Multi-objective Optimization Configuration of Capacitor Blocking Devices based on Field-Circuit Coupled Model and Improved Differential Evolution Algorithm

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Abstract. The dc current of grounding pole will invade the transformer windings nearby when the HVDC system is in ground return operation, which will cause DC bias and affect the safety and stability of the system. It is an effective method to restrain dc current in transformer to install capacitor blocking devices at transformer neutral wire, but it is shown that this may increase the bias current of nearby transformers. For this reason, the installation of blocking device in a certain area can be considered as an optimization problem. An improved differential evolution algorithm is proposed to optimize the multi-objective configuration of capacitor blocking devices to suppress DC bias globally. The field-circuit coupled model is established to solve the potential. The objective function is to minimize the number of installations of the devices and the absolute sum of the total DC current of the transformer in the region, and the constraint is all DC current at the neutral point of each transformer is under the limit, then the optimal configuration model is established. Finally, the chaos mapping theory, adaptive parameters and elitism preservation strategy are introduced into the difference evolution algorithm to solve the model and obtain the optimal allocation scheme.

1. Introduction
When HVDC system is in ground return operation, DC current passes through the transmission line and the earth to form a circuit, and a large amount of DC current is injected into the earth by the grounding pole. Part of DC current intrudes into the winding of neutral grounding transformer in nearby AC system, resulting in DC bias of transformer[1-2]. The phenomenon of DC bias will make the core of transformer saturated and increase noise and loss[3-4], and also distort the exciting current, making transformer a harmonic source. It may do harm to equipment and result in malfunction of protection, which will affect the security and stability of power grid[5-7]. Therefore, it is of great significance to study how to suppress DC bias effectively for the safe and stable operation of power grid.

In the Technical guide of HVDC earth electrode system in China, it is required that the allowable DC current of each phase winding of three-phase three-column transformer should not exceed 0.7% of the rated current[8]. DC bias suppression device should be installed when DC current of transformer neutral point exceeds the limit. At present, the commonly used suppression methods are generating reverse current, installing capacitor blocking devices, adding a small resistance, etc. [9-11]. Capacitor blocking devices can completely isolate DC current, and the device is simple and easy to operate, so it...
has obvious effect in suppressing DC current and is widely used in power system. However, some studies have shown that the distribution of DC current in the earth will change after the capacitor blocking device is put into operation, thus changing the DC current at the neutral point of the transformer nearby, which may cause some DC current to exceed the allowable value and make DC bias phenomenon more serious[12]. So it is necessary to consider this problem as a global optimization problem. On the one hand, DC bias should be effectively suppressed, and on the other hand, the DC current at each transformer neutral point should be under the limit. In[13], an optimal deployment method of DC magnetic bias isolation device caused by geomagnetic induction current is proposed. However, only for transformers whose DC current exceeds the limit, it is uncertain for potential transformers whose DC current may exceed the limit, so the scheme may not be applicable. In[14], the grid calculation model under magnetic bias condition is set up and solved by genetic algorithm, but the model is relatively simplified and the model formed by soil in the earth is not considered. In[15], an exhaustive method is proposed to solve the optimal position of device, but the method is too complicated to be suitable for large-scale systems.

In this paper, a multi-objective optimal allocation method of capacitor blocking devices based on improved differential evolution algorithm is proposed according to the operation characteristics of DC blocking devices. Firstly, the equivalent model of transformer and the soil layered model are established respectively. Then, the equivalent field-circuit coupled model is formed by combining the two models. The DC current is solved by finite-element method. Then, under the condition that the DC current of each transformer is under the limit, the optimal allocation model is established with the minimum number of devices put into operation and the minimum total DC current in the whole network as the objective function. Then an improved differential evolution algorithm is proposed. Chaos mapping theory is introduced into the generation of initial population, and adaptive factor and elitism preservation strategy are introduced to accelerate the convergence of the algorithm and solve the optimal allocation model. Finally, the effectiveness and superiority of the proposed method are verified by a simulation example of an HVDC transmission project.

2. Field-circuit Coupled Model

2.1 Modeling of Transformer and AC Transmission Line

The DC current from grounding pole mainly distributes in transformers and AC transmission lines. Because the interconnection of substation and AC system is relatively complex and the grid is huge, if each line is modeled one by one, the workload will increase dramatically. Therefore, the transformer and AC transmission system can be reasonably simplified and equivalent to the resistance model. In this paper, the autotransformer model is adopted, and its equivalent model is shown in figure 1.

![Equivalent circuit model of autotransformer with DC blocking device](image)

Figure 1. Equivalent circuit model of autotransformer with DC blocking device
For AC transmission lines, it is also considered as a resistance model, which is equivalent to the topological connection between resistors. The equivalent resistance can be expressed by the following formula.

\[ R_e = \frac{\rho L}{S} \]  

(1)

Where \( R_e \) represents the equivalent resistance of each line in the equivalent DC network model of AC system; \( S \) is the cross-sectional area of each line; \( \rho \) is the resistivity of transmission line; \( L \) is the length of transmission line.

When considering the change of resistance caused by temperature, the following formula should be used to correct it.

\[ R_T = R_e [1 + \alpha(T - 20)] \]  

(2)

Where \( \alpha \) is the temperature correction factor, 0.00382 for copper wire, 0.00347-0.00403 for aluminium wire and 0.024 for iron wire. If the temperature information is not available, \( R_T \) can take 1.05-1.1 times of \( R_e \[16\].

2.2 Soil Layered Model

When DC current is injected into the earth, it flows through the soil and then invades the AC system. Soil resistivity is the main factor determining the potential distribution. If the soil model is not established effectively and accurately, the error of potential distribution will be large. Because soil is a hierarchical structure formed over many years, in order to accurately calculate the potential distribution, a soil layered model[17] is used, which is shown in figure 2.

\[
\begin{align*}
\text{Ground} & \quad \rho_{z}, h_1 \\
\text{Layer 1} & \quad \rho_{z}, h_2 \\
\vdots & \quad \vdots \\
\text{Layer } m & \quad \text{Current source } (r_0, h_0) \\
\vdots & \quad \vdots \\
\text{Layer } n & \quad \rho_{z}, h_n
\end{align*}
\]

Figure 2. Soil layered model

Where \((r_0, h_0)\) represents the location of the point current source, \(\rho_i\) and \(h_i\) respectively represent the resistivity and thickness of the soil layer \(i\). If the current source is located in the layer \(m\), for any coordinates \((r, z)\), the potential distribution satisfies Poisson equation:

\[
\frac{\partial^2 \phi}{\partial r^2} + \frac{1}{r} \frac{\partial \phi}{\partial r} + \frac{\partial^2 \phi}{\partial z^2} = -\rho_m \delta \frac{\sqrt{r - r_0^2} + |z - h_0|}{r_0^2}
\]

(3)

Where\( \phi \) represents point potential function; \(\rho_m\) is the resistivity of layer \(m\); \(\delta\) is dirac function; \(\sqrt{r - r_0^2}\) represents horizontal distance from Point \((r, z)\) to current source, \(|z - h_0|\) represents vertical distance from Point \((r, z)\) to current source; the soil potential function of layer \(i\) is obtained by separating variables, which is shown in the following formula.

\[
\phi_i^n (r, z) = \frac{B_i^n}{4\pi} \left( \delta(m - i) e^{-i\lambda |z - h_i|} + A_i^n (\lambda) e^{-\lambda |z - h_i|} + B_i^n (\lambda) e^{i\lambda |z - h_i|} + J_i (\lambda |r - r_0|) \right) d\lambda
\]

(4)
Where $\phi^m(r, z)$ represents green's function of soil in layer $i$ when current source is in layer $m$; $J_0$ is the first kind zero-order Bessel function; $A^m(\lambda)$ and $B^m(\lambda)$ are undetermined coefficients of integral variable $\lambda$.

The resistivity of each layer in the layered model is different, so the boundary conditions are as follows:

\[
\begin{align*}
  z = 0 : & \quad \frac{\partial \phi^m}{\partial z} = 0 \\
  z \to +\infty : & \quad \phi^m = 0 \\
  z = h_i : & \quad \phi^m = \phi_{i+1}^m, \quad \frac{1}{\rho_i} \frac{\partial \phi^m}{\partial z} = \frac{1}{\rho_{i+1}} \frac{\partial \phi_{i+1}^m}{\partial z}
\end{align*}
\]

The above ground and underground models are coupled to establish the field-circuit coupled model. The model takes into account the specific parameters in soil and the structure of transformer and transmission line. The calculation results reflect the real situation of DC bias in substation near the grounding pole of HVDC transmission project. In this paper, finite-element analysis software ANSYS is used to solve the potential distribution in the soil model in the given area, and then it is combined with the coupled model to calculate the DC current of the neutral grounding transformer. In order to further ensure that the calculated DC current value can be closer to the measured value, the resistivity near the transformer grounding point is corrected based on the inversion method[18], and the calculated results are obtained again to make it close to the actual value.

3. Mathematical Model of Optimal Device Configuration

The DC current can be blocked obviously by capacitor blocking devices. Its operation is a discrete process. Therefore, the optimal allocation of devices can be regarded as a discrete, non-linear 0-1 combination problem. When a transformer substation is put into use with a blocking device, its DC current is suppressed, but this may cause redistribution of DC current, which may increase the DC current of some transformers and aggravate the severity of DC bias. At the same time, capacitor blocking devices are expensive. If each transformer is installed, the cost will increase. Therefore, it is necessary to optimize the installation location and quantity of the devices, and ensure that all DC current is under the limit. Therefore, a multi-objective optimal allocation model of device can be established.

Assuming that there are $n$ neutral grounding transformers in the area near the grounding pole, the installation of the device is represented by $m$, 0 represents no installation, and 1 represents installation. The final result is expressed by the n-dimensional vector $P=[m_1, m_2...m_n]$.

Objective function 1: minimum number of device

\[
    f_1 = \min \sum_{i=1}^{n} m_i
\]

Objective function 2: minimum sum of DC current

\[
    f_2 = \min \sum_{i=1}^{n} |I_{dci}|
\]

Where $I_{dci}$ represents the DC current of transformer $i$.

Constraint: The neutral point DC current of each transformer does not exceed the limit

\[
    \forall i \leq n, \quad I_{dci} \leq I_{\text{max, dci}}
\]

In this paper, a step-by-step optimization strategy is adopted. Firstly, the minimum number of device is found out. Then, the minimum sum of absolute DC current at transformer neutral point is selected from these schemes to ensure the realization of multi-objective optimization, so that the scheme can suppress DC bias from a global perspective.
4. Solution Method

4.1 Differential Evolution (DE) Algorithm

Differential evolution algorithm is an intelligent algorithm proposed by Storn. It consists of mutation, crossover and selection operations. It is simple and practical, with few parameters and fast speed, so it has been widely used in various fields.

Assume \( X_i(t) = [x_{i1}(t), x_{i2}(t), \ldots, x_{in}(t)] \) is the \( i \)th individual of the \( t \)th generation, and \( n \) is the dimension of the individual, that is, the number of neutral grounding transformers.

The mutation operation expression is:

\[
E_i(t+1) = X_i(t) + F(X_{r1}(t) - X_{r2}(t))
\]  
(9)

Where \( E_i(t+1) \) denotes the mutation vector of \( X_i(t) \); \( X_{r1}(t) \) and \( X_{r2}(t) \) are the two mutually different individuals selected in the \( t \)th generation; \( F \) denotes the scaling factor.

The crossover operation is to generate the vector \( N_i(t+1) \) by comparing the mutated vector \( E_i(t+1) \) and the target vector \( X_i(t) \) using following formula.

\[
n_j(t+1) = \begin{cases} 
  e_j(t+1), & \text{rand}[0,1] \leq \text{CR} \text{ or } j = \text{randn} \\
  x_j(t), & \text{rand}[0,1] > \text{CR} \text{ or } j \neq \text{randn}
\end{cases}
\]  
(10)

Where \( n_j \) denotes the \( j \)th component of \( N_i(t+1) \), \( e_j(t+1) \) denotes the \( j \)th component of \( E_i(t+1) \); \( \text{rand}[0,1] \) is a random number with uniform distribution between 0 and 1; \( \text{CR} \) is a real number between 0 and 1; \( \text{randn} \) is an integer generated randomly between \([1, n]\).

The selection operation is completed by comparing the new individual \( N_i(t+1) \) with the original individual \( X_i(t) \) using following formula:

\[
X_i(t+1) = \begin{cases} 
  N_i(t+1), & f(N_i(t+1)) < f(X_i(t)) \\
  X_i(t), & \text{else}
\end{cases}
\]  
(11)

Where \( f(N_i(t+1)) \) and \( f(X_i(t)) \) represent fitness functions of individual \( N_i(t+1) \) and individual \( X_i(t) \) respectively. This greedy mechanism ensures that the excellent individuals after mutation and crossover can be retained to the next generation.

4.2 Improved Differential Evolution Algorithm

4.2.1 Generation of Initial Population

Generation of initial population often plays a key role in the process of optimization. In the original algorithm, the initial solution is usually generated randomly, but this method may make the algorithm fall into local optimum and fail to converge globally. Therefore, chaos mapping theory is used to generate the initial population in this paper. This method can generate the initial population which is conducive to convergence and maintain the inherent performance of the algorithm.

The process of generating initial population by chaos mapping theory is as follows: randomly generate an \( n \)-dimensional chaotic vector \( Z_1 = [z_{11}, z_{12}, z_{13}, \ldots, z_{1n}] \), where each element is between 0 and 1. The transformation is carried out by formula (12):

\[
Z_{t+1} = \mu Z_t (1 - Z_t), t = 1, 2, \ldots
\]  
(12)

Where \( \mu \) is the control parameter and its value is between 0 and 4.

After \( M \) times transformation, \( M \) vectors \( Z_1, Z_2, Z_3, \ldots, Z_M \) are obtained. Then use the following formula to complete the chaotic mapping and the original chaotic vectors are transformed into variable intervals corresponding to the problem.

\[
q_{ij} = a_j + (b_j - a_j) z_{ij}
\]  
(13)

Where \( a_j \) and \( b_j \) represent the range of values of the variables respectively.

Since this problem is a 0-1 combination problem, it needs to be converted into binary form by sigmoid function using the following formula.
\[ \text{Sig}(q_y) = \frac{1}{1 + \exp(-q_y)} \]  
\[ x_y = \begin{cases} 1, & \text{rand}() \leq \text{Sig}(q_y) \\ 0, & \text{else} \end{cases} \]

After the above transformation, \( M \) chaotic vectors are transformed into reasonable intervals and binarized. The \( M \) variable is regarded as \( M \) individuals respectively, and its fitness value is calculated and sorted. \( N \) individuals are selected as the initial population for optimization. Thus, using chaos mapping method to generate the initial population can make the population more diversified.

### 4.2.2 Adaptive Parameters

In the original algorithm, its scaling factor \( F \) and crossover factor \( CR \) are fixed values. In order to improve the convergence speed of the algorithm, this paper adopts the method of parameter adaptation to adjust the two parameters. The expressions are as follows.

\[ F = F_{\text{max}} + (F_{\text{min}} - F_{\text{max}})(i / i_{\text{max}})^2 \]  
\[ CR = CR_{\text{max}} + (CR_{\text{min}} - CR_{\text{max}})(i / i_{\text{max}})^2 \]

Where \( F_{\text{max}}, F_{\text{min}}, CR_{\text{max}} \) and \( CR_{\text{min}} \) represent the maximum and minimum values of scaling factor and cross factor respectively; \( i \) represents the current iteration number, and \( i_{\text{max}} \) represents the maximum iteration number.

From the above adaptive adjustment, it can be seen that the two parameters decrease with the increasing of iteration times. In the initial stage of optimization, it is necessary to keep the global optimization performance of the algorithm, so the parameters are larger and the algorithm can search in larger areas. In the later stage of iteration, the intensity of mutation operation needs to be reduced, and the original vectors should be retained as far as possible in the crossover operation, so the parameters are smaller. Then the method can enhance local optimization and converges near the optimal solution.

### 4.2.3 Elitism Preservation Strategy

In the original algorithm, all individuals will be affected by mutation crossover operation, which is reasonable for individuals with poor fitness. Continuous mutation crossover operation can make the individuals close to the optimal solution. For excellent individuals in the population, mutation crossover operation should be avoided because of its better fitness. In order to avoid the change from good solution to bad solution, the strategy of elitism preservation is adopted in this paper. The optimal individuals of the population will not conduct crossover mutation operation, but directly reserved to the next generation.

After the above improvements, the steps of improved differential evolution algorithm are as follows:

- **Step1:** Read the data, initialize the maximum number of iterations, individual dimension and the upper and lower limits of scaling and cross factor.
- **Step2:** Use chaos mapping theory to generate initial population, and a population containing \( N \) diverse and uniform individuals is obtained, then find the current optimal individuals.
- **Step3:** Except for the optimal individual, each individual carries out one iteration optimization by improved differential evolution algorithm, and calculate the fitness value of the new individual.
- **Step4:** Compare all new individuals with the best individuals of the previous generation, find the global optimal individuals and record their corresponding solutions.
- **Step5:** Determine whether the number of iterations is greater than the maximum number of iterations, and if it is greater than the maximum number of iterations, stop calculating and output the optimal scheme; on the contrary, add 1 to the number of iterations and return to step 3.
5. Example Simulation
In this paper, a ±500kV HVDC transmission project is taken as a simulation example. Near the DC grounding pole, there are two 500kV substations and eight 220kV substations. Their geographical distribution is shown in figure 3, and each station is numbered in turn.

![Figure 3. Distribution of transformers near the grounding electrode](image)

A field-circuit coupled model including the AC transmission system and the layered model of soil is established near the DC grounding pole. Using the software ANSYS, the earth potential distribution in the field-circuit coupled model is solved by finite-element analysis method, so as to solve the DC current in the transformer neutral point. Finally, the improved differential evolution algorithm is developed by using MATLAB to solve the mathematical model of optimal configuration of capacitor blocking devices.

Based on the grounding pole, a soil layered model in the range of 50km is established. The resistivity and depth of each layer are determined according to the soil characteristics. The specific information is shown in table 1.

| Layer | Thickness/m | Resistivity/Ω·m |
|-------|-------------|-----------------|
| Layer 1 | 200         | 50              |
| Layer 2 | 500         | 200             |
| Layer 3 | 500         | 400             |
| Layer 4 | 400         | 800             |
| Layer 5 | 300         | 1000            |
| Layer 6 | 800         | 800             |

After the soil layered model is obtained, the equivalent field-circuit coupled model around the grounding pole is obtained by combining the above-ground AC system model. The simulation values of DC current at each transformer neutral point are obtained by solving the model, and the resistivity of the soil around the transformer grounded at the neutral point is adjusted continuously by inversion method, so that the simulated DC current obtained by finite-element analysis is closed to the measured value, and the field-circuit coupled model is more close to the actual system, improving the accuracy of the model. When the current injected into the earth by DC grounding pole is 5000A and the DC current limit is 10A, the final simulation and measured values of DC current at neutral points of transformers are shown in table 2.

| Serial number | Measured value/A | Simulation value/A |
|---------------|-----------------|--------------------|
| 1             | -3.377          | -3.649             |
| 2             | 5.368           | 5.591              |
| 3             | -13.357         | -13.118            |
| 4             | 15.221          | 15.405             |
From the simulation value in the table, it can be seen that when the DC current of transformer neutral point is limited to 10A, the number of transformer 3, 4, 7 and 10 exceeds the limit, and the blocking device needs to be installed. According to the original method, capacitor blocking devices are installed in each transformer whose DC current is beyond the limit. The model is simulated again, and the DC current of each transformer neutral point after installing the device is obtained. The results are shown in table 3.

Table 3. Comparison of DC current before and after optimization using original method

| Serial number | Before/A | After/A |
|---------------|----------|---------|
| 1             | -3.649   | -3.021  |
| 2             | 5.591    | 5.474   |
| 3             | -13.118  | 0       |
| 4             | 15.405   | 0       |
| 5             | 7.591    | 10.107  |
| 6             | -1.482   | -2.167  |
| 7             | 11.735   | 0       |
| 8             | -8.468   | -10.397 |
| 9             | 0.881    | 0.977   |
| 10            | 13.056   | 0       |

From table 3, it can be seen that the DC current in the neutral points of all over-limit transformers can be eliminated by installing the blocking device according to the original method. However, it should be noted that the DC current has been redistributed, and the DC current at each station has changed. For example, the DC current in transformers 5 and 8 are increased from 7.591A and -8.468A to 10.107A and -10.397A respectively, which has exceeded the limit and made DC bias more serious. So the original method has limitations.

Using the improved differential evolution algorithm proposed in Chapter 3, the optimal allocation model of blocking device is solved. The particle dimension is 10, the population number is 20, and the maximum number of iterations is 50. $F_{\text{max}}$, $F_{\text{min}}$, $CR_{\text{max}}$ and $CR_{\text{min}}$ are 0.8, 0.2, 0.9 and 0.2, respectively. The optimal number and location are solved by the optimization algorithm. Fifty simulations are repeated. The average optimization results are shown in table 4 and the results of each iteration are shown in figure 4.

Table 4. Comparison of DC current before and after optimization using proposed method

| Serial number | Before/A | After/A |
|---------------|----------|---------|
| 1             | -3.649   | -3.561  |
| 2             | 5.591    | 5.362   |
| 3             | -13.118  | 0       |
| 4             | 15.405   | 0       |
| 5             | 7.591    | 0       |
| 6             | -1.482   | -3.011  |
| 7             | 11.735   | 8.264   |
| 8             | -8.468   | -8.942  |
| 9             | 0.881    | 1.025   |
| 10            | 13.056   | 0       |
From table 4, it can be seen that after optimization, the installation location is transformer 3, 4, 5 and 10. This scheme not only effectively suppresses the DC bias phenomenon of transformer near the grounding pole in this area, but also does not exceed the DC current limit at the neutral point of transformer. It shows that the improved differential evolution algorithm proposed in this paper can minimize the number of installations, save costs, and minimize the total DC current, and ensure that the DC current is under the limit, which shows the effectiveness of the algorithm. From figure 4, we can see that this method can reliably converge to the optimal solution, and can maintain a high success rate of optimization, which reflects the efficiency of the improved method.

For different DC current constraints, combined with the optimization model and algorithm proposed in this paper, the optimization results in each case are shown in table 5.

| Limit/A | Numbr of devices | Location of devices |
|---------|------------------|---------------------|
| 3       | 6                | 2, 3, 4, 7, 8, 10   |
| 5       | 5                | 3, 4, 7, 8, 10      |
| 7       | 5                | 3, 4, 7, 8, 10      |
| 10      | 4                | 3, 4, 5, 10         |
| 13      | 2                | 3, 4                |

In order to verify the superiority of the improved differential evolution algorithm, different intelligent algorithms are used to optimize the problem, and the results are shown in figure 5. Taking the limited value of 5A as an example, 50 simulations are repeated to obtain various performance indicators, and the results are compared with proposed method, as shown in table 6.
Figure 5 shows that proposed algorithm can accurately solve the optimal configuration model of the device. From the global point of view, it overcomes the shortcomings of other algorithms that easily fall into local optimum. It shows that the number of installations of blocking devices is minimized, and the cost of installation and DC bias control is effectively reduced. Table 6 shows that compared with other intelligent algorithms, the proposed method in this paper has fewer average iterations and convergence time, which effectively improves the calculation speed. In 50 simulation examples, the success rate of optimization reaches 90%, reducing the running time and ensuring a higher success rate of optimization.

6. Conclusion
(1) The input of blocking device may increase the DC current at the neutral point of transformer nearby, aggravating the DC bias phenomenon. Installation of each transformer is not an economic choice as the device is expensive. Therefore, this problem should be regarded as a global optimization problem.

(2) This paper establishes a field-circuit coupled model which combines AC system with soil layered structure, and calculates the DC current of transformer neutral point more accurately. Improved differential evolution algorithm is proposed and is used to solve the configuration scheme which can keep the global optimum.

(3) Compared with the traditional optimization algorithm, the results show that the improved differential evolution algorithm has faster convergence speed and fewer iterations, and the scheme can save cost and effectively suppress DC bias.

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