Reactive Power Optimization of Distribution Network with Distributed Generators by Improved Evolutionary Programming Algorithm

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Abstract. In the distribution network containing distributed generators (DG), both DG and capacitors can be adjusted for reactive power, and there is a strong complementarity between the two. If the reactive power compensation ability of each grid-connected DG can be fully utilized, it will effectively reduce the voltage fluctuation and the number of equipment actions, which will help to improve the operation level of the distribution network. In this paper, reactive power optimization of distribution networks containing distributed power sources has been studied. An improved evolutionary programming (EP) method is proposed to solve the optimization goal, using a variable step-size evolution method and optimization strategy with small population and high convergence accuracy. The algorithm improves the random dynamic step method. In different stages of optimization, different step sizes are used to improve the optimization effect. At the same time, considering that some wind farms are equipped with AVC and some wind farms are equipped with capacitor banks, the evolutionary operator is improved. The operator evolves directly on the integer, so it is easier to find the global optimal solution. This paper has used IEEE33 bus system to verification. Results show that the DG can reduce active power loss in distribution network and ameliorate the voltage level. Meanwhile, the improved evolutionary programming method has good optimization effect, fast convergence speed and high search efficiency.

1. Introduction
When distributed generation (especially wind power) is inserted to the distribution network, the reactive power of the system is greatly supported [1-2]. An integrated control strategy for low voltage ride through (LVRT) of direct drive wind turbine is proposed, which improves the stability and economy of the system [3-4]. Wang Haona [5] uses improved particle swarm optimization algorithm to solve reactive power regulation problem, and avoids the degradation of genetic algorithm. Directional genetic particle swarm optimization hybrid algorithm is applied to reactive power regulation of active distribution network, which avoids the randomness of genetic algorithm and improves the solution efficiency [6]. The reactive power transient control strategy proposed in reference not only satisfies the transient voltage stability of the grid connection point, but also has larger reactive power compensation margin and more balanced transient voltage margin [7]. The power flow model of photovoltaic power generation and wind power is established, refer to [8-10]. Then, this paper proposes an objective function basing on loss reduction. Meanwhile, according to the radial characteristics of the distribution network, combined with the experience of some experts to
constrain the optimization process, by improving the evolution operator, selecting the appropriate population size and convergence accuracy, on the premise of ensuring the optimization effect, the optimization efficiency of the entire algorithm is obviously improved.

2. **Mathematical model of reactive power optimization in distribution network with DG**

   In distribution network with DG, reactive power optimization mathematical model mainly includes objective function and restrictions. The control variables include not only generator voltage, tap position of transformer, but also DG's active and reactive output.

   (1) **Objective function**

   To ensure the security and economy of power grid, the objective function is to minimize the active power loss. The objective function is expressed as follows:

   \[
   \min F = \frac{\sum_{j=1}^{n} V_j \sum_{i=1}^{n} V_i (B_{ij} \sin \delta_{ij} + G_{ij} \cos \delta_{ij})}{P_0}
   \] (1)

   Where \( P_{\text{loss}} \) is the active loss, \( P_0 \) is the initial loss, \( n \) is the bus numbers, \( V_i \) and \( V_j \) are voltage amplitude, \( G_{ij} \) is branch conductance, \( B_{ij} \) is branch electrical susceptance, \( \delta_{ij} \) is phase angle difference.

   (2) **Restrictions**

   Restrictions are expressed as follows:

   (a) **Equality constraints**

   In reactive power optimization, each bus needs to meet the conditions of reactive power and active power balance, which are expressed as follows:

   \[
   \begin{align*}
   \Delta P_i - V_i \sum_{j=1}^{n} V_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) &= 0 \\
   \Delta Q_i - V_i \sum_{j=1}^{n} V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) &= 0
   \end{align*}
   \] (2)

   Where \( \Delta P_i \) is the power algebraic sum of generator, DG, and load, \( \Delta Q_i \) is the reactive power algebraic sum of generator, DG, and load.

   (b) **Inequality constraints**

   To ensure safety and stability in power system and the normal operation of the power equipment, each variable in reactive power optimization must satisfy inequality constraints, including state variable constraints and control variable constraint.

   Control variable constraints include generator terminal voltage, tap position of on-load voltage-regulating transformer, reactive power switching capacity of capacitor bank, and reactive power output of DG. The specific constraints are as follows:

   \[
   \begin{align*}
   V_{\text{min}}^{Gi} &\leq V_{Gi} \leq V_{\text{max}}^{Gi} \\
   T_{\text{min}}^{i} &\leq T_{i} \leq T_{\text{max}}^{i} \\
   Q_{\text{min}}^{Ci} &\leq Q_{Ci} \leq Q_{\text{max}}^{Ci} \\
   Q_{\text{min}}^{DGi} &\leq Q_{DGi} \leq Q_{\text{max}}^{DGi}
   \end{align*}
   \] (3)

   State variable constraints include load bus voltage \( V_i \) and reactive power output \( Q_i \) of thermal power unit on the PV node. The specific constraints are as follows:

   \[
   \begin{align*}
   V_{\text{min}}^{i} &\leq V_{i} \leq V_{\text{max}}^{i} \\
   Q_{\text{min}}^{Gi} &\leq Q_{Gi} \leq Q_{\text{max}}^{Gi}
   \end{align*}
   \] (4)
3. Improved EP algorithm

This paper has used EP algorithm to solve the optimization problem of reactive power in distribution network. In the solution process, the traditional evolutionary planning method is partially improved. The purpose is to ensure the optimization accuracy and improve the search efficiency of algorithm.

(1) Improving variation

The mutation process of the evolutionary programming algorithm is: introducing a Gaussian random distribution variable \( N(0, \sigma^2) \) with mean 0 and variance \( \sigma^2 \), and the parent individual \( X_i \) produces the child individual \( X_{i+n} \):

\[
X_{i+n} = X_i + N(0, \sigma^2)
\]  

(5)

The reactive power compensation devices currently equipped in wind farms have both AVC and capacitor banks. AVC can achieve continuous reactive power regulation, but the capacitor bank can only be switched on and off. In the past, the optimal real number solution of the system was obtained first, and then it was rounded. Through a large number of simulation calculations, it is found that the compensation effect after optimal real number deregulation is often inferior to that of non-optimal real number deregulation. The reason for the analysis is due to overcompensation caused by the regulation. Therefore, in the optimization process of this paper, each solution is first regularized, and then the objective function value is compared, to ensure that the optimal integer solution is not eliminated.

When using the evolutionary programming method to solve the optimization of reactive power, the choice of step size is a problem worthy of attention. If the algorithm step size (variation) is too large, when approaching the optimal solution, considering the influence of the rounding strategy at each step, it is possible to "skip" the optimal solution and "sink" near the local optimal solution. If the dimensions number of the optimization problem is larger, the possibility is greater. However, if the step size is too small, the speed of search in the solution space will be slower, which will affect the optimization efficiency of the algorithm. Therefore, the choice of step size will affect the accuracy and efficiency of the evolutionary programming algorithm. Through calculation, it is found that when using evolutionary programming to solve the optimization of reactive power in distribution network, the search speed is faster at the beginning of the optimization process, and the network loss decreases much. Near the optimal solution, the optimization speed becomes slower and the network loss declines more slowly. After comprehensively considering the characteristics of "first hurry and then slow" in each step of the rounding and optimization process, this paper adopts the following evolutionary methods in the mutation process of the algorithm:

\[
Q_{i+n} = Q_i + Q_{i0} \left[ N_i(0, \sigma^2) \right]
\]

(6)

There \( \left[x\right] \) indicates an integer less than or equal to \( x \); \( Q_{i0} \) is the capacity of a single group of \( i \)-th DG.

\[
N_i(0, \sigma^2) = \beta \frac{f_i}{f_{max}} (Q_{C_{i max}} - Q_{C_{i min}})(\sum_{j=1}^{12} r_j - 6)
\]

(7)

Where \( \beta \) is the variation scale factor, \( r_j \) is a random evenly between (0,1).

Analysis formula (10), the \( N_i(0, \sigma^2) \) is mainly composed of four items: the \( \beta \) is the scale factor of variable; after the algorithm is iterated several times, \( \frac{f_i}{f_{max}} \) value is close to 1; the third item \( (Q_{C_{i max}} - Q_{C_{i min}}) \) is the reactive adjustment range of each DG, it is a certain value during the iteration process; the fourth item \( (\sum_{j=1}^{12} r_j - 6) \) is random. It can be seen that the control of the variation amount
can be achieved by controlling the variation scale factor $\beta$. Adopted strategy is: at the initial evolution stage, the amount of variation is appropriately larger, that is the $\beta$ can be appropriately larger. When the search process is slowing, the amount of variation should be appropriately reduced. When the search process slows down and approach the optimal solution, $N_i(0,\sigma^2)$ keep the amount of variation about one or two capacitors. Choosing such a small step size is more conducive to finding a better solution. Since the fourth term is a random number, the probability of its value appearing near 1 is relatively large, So let the product of $\beta$ and $(Q_{C\text{max}} - Q_{C\text{min}})$ be $Q_{C\text{10}}$. And then get the $\beta$ when the optimization process slows down. Because systems and different reactive power adjustment ranges of DG are different, factor $\beta$ should also be different. This paper has a 5 times relationship in the calculation process.

When using the evolutionary programming method to solve the optimization of reactive power, the tracking of optimization process found that the optimization process is prone to fall into certain solutions and stagnate. Therefore, the algorithm is improved as follows: when the search process is stuck in a certain solution, the current solution $X_{\text{op}}$ is used to generate a pair of new solutions $X_+$, $X_-$. The principle of production is as follows:

$$
X_{+i} = \begin{cases} 
X_{opi} + Q_{i0} & \text{if } i = \text{rand} \\
X_{opi} & \text{if } i \neq \text{rand} 
\end{cases} 
$$

$$
X_{-i} = \begin{cases} 
X_{opi} - Q_{i0} & \text{if } i = 1 \\
X_{opi} & \text{if } i \neq 1 
\end{cases} 
$$

There $m$ is the number of DG, $\text{rand}, \text{rand1}$ is randomly generated integer with a value between 1 and $m$.

4. Optimization of reactive power in distribution network with distributed generators by improved EP algorithm

The specific implementation of the algorithm is as follows:

(1)Form the initial feasible solution population
Express the solution population in the following vector form:

$$X=[X_1,X_2,\ldots,X_n]^T$$

$$X_i=[Q_{DG1},Q_{DG2},\ldots,Q_{DGk},\ldots,Q_{DGm}]$$

Where $n$ is population size, $X_i$ is the $i$-th individual, $m$ is total number of DG in system.

(2)Power flow calculation with DG
Carry out the power flow calculation of the distribution network with DG, and calculate the active power loss corresponding to each individual in the current population. Check whether the voltage exceeds the limit in the system. When a violation is found, the individual is eliminated directly. If the individual has not exceeded the limit, calculate the fitness value.

(3)Mutations
According to the improved operator mutation proposed in this paper, a new solution is generated.

(4)According to the process (2), the power flow of the distribution network is calculated
Bring the new generated individuals after the mutation into the power flow to calculate and find the fitness. If an individual who violates the constraint is found, he will be eliminated.

(5)Competition
Calculate the weight corresponding to every individual in population.

(6)Select
Sort all the individuals in population according to weight, save the top $n$ individuals with the largest weight, evolve to the next generation, and eliminate the remaining individuals. In addition, this paper
also follows a principle in the selection process: the principle of best individual preservation. During the evolution process, the individual with the highest fitness value is automatically saved to the next generation. This is to take into account that some random quantities are introduced when calculating the weight. For individuals with a large fitness value, the weight is not necessarily large. Individuals may lose the most adaptable individuals.

(7) Algorithm convergence criterion

If the evolutionary algebra reaches the preset maximum evolutionary algebra or meets the convergence accuracy requirements, the search is stopped. Otherwise, return to step (3) to continue the search.

5. Example analysis

To verify effectiveness and feasibility of the proposed evolutionary programming algorithm, and to further explore the impact of optimizing DG reactive power output in the distribution network, the paper takes the IEEE33 nodes distribution system as an example for simulation analysis.

The IEEE33 nodes system diagram is shown in Figure 1. The relevant parameters are set as follows: system reference voltage 12.66kV, system reference capacity 10MVA, convergence accuracy of power flow $10^{-5}$, the initial voltage of bus is 1.00 (standard unit value, below same), allowable voltage range 0.93–1.07.

**Figure 1.** IEEE33 bus distribution network

Connect DG1, DG2, DG3, and DG4 to Bus3, Bus8, Bus18, and Bus33 respectively. The active output of grid-connected each DG is 300kW, and the reactive output is restricted to 0–1500kVar. The objective function is formula (1), and the improved EP algorithm is used for optimization simulation. The parameter settings are as follows: population size $N=100$, maximum iteration number $T_{\text{max}}=100$, as shown in Figure 2.

**Figure 2.** IEEE33 bus distribution network with 4 DGs
Table 1. Comparison of simulation results with 4 DGs and no DGs

|                              | Without DG | Contains DG but DG reactive power output is 0 | DG participates in reactive power regulation |
|------------------------------|------------|-----------------------------------------------|---------------------------------------------|
| Active loss (pu.)            | 0.0204     | 0.0115                                        | 0.0060                                      |
| Objective function value     | no         | no                                            | 0.6149                                      |
| DG1 reactive power (pu.)     | no         | 0                                             | 0.0177                                      |
| DG2 reactive power (pu.)     | no         | 0                                             | 0.0342                                      |
| DG3 reactive power (pu.)     | no         | 0                                             | 0.0220                                      |
| DG4 reactive power (pu.)     | no         | 0                                             | 0.0526                                      |
| DG total reactive power (pu.)| no         | 0                                             | 0.1265                                      |

It can be seen from Table 1: Before optimization, compared with the case without DG, the active network loss of the system is reduced after DG is connected to the grid; after optimization, the active network loss of the distribution system with DG is smaller than before optimization.

Figure 3. The results of successive iterations

Figure 3 shows the successive optimization results of IEEE33 system calculated by conventional evolutionary planning algorithm and improved evolutionary planning algorithm. Obviously, the conventional evolutionary algorithm needs to iterate 8 times to converge to the optimal solution, and the improved evolutionary algorithm adopted only needs to iterate 4 times. Under the premise of ensuring the optimization accuracy, the optimization efficiency is also improved.

Figure 4. The bus voltage curve
Figure 4 shows: after optimization, the voltage of bus in distribution system with DG is significantly higher than that before optimization.

6. Conclusions
When DG is connected to the system, it has enriched the reactive power adjustment methods of the distribution network. This paper studies the optimization of reactive power in distribution system considering distributed generator. After establishing the objective function, an improved EP algorithm is used to solve the optimization problem. The result of the calculation example shows that after the distributed generator participates in the system optimization of reactive power, the loss of system decreases significantly and the voltage quality improves. The improved evolutionary programming algorithm has faster optimization speed and higher accuracy.

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