: 1, 2, 5, 8, 11, 13; The four adjustable transformer nodes are: 6-9, 6-10, 4-12 and 28-27; Set two reactive power compensation nodes as 10 and 24.

![IEEE30 node system wiring diagram](image)

Figure 1. IEEE30 node system wiring diagram

The impedance, admittance, voltage and power involved in the distribution network are expressed by the unit value, and the data of each branch are reduced to the same voltage level. The reference voltage and reference capacity of the model are given as 10kV and 10MW respectively. Set node 1 as the balance node, and the node maintaining voltage is 1.05. Where, node types are described as follows: 0 represents equilibrium node, 1 represents PQ node, and 2 represents PV node.
5.2. optimization results
In the MATLAB environment, the reactive power optimization calculation is carried out by genetic algorithm, and the final node voltage optimization result is shown in table 1.

### Table 1. Optimization calculation results (unit value)

| Node number | The initial voltage | Optimized voltage | Node number | The initial voltage | Optimized voltage | Node number | The initial voltage | Optimized voltage |
|-------------|---------------------|-------------------|-------------|---------------------|-------------------|-------------|---------------------|-------------------|
| 1           | 1.04                | 1.06              | 11          | 0.9151              | 0.9981            | 21          | 0.9206              | 1.0032            |
| 2           | 0.9256              | 1.0078            | 12          | 0.9147              | 0.9978            | 22          | 0.9200              | 1.0027            |
| 3           | 0.9242              | 1.0065            | 13          | 0.9152              | 0.9982            | 23          | 0.9198              | 1.0025            |
| 4           | 0.9233              | 1.0057            | 14          | 0.914              | 0.998             | 24          | 0.9194              | 1.0021            |
| 5           | 0.9231              | 1.0055            | 15          | 0.9145              | 0.9975            | 25          | 0.9192              | 1.0019            |
| 6           | 0.9177              | 1.0006            | 16          | 0.9144              | 0.9975            | 26          | 0.9187              | 1.0014            |
| 7           | 0.9172              | 1.0001            | 17          | 0.9132              | 0.9964            | 27          | 0.9187              | 1.0014            |
| 8           | 0.9172              | 1.0001            | 18          | 0.9138              | 0.997             | 28          | 0.9188              | 1.0015            |
| 9           | 0.9163              | 0.9992            | 19          | 0.9217              | 1.0042            | 29          | 0.9186              | 1.0014            |
| 10          | 0.9156              | 0.9986            | 20          | 0.9215              | 1.004             | 30          | 0.9185              | 1.0013            |

The minimum network loss is regarded as the objective function of genetic algorithm, so the size of network loss before and after optimization can best reflect whether the optimization algorithm is effective or not. Table 2 shows the situation of balance node and system network loss before and after optimization.

### Table 2. Optimization calculation results (unit value)

| Node number | The initial Balanced node power | Optimized 3.5856 + 1.9676i | Optimized 3.5716 + 1.9556i |
|-------------|---------------------------------|-----------------------------|-----------------------------|
| Node number | The initial Balanced node power | Optimized 0.3847 | Optimized 0.3753 |
| Node number | The initial Balanced node power | Optimized 10.73% | Optimized 10.51% |

After genetic algorithm optimization, the values of each control variable are shown in table 3.

### Table 3. Control variable optimization results

| The variable name | The starting value | The lower limit | The ceiling | The optimal value | The variable name | The starting value | The lower limit | The ceiling | The optimal value |
|-------------------|-------------------|-----------------|-------------|-------------------|-------------------|-------------------|-----------------|-------------|-------------------|
| V_G1              | 1.05              | 0.95            | 1.06        | 1.05              | Q_C10             | 0.18              | 0.0             | 0.5         | 0.34              |
| V_G2              | 0.9256            | 0.95            | 1.05        | 1.0077            | Q_C24             | 0.03              | 0.0             | 0.5         | 0.14              |
| V_G5              | 0.9231            | 0.95            | 1.05        | 1.0054            | T_16-9            | 1.0154            | 0.9             | 1.1         | 1.1000            |
| V_G8              | 0.9172            | 0.95            | 1.05        | 1.0001            | T_26-10           | 0.9628            | 0.9             | 1.1         | 0.9130            |
| V_G11             | 0.9151            | 0.95            | 1.05        | 0.9980            | T_14-12           | 1.0128            | 0.9             | 1.1         | 1.0750            |
| V_G13             | 0.9152            | 0.95            | 1.05        | 0.9981            | T_28-27           | 0.9580            | 0.9             | 1.1         | 1.0280            |

The capacitors are switched and cut in groups. The capacity of each group of capacitors is equal, and its unit value is 0.04 when denoted by sodium. Thus, the compensation status at the compensation node is shown in table 4.

### Table 4. Status of compensation nodes

| Serial number | Compensation node | Number of sets of compensation |
|---------------|-------------------|--------------------------------|
| 1             | 10                | 4                              |
| 2             | 24                | 3                              |
According to the analysis in table 4-2 and 4-3, the average node voltage before optimization is 9.227kv, and the average node voltage after optimization is 10.031kv. The voltage of each node is generally improved. In addition, the optimized active power loss is reduced by 0.094mw, and the network loss is obviously reduced.

6. Conclusion
Aiming at the problem of reactive power optimization in power system, genetic algorithm is a feasible scheme. Genetic algorithm adopts the characteristic of probabilistic search, which has unique advantages for solving the problem of reactive power optimization of power system, which is characterized by nonlinearity, discontinuity and many uncertain factors. The results show that the loss can be reduced by genetic algorithm, which proves that the method has great practical value.

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