Reactive power optimization of AC and DC system based on improved genetic algorithm

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Abstract. In the context of the rapid development of DC transmission, this paper studies the multi-objective reactive power optimization of AC and DC transmission systems. By studying the relevant basic knowledge, it provides a theoretical basis for studying reactive power optimization of AC-DC distribution networks. This paper provides an improved genetic algorithm that uses node voltage offset and total active network loss as two objective functions. A fast non-dominated sequencing genetic algorithm with elite strategy NSGAII is applied to the multi-target reactive power of AC and DC systems. During the optimization, a corresponding reactive power optimization program was written, and the feasibility of the proposed method was verified by an example of the IEEE 9-node system.

1. Introduction
With the increase of power system operation requirements, the optimal solution based on a single objective function will make other objectives fail to meet the requirements. Therefore, the multi-objective reactive power optimization problem that comprehensively considers various operating indicators including economics and safety has been widely used [1,2]. In view of the above problems, In this paper, the network loss and node voltage offset of AC-DC distribution network are used as the objective functions to solve the reactive power optimization problem of AC-DC distribution network. Generally, the general idea for solving multi-objective optimization problems is to use the weight method, constraint method or other methods to convert multi-objective problems into single-objective problems, and then use existing mature single-objective optimization algorithms to solve reactive power optimization problems. Reference [3] weighted the system network loss and voltage quality, and took different values for the weights, and discussed the impact of different weight values on the optimization results. However, because the dimensions of different objective function values are different, doing so will make the result of reactive power optimization greatly affected by the weight value or membership function [4,5]. In this paper, a fast non-dominated genetic algorithm with an elite strategy is used to solve the multi-objective reactive power optimization problem of AC and DC systems. There is no need to adjust the value of the objective function weight value in advance, and a series of pareto optimal solutions can be directly obtained for decision-making. In order to obtain the appropriate optimal solution according to different needs.
2. Improvement of genetic algorithm
The genetic algorithm is to simulate the reproduction process of species. The three mechanisms of biological evolution are mapped to the genetic algorithm, that is, the three genetic operations in the genetic algorithm: selection, crossover, and mutation. When the genetic algorithm is used to solve the reactive power optimization problem, the coding space is used instead of the parameter space, each solution in the problem is regarded as an individual in the group, and the adaptive value determined by the objective function is regarded as the environment to evaluate the individual. The solution is analogized to selection, hybridization, and gene mutation in biological genetics, and finally individuals with different fitness values are obtained. Individuals with high fitness values are selected according to the fitness evaluation function, and individuals with low fitness values are eliminated. Iterative iteration is most likely to approximate The actual optimal solution set finally selects the individual with a high fitness value, that is, the optimal solution of the optimization problem itself.

The NSGAII algorithm is derived from the traditional genetic algorithm. Based on the traditional genetic algorithm, it introduces non-dominated sorting and elite retention strategies to solve multi-objective optimization problems [6]. The application of NSGAII algorithm to reactive power optimization can be described as follows:

1. First randomly generate an initial population of size P, perform non-dominated sorting and stratification of the initial population, and genetic operations until the first generation subgroup is generated.
2. Secondly, during the evolution, the elite retention strategy was cited to merge the parent population with the offspring population to prevent the loss of outstanding parents. In this process, if it is not possible to generate a new parent population, then perform Non-dominated sorting is performed by calculating the crowding degree of individuals in each non-dominated layer until a new parent population is selected.
3. Finally, genetic operations are performed on the new parent population, and iterative until it meets the conditions for the end of the program.

3. Objective function and constraints

3.1. Objective function
In this paper, the total network loss and voltage offset of the AC-DC system taking into account the network loss of the DC transmission line are taken as the objective functions. Since the DC transmission line loss accounts for 5% to 10% of the rated transmission capacity, only the DC system transmission line loss. The objective function is expressed as:

\[
F = \min [f_{\text{actoss}} + f_{\text{dcloss}}, f_{\text{vd}}] \tag{1}
\]

\[
f_{\text{actoss}} = \sum_{i,j \in N_L} g_{ij} [U_i^2 + U_j^2 - 2U_iU_j \cos \theta_{ij}] \tag{2}
\]

\[
f_{\text{dcloss}} = I_{dc}^2 R \tag{3}
\]

\[
f_{\text{vd}} = \sum_{i \in N_{PQ}} \left| \frac{U_{i}^{\text{spec}} - u_i}{U_{i}^{\text{max}} - u_i^{\text{min}}} \right| \tag{4}
\]

In the formula, \( \min [f_{\text{actoss}} + f_{\text{dcloss}}, f_{\text{vd}}] \) is the minimum integrated network loss and voltage offset. \( f_{\text{actoss}}, f_{\text{dcloss}}, \) and \( f_{\text{vd}} \) are the ac network loss, dc network loss, and voltage offset, \( g_{ij} \) is the conductance of the line between nodes i and j; \( \theta_{ij} \) is the phase angle difference between the voltages at node i and node j; \( N_L \) is the transmission line; \( U_i, U_{i}^{\text{spec}}, U_{i}^{\text{max}}, u_i^{\text{min}} \) are the voltage amplitude, voltage reference value, upper limit and lower limit of node i respectively; \( N_{PQ} \) is the pq bus set.
3.2. Restrictions

3.2.1. Equality constraint. The equality constraint is the power flow constraint power balance equation of the power system. Compared to the AC system equation constraint, which includes the active and reactive power balance equations of the AC node, the AC and DC system equation constraints include the active power constraint equation of the AC and DC system node. And reactive power constraint equation.

\[ P_{Gi} - P_{li} - \varepsilon P_{ti(dc)} = U_i \sum_{j=1}^{N} U_j \left( G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij} \right) \ i e N \]  \hspace{1cm} (5)

\[ Q_{Gi} + Q_{ci} - Q_{li} - \varepsilon Q_{ti(dc)} = U_i \sum_{j=1}^{N} U_j \left( G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij} \right) \ i e N \]  \hspace{1cm} (6)

In the formula, \( N \) is the total number of system nodes; \( P_{li} \) and \( Q_{li} \) are the active and reactive load power of the load node; \( P_{Gi} \) and \( Q_{Gi} \) are the active and reactive power output of the AC system generator node; \( P_{ti(dc)} \) and \( Q_{ti(dc)} \) are DC Active and reactive input of the node; \( Q_{ci} \) is the reactive power compensation capacity of the node; \( G_{ij}, B_{ij}, \) and \( \theta_{ij} \) are the conductance, sonar, and voltage phase difference angle between the nodes i and j, respectively. \( \varepsilon=0 \) when the node is an AC node, \( \varepsilon=1 \) when the node is connected to the rectifier, and \( \varepsilon=-1 \) when the node is connected to the inverter.

3.2.2. Inequality constraint. Inequality constraints can be divided into state variable constraints and control variable constraints

State variable constraints:

\[
\begin{align*}
Q_{G0 \min} & \leq Q_{G0} & \leq Q_{G0 \max} \ o = 1,2, \ldots, N_g \\
U_{l p \min} & \leq U_{lp} & \leq U_{lp \max} \ p = 1,2, \ldots, N_d \\
Q_{zq \min} & \leq Q_{zq} & \leq Q_{zq \max} \ q = 1,2, \ldots, N_z \\
K_{ds \min} & \leq K_{ds} & \leq K_{ds \max} \ s = 1,2, \ldots, N_{dc}
\end{align*}
\]  \hspace{1cm} (7)

In the formula, \( Q_{G0}, Q_{G0 \max}, \) and \( Q_{G0 \min} \) are the reactive power output of the generator and its upper and lower limits respectively; \( U_{lp}, U_{lp \max}, \) and \( U_{lp \min} \) are the load node voltage and its upper and lower limits; \( Q_{zq}, Q_{zq \max}, \) and \( Q_{zq \min} \) are Branch reactive power and its upper and lower limits; \( K_{ds}, K_{ds \max}, \) and \( K_{ds \min} \) are the transformer ratio and its upper and lower limits.

Control variable constraints:

\[
\begin{align*}
U_{G0 \min} & \leq U_{Gi} & \leq U_{G0 \max} \ i = 1,2, \ldots, N_g \\
T_{tk \min} & \leq T_{tk} & \leq T_{tk \max} \ k = 1,2, \ldots, N_t \\
Q_{cj \min} & \leq Q_{cj} & \leq Q_{cj \max} \ j = 1,2, \ldots, N_c \\
U_{dl \min} & \leq U_{dl} & \leq U_{dl \max} \ l = 1,2, \ldots, N_d \\
I_{dm \min} & \leq I_{dm} & \leq I_{dm \max} \ im = 1,2, \ldots, N_d \\
P_{dm \min} & \leq P_{dm} & \leq P_{dm \max} \ n = 1,2, \ldots, N_d \\
\cos \theta_{dr \min} & \leq \cos \theta_{dr} & \leq \cos \theta_{dr \max} \ r = 1,2, \ldots, N_d
\end{align*}
\]  \hspace{1cm} (8)

In the formula, \( U_{G0}, U_{G0 \max}, U_{G0 \min} \) are the generator terminal voltage and its upper and lower limits; \( T_{tk}, T_{tk \max}, \) and \( T_{tk \min} \) are the adjustable transformer tap positions and their upper and lower limits; \( Q_{cj}, Q_{cj \max}, \) and \( Q_{cj \min} \) are Reactive compensation point Reactive compensation output and its upper and lower limits; \( U_{dl}, I_{dm}, P_{dm} \) are the converter control voltage, control current, and control power, respectively; \( \cos \theta_{dr} \) is the cosine value of the converter control angle; \( N_g, N_t, N_c, N_d \) Represents the
total number of generator nodes, the number of transformer adjustable tap groups, the number of compensation nodes and the number of network nodes.

4. Program Realization of AC and DC Reactive Power Optimization

NSGAII algorithm is a multi-objective optimization algorithm based on genetic algorithm. A fast non-dominated sorting method is added to the traditional genetic algorithm, and an elite retention strategy is used in the genetic process to prevent the loss of excellent individuals, and an optimization algorithm that obtains multiple pareto non-inferior solution sets. The main steps of the program implementation are as follows:

(1) Solve the network equations of AC and DC systems, and get the initial solutions $U_G(0), T_j(0), Q_G(0), U_d(0), I_d(0), P_d(0), \cos\theta_d(0)$, and System raw parameters, GA parameters and system variables.

(2) Encoding the above variables. Generate initial population. All decision variables for each individual are randomly selected within constraints.

(3) The alternating flow method is used for power flow calculation, and the objective function value is calculated based on the obtained results.

(4) Quick non-dominated sorting, then select, cross, and mutate. This article selects the operation by the round game system selection method.

(5) Elite retention strategy. The elite strategy is to keep the good individuals of the parents directly into the offspring to prevent the loss of the good individuals.

(6) Convergence criterion: Given the number of iterations, the result is output if the number of iterations is satisfied. Repeat step (3) if the iteration conditions are not met.

(7) Output the pareto optimal solution set.

5. Practical example verification

5.1. Study data processing

The IEEE9 node system is shown in Figure 1. There are three generators. Node 9 is selected as the balance node, and the remaining two are PV nodes. There are 9 branches, 3 adjustable transformers (branch 1-9, 5-7, 3-8) and two reactive power compensation points (nodes 4, 5). In this paper, branches 4-5 are replaced with DC transmission lines to form a double-ended AC-DC transmission system, where node 4 is connected to the rectifier station and node 5 is connected to the inverter station.

![Figure 1. The IEEE9 node system.](image)
The DC node parameters are shown in Table 1. The reference value is 100MVA. A self-compensation device is installed in the converter station to provide its own converter reactive power compensation.

| Converter | Node number | Control angle (°) | Commutation reactance (p.u.) | Transformer ratio limit | Line resistance (p.u.) | Rectified side transmission power (p.u.) | Inverter-side DC voltage (p.u.) |
|-----------|-------------|-------------------|------------------------------|------------------------|-----------------------|------------------------------------------|-------------------------------|
| Rectifier | 4           | 10                | 0.1260                       | ±15%                   | 0.00334               | 1.5                                      | —                             |
| Inverter  | 5           | 18                | 0.07275                      | ±15%                   | 0.00334               | —                                        | 1.0                           |

5.2. Simulation variable processing
The AC and DC system optimization variables include generator active and reactive output power, generator end voltage and transformer ratio, and converter control voltage, control current, control power, and control angle in the DC system. The state variables include the reactive power output of the generator node, the load node voltage, the size of the branch power, and the converter transformer ratio. The upper and lower limits of each control quantity are shown in Table 2. Among the optimization variables, the adjustable on-load transformer is considered as a discrete variable, and the gear is divided into 8 sections, and the adjustment step size is 0.025. Add reactive power compensation at nodes 4 and 5.

5.3. Analysis of optimization results
The population given in this paper is 20, the crossover rate is 0.9, and the mutation rate is 0.1. The control method uses a constant current on the rectifier side and a fixed quenching angle on the inverter side. Select different number of iterations and run the program multiple times to find that the pareto solution set space with relatively uniform optimal solution distribution can already be obtained by 60 iterations. When the number of iterations is 60, the pareto solution set is shown in Figure 2. In the figure, the horizontal and vertical coordinates represent the two objective functions of active network loss and voltage offset, respectively.
Select the group with the largest voltage offset in the above figure as the first group, and the value with the largest network loss as the fifth group. Select the three points in the middle as the second, third, and fourth groups of data. The results of these five sets of optimization variables are shown in Table 3.

|                | Active network loss | Voltage offset | Crowded distance |
|----------------|---------------------|----------------|-----------------|
| Before optimization | 26.8640             | 3.2614         | 0               |
| First group      | 13.2808             | 6.0861         | ∞               |
| Second Group     | 18.2192             | 4.2800         | 0.2452          |
| Third group      | 18.2762             | 4.9067         | 0.1866          |
| Fourth group     | 18.3359             | 3.9005         | 0.2458          |
| Fifth group      | 19.2907             | 3.0131         | ∞               |

Before optimization, the active network loss of the AC and DC system was 26.8640 and the voltage offset was 3.2614. After optimization, the maximum active network loss value was 19.2907 and the maximum voltage offset was 6.0861. It can be seen that after optimization, the AC and DC system always has active power. Network loss and node voltage offset cannot be reduced at the same time.

When the maximum value of the active power loss is 19.2907, the voltage offset is 3.0131; when the maximum value of the voltage offset is 6.0861, the minimum value of the active power loss reaches 13.2808. It can be seen that the two objective functions are contradictory, cannot reach the optimal at the same time.

6. Conclusion
This paper mainly studies the application of the non-dominated sequencing genetic algorithm with elite selection strategy to the multi-objective reactive power optimization of AC and DC systems, and studies the specific operation of the algorithm to solve the reactive power optimization problem of AC and DC systems. The program implements the idea of applying the NSGAII algorithm to the reactive power optimization of AC and DC systems in this paper. Taking the total network loss of the system and the node voltage offset as the two objective functions, multiple groups of pareto optimal values are solved through an IEEE9 node system example the optimal solution set proves the effectiveness of the algorithm in this paper. The optimization results show that the two objective functions cannot reach the optimum at the same time. When the active network loss is the smallest, the voltage offset is the largest.
Therefore, when multiple objective functions are established, a series of pareto optimal solution sets can be solved by NSGAII.

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