Research on voltage reactive power optimization considering fuzzy load characteristics

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Abstract. For the distributed load output is uncertain, which leads to the over-limit of voltage and line power, this paper proposes a load representation method based on fuzzy set theory, and establishes a voltage reactive power optimization model based on fuzzy number. The influence of different control equipment on node voltage and reactive power is analyzed. Combined with the sensitivity analysis method, the selection rules of control equipment with heuristic method are developed. A method of Genetic calculation based on fuzzy power flow calculation is presented. Finally, this method is applied to build a 30-node model in Matlab for simulation calculation. The results of the example show that the proposed model and method can accelerate the convergence speed, reduce the solution space and reduce the network loss.

1. Introduction
With distributed energy taking an increasingly high proportion in the power grid, distributed energy has accounted for more than 20% of the world's total power generation by the end of 2020. A large number of distributed energy sources are connected to the grid, which improves the grid voltage distribution and reduces the load side grid-connection loss. However, due to the greater randomness of distributed generation, it brings many difficulties to the reactive power optimization of the power grid [1-3].

Power grid voltage reactive power optimization is a nonlinear hybrid optimization problem which optimizes one or some power grid indexes under the condition of satisfying constraints. At present, a series of researches have been carried out in the field of voltage and reactive power optimization for new energy grid connection. Literature [4] combined the particle swarm optimization algorithm with the sensitivity analysis method, and the optimal compensation position and capacity were obtained through continuous iterative optimization. In addition to particle swarm optimization (PSO), some studies also start with the local linearization of the control effect of compensation device. For example, Literature [5] studied the sensitivity coefficient of each control point and proposed a full optimization method based on linear programming form. Literature [6] proposed the method of training, testing and correcting system voltage reactive power control through artificial neural network, but there are still some inherent defects that cannot be remedied, such as long training time and the need to relearn when changes occur. Literature [7] proposed a heuristic algorithm based on the minimum energy loss, which can accurately calculate the capacitor compensation amount and tap action times of on-load voltage regulating transformer. However, it is difficult to obtain the global optimal solution due to the large amount of calculation. Literature [8] proposed a voltage reactive power control method based on
sensitivity analysis, but it only improved the level of voltage reactive power to a certain extent, and could not realize the optimal operation of voltage reactive power in the whole cycle.

The research of many experts and scholars is carried out under the deterministic load characteristics. It is assumed that the load at a time is a definite value or is constant over a divided period of time. But the actual load is variable and has some randomness. In the calculation and analysis of some load forecasting, the load data is also uncertain because of the forecasting method. The advantage of fuzzy set theory is that it can represent and process fuzzy information. Therefore, load modeling using fuzzy set theory can deal with the above uncertain problems [9]. In order to accelerate the solving speed, sensitivity analysis and expert experience were combined in this paper [10]. It formulates the selection rules of voltage reactive power control equipment, selects the equipment with good control effect for optimization, and greatly reduces the solution space.

2. Fuzzy load and power flow calculation

2.1. Ambiguity of load

According to the characteristics of the load, the trapezoidal fuzzy number is used to represent the uncertainty of the load. Assuming that the load size of a node is usually between $L_2$ and $L_1$, and is always greater than $L_1$ and less than $L_4$, then the load of this node can be represented by the trapezoidal fuzzy number $\hat{L} = (L_1, L_2, L_3, L_4)$. This is shown in Fig. 1. Its membership function can be expressed by Eq. 1, meaning that the load is fully subordinated between $L_2$ and $L_3$, and the membership degree is 1. From $L_2$ to $L_1$ and from $L_3$ to $L_4$, the membership degree gradually decreases to 0, and $(L_2 + L_3)/2$ is called the central value of the fuzzy number.

$$
\mu_L(x) = \begin{cases} 
0 & x < L_1 \\
\frac{x - L_1}{L_2 - L_1} & L_1 \leq x < L_2 \\
1 & L_2 \leq x \leq L_3 \\
\frac{L_4 - x}{L_4 - L_3} & L_3 < x \leq L_4 \\
0 & x > L_4 
\end{cases}
$$

Fig 1 Trapezoidal membership function

2.2. Fuzzy power flow calculation

When the load is represented by trapezoidal fuzzy number, the calculation of power flow involves the operation between trapezoidal fuzzy number, and the power flow is determined to be a fuzzy power flow. The voltage amplitude, phase angle, active and reactive power of the branch are also trapezoidal fuzzy numbers. In this paper, an incremental model based on Newton-Raphson method is used to calculate fuzzy power flow.
3. Voltage reactive power optimization model

3.1. Objective function

After the trapezoidal fuzzy number is adopted to represent the node load, the objective function of voltage reactive power optimization is also a trapezoidal fuzzy number, as shown in Eq. 2.

\[
\min F = P_{\text{loss}} = (P_{11}, P_{12}, P_{13}, P_{14})
\]  

(2)

In order to measure the network loss and find the minimum network loss, it is necessary to compare the trapezoidal fuzzy number. The transfer degree \( b \) of the fuzzy number \( A \) to the real number 0 is taken as the size of the fuzzy number, and the calculation formula is shown in Eq. 3.

\[
R_{\text{em}}(\tilde{L}, 0) = (L_1 + L_2 + L_3 + L_4)/4
\]  

(3)

Considering the practical application, the results of network loss optimization hope that the network loss is small in most operating cases. Therefore, weighted displacement value is used as fuzzy network loss in this paper. To enlarge the weight of the interval with high network loss membership expressed by trapezoidal fuzzy number, the calculation formula is shown in Eq. 4.

\[
P_L = \frac{\omega_1 P_{11} + \omega_2 P_{12} + \omega_3 P_{13} + \omega_4 P_{14}}{\omega_1 + \omega_2 + \omega_3 + \omega_4}
\]  

(4)

Where, \( \omega_1, \omega_2, \omega_3 \) and \( \omega_4 \) are weight coefficients.

3.2. Constraint condition

Since node voltage amplitude is expressed by trapezoidal fuzzy number \( V_i = (V_{i1}, V_{i2}, V_{i3}, V_{i4}) \), in order to ensure that load node voltage amplitude does not exceed the limit in all cases, the power-saving voltage constraint inequality is expressed by Eq. 5.

\[
V_{i_{\text{min}}} \leq V_{i1} \leq V_{i2} \leq V_{i3} \leq V_{i4} \leq V_{i_{\text{max}}}
\]  

(5)

4. Control device selection

In order to reduce the solution space, and achieve a better optimization effect. The sensitivity analysis based control equipment selection strategy is established in this paper. The most effective control equipment is selected and optimized according to the different operating conditions of the power network. Calculate the sensitivity of each control device to the network loss and the voltage of load node respectively, and then draw on the experience of experts. Finally, the selection rules of control equipment are made by using heuristic rules.

The voltage overlimit is divided into simple overlimit and complex overlimit. Voltage - dependent control devices are selected according to different principles. The voltage only exceeds the upper limit or the lower limit, and only a few nodes exceed the limit when it is a simple case, otherwise it is a complex case. First of all, will all control equipment Vietnam limit of node voltage sensitivity for sorting; Then, for each of the nodes to select several sensitivity control equipment. If it is a simple case, choose from the reactive power compensation control equipment; if it is a complex case, choose from all control equipment.

5. Optimization of control variables based on genetic algorithm

In order to improve the optimization effect of genetic algorithm, a variety of improvement measures have been proposed, such as: hybrid coding technology, niche genetic algorithm, adaptive genetic algorithm, catastrophic genetic algorithm, parallel genetic algorithm, etc. Hybrid coding technology and adaptive genetic algorithm are used in this paper.

5.1. Individual representation

Individuals in the genetic algorithm in this paper represent the control variables that need to be optimized, including the terminal voltage of the generator for control, the number of capacitor banks and the location of adjustable transformer taps. Individual expression is shown in Eq. 6.
\[ p = [V_1, \cdots, V_M | C_1, \cdots, C_L | T_1, \cdots, T_K] \]  

Where: \( V(i = 1, \cdots, M) \) represents the terminal voltage of the generator for control, which is coded by floating-point number; \( C(i = 1, \cdots, L) \) represents the number of capacitor banks input, using integer code; \( T(i = 1, \cdots, K) \) represents the adjustable transformer tap position, using integer coding.

### 5.2. Realization of genetic manipulation

In this paper, the roulette wheel method is used to select the operation. The crossover operation requires that the excellent new individual pattern can be generated effectively without destroying the excellent string condition in the individual code. Therefore, in view of the characteristics of mixed floating-point and integer coding, this paper adopts the single-point crossing method. Mutation operation replaces old gene value with new gene value, which has the advantage of maintaining population diversity and expanding search range. In the initial stage of optimization calculation, the variation rate usually does not adopt fixed values and smaller values. Therefore, this paper adopts the adaptive mutation probability. It is shown in Eq. 7 and Eq. 8.

\[
P_c = \begin{cases} 
P_{c1} - \frac{(P_{c1} - P_{c2})(f' - f_{avg})}{F_{max} - f_{avg}} & f' \geq f_{avg} \\
p_{c2} & f' < f_{avg} 
\end{cases} 
\]

\[
P_m = \begin{cases} 
P_{m1} - \frac{(P_{m1} - P_{m2})(f_{max} - f)}{f_{max} - f_{avg}} & f' \geq f_{avg} \\
p_{m2} & f' < f_{avg} 
\end{cases} 
\]

Where, \( P_c \) and \( P_m \) represent the crossover and mutation probability of the current individual respectively; \( P_{c1} \) and \( P_{m1} \) represent the maximum crossover and mutation probability respectively; \( P_{c2} \) and \( P_{m2} \) represent the minimum crossover and mutation probability respectively; \( f' \) stands for greater fitness in crossover individuals; \( f \) represents the fitness of the current individual; \( f_{avg} \) represents the average fitness of the contemporary population; \( f_{max} \) represents the maximum fitness of the contemporary population.

### 6. Example analysis

In order to verify the effectiveness of the method proposed in this paper, IEEE 30-node model is adopted to conduct simulation analysis in MATLAB. The injected power of all nodes is increased to 1.5 times, and the 30-node power grid model is shown in Fig. 2. Node numbers (1-30) are shown in larger font and control device numbers (1-19) are shown in smaller font with an underscore. Among them, the serial number 1-5 is the generator, 6-15 is the capacitor bank, 16-19 is the four newly set adjustable transformers. It is assumed that the load of nodes 3, 4, 6, 8, 10, 12, 14, 16, 18, 20, 24, 26, 28, 29 and 30 is uncertain, and the trapezoidal fuzzy number is obtained by multiplying the load value by the coefficients 0.99, 0.995, 1.005 and 1.01, respectively. Set the upper and lower limits of node voltage as 1.05 and 0.95 respectively.
According to the sensitivity analysis results, the control equipment selection strategy presented in this paper is used. It is calculated that control equipment 1, 3, 4, 16, 18 is only needed to control, which greatly reduces the number of control equipment and reduces the understanding space. On this basis, genetic algorithm was adopted for optimization, and the optimization results are shown in Tab. 1 to Tab. 5.

Table 1  Optimization results of control generator terminal voltage

| Number | Node | Initial Value (p.u.) | Optimum Value (p.u.) |
|--------|------|----------------------|----------------------|
| 1      | 2    | 1.000                | 1.013                |
| 3      | 22   | 1.000                | 1.011                |
| 4      | 23   | 1.000                | 1.024                |

Table 2  The result of capacitor switching

| Number | Node | Initial Groups | Optimal Groups |
|--------|------|----------------|----------------|
| 8      | 3    | 0              | 3              |

Table 3  The adjustment result of transformer tap

| Number | First Node | Last Node | Initial Gear | Optimum Gear |
|--------|------------|-----------|--------------|--------------|
| 16     | 6          | 9         | 1            | 4            |
| 17     | 6          | 10        | 3            | 4            |
| 18     | 4          | 12        | 3            | 7            |

Table 4  Fuzzy weighted loss before and after optimization

|                      | Loss without Optimization (p.u.) | Optimized Loss (p.u.) |
|----------------------|----------------------------------|-----------------------|
|                      | 0.0859                           | 0.0849                |

Table 5  The results of node voltage optimization

| Node | $V_1$ | $V_2$ | $V_3$ | $V_4$ |
|------|-------|-------|-------|-------|
| 1    | 1.000 | 1.000 | 1.000 | 1.000 |
| 2    | 1.013 | 1.013 | 1.013 | 1.013 |
| 3    | 1.001 | 1.002 | 1.003 | 1.004 |
| 4    | 0.985 | 0.985 | 0.987 | 0.987 |
| 5    | 0.985 | 0.985 | 0.986 | 0.987 |
| 6    | 0.972 | 0.972 | 0.974 | 0.975 |
| 7    | 0.963 | 0.963 | 0.964 | 0.965 |
| 8    | 0.954 | 0.954 | 0.955 | 0.956 |
| 9    | 1.001 | 1.001 | 1.002 | 1.003 |
| 10   | 0.993 | 0.994 | 0.995 | 0.996 |
| 11   | 1.001 | 1.001 | 1.002 | 1.003 |
| 12   | 1.002 | 1.002 | 1.004 | 1.005 |
After optimization, all voltage overlimits are eliminated, and no new node voltage overlimits occur. The results meet the voltage constraint requirements. After the optimization of the control equipment, the network loss can be reduced from 0.0859 to 0.0849, which is reduced by 1.164%.

7. Conclusions
In this paper, the operation of power grid with new energy sources is analyzed, and the optimal model of voltage and reactive power is established based on trapezoidal fuzzy number. Combined with the sensitivity analysis method, the selection rules of control equipment with heuristic method are developed. A method of genetic calculation based on fuzzy power flow calculation is presented. IEEE 30 node model was built to simulate. The simulation results show that this method can meet the requirement of selecting equipment with good control effect, reduce the solution space, improve the calculation speed and reduce the loss of power grid. In addition, the research content of this paper still needs to be further studied. For example, the treatment of coupling effect constraint in reactive power real-time optimization control is the focus of the next research.

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