MOEAD based transmission network planning with wind power generation

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Abstract: This paper applies the planning model of transmission network with wind power generation considering the economy and security of power systems, and optimizes the model based on Multiobjective Evolutionary Algorithm Based on Decomposition (MOEAD) method. In the process of optimization, a topology repair strategy is used to improve the computational efficiency of solutions. Through testing on the 18-node transmission network system with wind power generation, the correctness of the transmission network planning model with wind power generation is verified, and the diversity and effectiveness of the MOEAD optimization method for solving the planning model are also discussed.

1. Introduction

New energies, represented by wind power generations and photovoltaic power generations are growing at a speed much higher than that of conventional energy sources [1]. Due to the randomness and uncertainty of new energy power generations, the transmission network with wind power generations is different from the conventional transmission network in planning models and optimization methods. At present, intelligent optimization algorithms have been developed to solve the planning model of the transmission network. In reference [2], a multi-objective particle swarm algorithm is used to plan the multi-objective transmission network with large-scale wind farms. In reference [3], the NSGA-II algorithm is used to plan an IEEE 24-node transmission network system with a wind power generator. In reference [4], a genetic algorithm is used to plan the grid in a certain area of Zhejiang Province. In reference [5], artificial bee colony algorithm is used to carry out multi-objective transmission network planning for Garver-6 node system. In reference [6], a bacterial foraging algorithm is used to plan a 133-node transmission network system. In reference [7], a genetic algorithm is used to plan the 18-node system. The convergence speed of the multi-objective particle swarm optimization algorithm in reference [2] depends on the setting of parameters. In these existing researches, the convergence of the results based on the NSGA-II algorithm in reference [3] needs to be improved. The genetic algorithm in reference [4] is easy to converge to local solutions. Furthermore, the transmission network planning model in references [5-7] does not consider the access of new energy such as wind power.
In this paper, the MOEAD optimization algorithm is applied to optimize the planning model \([8]\) of transmission network with wind power generation, and a 18-node test system is used to verify the effectiveness of the transmission network planning model and optimization algorithm. The main contributions are: 1) A topology repair strategy is applied to repair the disconnected transmission network, eliminating ‘islands’ and ‘isolated nodes’ in the transmission network topology and improving the calculation efficiency for solving; 2) The MOEAD optimization algorithm and DC probabilistic power flow method are applied to the transmission network planning with wind power generation. 3) Through the analysis of results, the effectiveness of the planning model and the MOEAD optimization algorithm are validated.

2. The planning model of the transmission network with wind power generation

2.1 Objective function

2.1.1 The minimum cost of system line construction

The objective function that represents the minimum cost of system line construction is\([8]\):

\[
 f_1 = \min \left( \sum_{i=1}^{N_L} C_i Z_i l_i \right)
\]

where \(C_i\) is the cost of the \(i^{th}\) branch per kilometre (10,000 yuan/km), \(Z_i\) is the extension lines’ number of the \(i^{th}\) branch, \(l_i\) is a single line’s length of the \(i^{th}\) branch (km), \(N_L\) is the total number of corridors in the entire transmission network system.

2.1.2 The minimum cost of system line loss

The objective function that represents the minimum cost of system line loss is\([8]\):

\[
 f_2 = \min \left( \sum_{i=1}^{N_L} \left( Z_i^0 + Z_i \right) r_i P_{li}^2 \right)
\]

where \(Z_i^0\) is the original lines’ number of the \(i^{th}\) branch, \(Z_i\) is the extension lines’ number of the \(i^{th}\) branch, \(r_i\) is a single line resistance of the \(i^{th}\) branch (Ω), \(P_{li}\) is the active power flow of the \(i^{th}\) branch.

2.2 Constraints

The following constraints need be met during the optimization of the planning model of the transmission network with wind power generation.

1) Constraints on extension lines of branches

The number of lines that can be expanded for each branch in the transmission network needs to satisfy the following inequalities \([8]\):

\[
 0 \leq Z_i \leq \overline{Z}_i
\]

where \(\overline{Z}_i\) is the maximum number of extension lines for the \(i^{th}\) branch.

2) Constraints on branch power flow

The power flow of each branch line in the transmission network needs to satisfy the power flow constraints under “\(N\)” operation state \([8]\):

\[
 \frac{E(P_i)}{\lambda \sigma(P_i)} \leq \overline{P}_i
\]

\[
 \underline{P}_i \leq E(P_i) - \lambda \sigma(P_i)
\]
Where $E(P_i)$ is the expectation of the active power flow in branch line, $\lambda$ is the control parameters, $\sigma$ is the standard deviation of the power flow $P_i$ in branch line, $\bar{P}$ is the upper limit of the active power in branch line; $\underline{P}$ is the lower limit of the active power in branch line.

3. MOEAD

3.1 Principle of MOEAD

The multi-objective optimization problem (MOP) is:

$$\min \quad F(x) = (f_1(x), \ldots, f_m(x))^T \quad x \in \Omega$$

where $F(x)$ is multi-objective function, $f_i(x)$ is single objective function, $m$ is the number of objective functions in the multi-objective optimization problem (MOP), $\Omega$ is decision space. Because each objective function in formula (5) is restricted by each other, there is no point that can minimize all the objective functions at the same time. Pareto optimal solution is the best way to weigh these objective functions [9].

Let $u \cdot \nu$ is a solution set consisting of multi-objective function values, $u$ dominate $\nu$ can be defined as: for each $i \in \{1, \ldots, m\}$, $u_i \leq \nu_i$, there is one $j \in \{1, \ldots, m\}$ makes $u_j < \nu_j$, then $u$ dominate $\nu$. Therefore, the Pareto optimal solution is defined as [10]. For any $x \in \Omega$, if it does not exist $F(x)$ dominate $F(x^*)$, then $x^*$ is the Pareto optimal point, $F(x^*)$ is Pareto optimal target vector. The collection of all Pareto optimal points is called Pareto set (PS), and the set of all Pareto optimal target vectors is called Pareto fronties (PF).

MOEAD decomposes PF approximately into $N$ scalar optimization problems using Tchebycheff method. Each scalar optimization problem can be expressed as:

$$\min \quad g^p \left( x^t \lambda^t, z^t \right) = \max_{1 \leq i \leq m} \{ f_i(x) - z_i \} \quad \lambda^t = (\lambda^t_1, \ldots, \lambda^t_m)^T$$

where $z^t = (z^t_1, \ldots, z^t_m)^T$ is the reference point; for each $i \in \{1, \ldots, m\}, z_i^t = \min_{x \in \Omega} f_i(x); \lambda^t_1, \ldots, \lambda^t_N$ is a set of uniformly distributed weight vectors. The optimal solution of formula (6) $x^*$ is both the Pareto optimal solution of formula (6) and the Pareto optimal solution of the multi-objective formula (5) [9].

MOEAD optimizes each scalar optimization problem based on the information of adjacent scalar optimization problems. The adjacent relations between them are defined by the distance between the weight vectors of each scalar optimization problem. Finally, the computational resources are allocated according to the utility $\pi^i$ of each scalar optimization problem [11].

3.2 The implementation process of MOEAD

Step 1) Initialize

Step 1.1) Calculate the Euclidean distance between any two weight vectors in a set of uniformly distributed weight vectors $\lambda^1, \ldots, \lambda^N$, find the $T$ weight vectors closest to each weight vector. For each $i = 1, \ldots, N$, $\lambda^i_1, \ldots, \lambda^i_t$ is the closest $T$ weight vectors of $\lambda^i$, $B(i) = \{i_1, \ldots, i_T\}$.

Step 1.2) Generate $N$ initial populations $x^1, \ldots, x^N$ randomly.

Step 1.3) Initialize $z = (z_1, \ldots, z_m)^T$, $z_i = \min \{ f_i(x^1), f_i(x^2), \ldots, f_i(x^N) \}$.

Step 1.4) For each $i = 1, \ldots, N$, let $gen = 0, \pi^i = 1$. 


Step 2) Select sub-questions that need to be searched: Each independent objective function $f_i$ in MOP represents the index of a sub-problem. The index of all sub-problems is initialized into a set $I$. The computational resources for each sub-problem in Set $I$ are determined by its utility $\pi^i$.

Step 3) For each $i \in I$, implement the following steps:

Step 3.1) Set update range: Generate a random number $\text{rand}$ uniformly in $(0,1)$. Then set
\[
P = \begin{cases} 
B(i) & \text{if } (\text{rand} < \delta) \\
\{1,\ldots,N\} & \text{else}
\end{cases}
\] (7)

Step 3.2) Reproduction: Let $r_1 = i$, select two indicators $r_2, r_3$ from $P$; use DE evolutionary operations to generate solutions $\tilde{y}$ from $x^{r_1}, x^{r_2}, x^{r_3}$; then generate a new solution $y^{[11]}$ by a mutation operation with a certain probability $p_m$.

Step 3.3) Fix: If $y$ is not in the boundary, its value is reset to the randomly selected value within the boundary.

Step 3.4) Update $Z$: For each $j = 1,\ldots,m$, if $z_j > f_j(y)$, let $z_j = f_j(y)$.

Step 3.5) Update field solution:
(1) Select random index $j$ from $P$ in turn, if $g^\omega \left( y^j \left| \lambda_j', z \right. \right) \leq g^\omega \left( x^j \left| \lambda_j', z \right. \right)$, then $x^j = y, F(x^j) = F(y)$.
(2) Delete $j$ from $P$ and go to (1).

Step 4) Stop criteria:
If the stop condition is satisfied, stop and output $\{x^1,\ldots,x^N\}$ and $\{F(x^1),\ldots,F(x^N)\}$. Otherwise go to Step 5.

Step 5) $\text{gen} = \text{gen} + 1$
If $\text{gen}$ is a multiple of 50, calculate the relative reduction $\Delta$ in the objective function of each sub-problem over the past 50 generations [11], update formula (8) listed as follows and go to Step 2.
\[
\pi^i = \begin{cases} 
1 & \text{if } \Delta^i < 0.001 \\
(0.95 + 0.05 \frac{\Delta^i}{0.001})\pi^i & \text{else}
\end{cases}
\] (8)

4. The transmission network with wind power generation planning based on MOEAD
MOEAD belongs to a stochastic optimization algorithm, which generates a large number of disconnected transmission network topologies in initialization and evolution. Therefore, these disconnected transmission network topologies need to be repaired to improve the overall computational efficiency of the algorithm. After the transmission network topology is connected, the power flow of the entire transmission network based on DC probabilistic power flow method is carried out, and the planning scheme of the transmission network, which does not meet the power flow constrains (4), is deleted to ensure the feasibility of the solution generated by MOEAD.

4.1 Transmission network topology repairing
It is assumed that the existing transmission network topology is disconnected, where several isolated nodes and isolated islands exist. In order to ensure the connection of the whole transmission network topology, the topology needs to be repaired by removing isolated nodes and isolated islands in turn. The following steps are to remove isolated nodes in each iteration.

Step 1) Initialize the parameters of the transmission network.
Step 1.1) Number the nodes and corridors in the transmission network.
Step 1.2) Let $i = 1$, node 1 is the starting node.
Step 1.3) Establish the adjacent matrix of the transmission network $L_{\text{tran}}$, expansion matrix $K_{\text{expm}}$, and grid parameter matrix $B_{\text{m/g}}$.

Step 2) According to the adjacent matrix $L_{\text{tran}}$, determine whether node $i$ is an isolated node. If YES, go to Step 3. If NO, determine whether the next node is an isolated node in turn.

Step 3) According to formula (1), expand a line with node $i$ which has the minimum cost of line construction and retain the expanded line.

Step 4) Update the adjacent matrix $L_{\text{tran}}$.

Step 5) Determine whether the value $i$ is less than the total number of nodes $m$. If YES, go to Step 2) and determine whether the next node is an isolated node in turn. If NO, all isolated nodes are removed.

After removing the isolated nodes, the topology of the transmission network may still cause the disconnection due to the existence of islands. To ensure the connectivity of the transmission network topology, the isolated islands that may exist in the transmission network topology need to be removed. The following steps are to remove isolated islands.

Step 1) Establish node 1 as the central node.

Step 1.1) $j=1$.

Step 1.2) $P=\emptyset$, Maintain node 1 in set $P$.

Step 1.3) Retrieve node $i$ which is connected to node $j$ in set $P$ based on adjacent matrix $L_{\text{tran}}$.

Step 1.4) Retain all the nodes which are connected to node $j$ in set $P$.

Step 2) Whether all nodes in set $P$ are retrieved. If NO, go to Step 1.3) and search for the next node in set $P$. If YES, go to Step 3.

Step 3) Check whether set $P$ contains every node in the transmission network system. If YES, the transmission network topology is connected. If NO, go to Step 4.

Step 4) Remove the isolated islands in the transmission network.

Step 4.1) $a=1$, $T=\emptyset$.

Step 4.2) Node $a$ which isn’t in set $P$ are sequentially retained in set $T$.

Step 4.3) $i \in P$, $a \in T$. According to formula (1), expand a line with node $i$ and node $a$ which has the minimum expansion cost.

Step 4.4) Update adjacent matrix $L_{\text{tran}}$, and go to Step 1).

Figure 1 shows the transmission network system consists 8-node and 12 corridors. Formula (11) is the adjacent matrix of the transmission network. Formula (12) is the expansion matrix of the transmission network system. Equation (13) is the parameter matrix of the transmission network.

Figure 1. The 8-node transmission network

In figure 1, node 4 is an isolated node; nodes 5 and node 6 constitute an isolated island.
In the adjacent matrix $L_{8 \times 8}$, $l_{12} = 2$ denotes two lines connecting node 1 and node 2. So $l_{18} = l_{81} = 1$ means one line connecting node 1 and node 8.

$$L_{8 \times 8} = \begin{bmatrix}
0 & 2 & 1 & 0 & 0 & 0 & 0 & 1 \\
& & & & & & & \\
& & & & & & & \\
& & & & & & & \\
1 & 0 & 0 & 0 & 0 & 1 & 0 & \end{bmatrix}_{8 \times 8} \quad (9)$$

In the expansion matrix $K_{8 \times 8}$, $k_{12} = 1$ means that one line can be expanded between the node 1 and node 2.

$$K_{8 \times 8} = \begin{bmatrix}
0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\
& & & & & & & \\
& & & & & & & \\
& & & & & & & \\
0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \end{bmatrix}_{8 \times 8} \quad (10)$$

In the expansion matrix $K_{8 \times 8}$, $k_{12} = 1$ means that one line can be expanded between the node 1 and node 2.

$$K_{8 \times 8} = \begin{bmatrix}
0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\
& & & & & & & \\
& & & & & & & \\
& & & & & & & \\
0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \end{bmatrix}_{8 \times 8} \quad (10)$$

In the expansion matrix $K_{8 \times 8}$, $k_{12} = 1$ means that one line can be expanded between the node 1 and node 2.

$$K_{8 \times 8} = \begin{bmatrix}
0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 \\
& & & & & & & \\
& & & & & & & \\
& & & & & & & \\
0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \end{bmatrix}_{8 \times 8} \quad (10)$$

In the expansion matrix $K_{8 \times 8}$, $k_{12} = 1$ means that one line can be expanded between the node 1 and node 2.

$$B_{12 \times 7} = \begin{bmatrix}
1 & 1 & 2 & 3 & 4 & 5 & 6 & 0.6 \\
& & & & & & & \\
& & & & & & & \\
& & & & & & & \\
& & & & & & & \\
12 & 7 & 8 & 1 & 2 & 3 & 4 & 0.3 \end{bmatrix}_{12 \times 7} \quad (11)$$

Take the first row of $B_{12 \times 7}$ as example, $b_{11} = 1$ means that the data of first row is the electrical information of the first corridor. $b_{12} = 1$ means that the starting node of the branch is node 1. $b_{13} = 2$ means that the ending node of the branch is node 2. $b_{14} = 3$ means that the total reactance of each branch line is 3 $\Omega$; $b_{15} = 4$ means that the upper limit of the active power flow of each branch line is 4 MVA; $b_{16} = 5$ means that the length of each line is 5 km; $b_{17} = 0.6$ means that the unit impedance of each branch line is 0.6 $\Omega$/km.

4.2 DC probabilistic power flow method

The uncertainty of wind power leads to the uncertainty of branch power flow in transmission network. Calculated by the probabilistic power flow method, the 1st-8th order cumulant of the random variable of the branch flow can clearly describe this uncertainty. The calculation steps are listed as follows.

Step 1) When each node takes the expectation as the injection active power according to formula (12), calculate the DC power flow. Find the voltage phase angle $\theta_0$ and the branch power flow $P_{ij}$.

$$\begin{bmatrix} P = B_x \theta_0 \\ P_{ij} = (\theta_i - \theta_j) / x_{ij} \end{bmatrix} \quad (12)$$

Step 2) According to the wind power generator output and active power load which distribute respectively in Weibull distribution and Gaussian distribution, calculate each order matrix $m_j(P)$ of the input active power for each node by formula (13).

$$m_j = \int_{-\infty}^{\infty} (x - E(x))^j f(x) dx \quad (13)$$
where $m_r$ is the $r^{th}$ order matrix of the random variable; $E(X)$ is the expectation of random variable $x$ (input active power for each node); $p_i$ is the probability of taking $x_i$ for $x$.

Step 3) Using the relationship between the random variable matrix and the cumulant by formula (14), get the cumulant $k_r(P)$ by $m_r(P)$. In order to meet the requirement of engineering calculation accuracy and calculation speed, it is more appropriate to calculate to the eighth order cumulant $[12]$. 

$$
\begin{align*}
  k_i &= m_1 \\
  k_{r+1} &= m_{r+1} - \sum_{j=1}^{r} C^r_j m_j k_{r-j+1} \\
  C^r_j &= \frac{r!}{j!(r-j)!}
\end{align*}
$$

where $k_i$ is the $i^{th}$ order cumulant of random variable, $C_i^r$ is polynomial coefficients.

Step 4) Calculate each order cumulant of the each branch line’s active power flow by formula (12).

Step 5) The expectation and standard deviation of the branch power flow correspond to the square root of its first-order cumulant and second-order cumulant.

4.3 Population selection

In a population generated randomly by MOEAD, a large number of individuals exist which represents the branch overloading. As a result, these individuals which do not satisfy the branch power flow constraints need to be deleted by formula (4). The implementation steps are listed as follows.

Step 1) Initialize population individual.
Step 1.1) Determine the planning scheme of the transmission network for populations.
Step 1.2) Obtain the expectation and standard deviation of the branch power flow by DC probabilistic power flow method.
Step 2) Determine if the branch power flow under “N” operation state satisfies the power flow constraints according to formula (4). If YES, retain this individual, otherwise, delete the individual.

Taking the 8-node transmission network system in Figure 1 as an example, formula (15) is a population of individuals consisting of the number of lines which is contained in the corridor branch.

$$
L = [2101100101]_{12}
$$

4.4 Implementation steps of transmission network planning based on MOEAD

Step 1) Initialize
Step 1.1) Initialize algorithm parameters and system parameters.
Step 1.2) Initialize initial population.
Step 1.3) Repair the transmission network topologies for initial individuals and initialize the objective function value $f_1, f_2$ in formula (1) and formula (2).
Step 2) Generate subpopulation individuals through evolution based on MOEAD.
Step 3) Repair the transmission network topologies for individuals of subpopulation.
Step 3.1) Compute the adjacent matrix of the subpopulation individuals.
Step 3.2) Repair the adjacent matrix through the topology repair strategy of the transmission network.
Step 4) Calculate the power flow of each branch corresponding to the individuals of the subpopulation by the DC probabilistic power flow method.
Step 5) Determine whether the power flow of each branch corresponding to the individuals of the subpopulation meet the branch power flow constraints as formula (4). If YES, go to Step 6), otherwise, delete the population individuals.
Step 6) Calculate the objective function value $f_i, f_2$ corresponding to the individuals of the subpopulation by formulas (1) and (2).

Step 7) Update the individuals of the subpopulation and objective function values $f_1, f_2$.

Step 8) Determine whether reach the stop condition. If YES, end the evolution process, otherwise, return to Step 2.

Step 9) Output the optimal planning scheme of transmission network.

5. Case analysis

The transmission network [13] used in this paper includes 18 nodes and 27 corridors, which is shown in Figure 2. The system parameters are set as follows: the load of the transmission network follow normal distribution, the standard deviation takes 2% of the expectation, and it is connected at node 13 with a 1000 MW wind generator, the cut-in wind speed is $v_{ci} = 3$m/s, the rated wind speed is $v_r = 15$m/s, and the cut-out wind speed is $v_{co} = 25$m/s. The wind speed is two-parameter Weibull distribution. Shape parameter is $k_s = 2.80$, scale parameter is $c_i = 5.14$, control parameter is $\lambda = \sqrt{5}$, unit length cost of each corridor is $C_l = 10000$ yuan/km, $r_i$ is approximate to single-circuit reactance. Lower active power flow limit of each branch is $P_l = 0$ MVA. Upper active power flow limit of each branch is $P_u = 230$ MVA. The parameters of MOEAD are: 100 random individuals, 20 populations, 10 neighbourhoods, 500 iterations, and 30000 evaluations per iteration.

![Fig 2. The 18-node transmission network with wind power generation](image)

Ten schemes obtained by MOEAD is listed as table 1.

| Proposal | Cost ($f_1, f_2$) (10000yuan) | Weight coefficient |
|----------|--------------------------------|--------------------|
| Scheme 1 | (411400, 980570)               | (0.05, 0.95)       |
| Scheme 2 | (391400, 997880)               | (0.15, 0.85)       |
| Scheme 3 | (371400, 1021700)              | (0.30, 0.70)       |
| Scheme 4 | (354400, 1065500)              | (0.40, 0.60)       |
| Scheme 5 | (351400, 1067300)              | (0.50, 0.50)       |
| Scheme 6 | (334400, 1110900)              | (0.60, 0.40)       |
| Scheme 7 | (331400, 1141700)              | (0.65, 0.35)       |
In the 10 planning results, as the weight coefficient $f_1$ increases and the weight coefficient $f_2$ decreases, the total line construction cost $f_1$ decreases continuously, and the total system line loss cost $f_2$ decreases.

This paper chooses scheme 5 to further illustrate the availability of the planning scheme.

![Fig 3. The initial circuit diagram of scheme 5](image)

It can be seen from figure 3 that the nodes of the entire network are connected with each other and there are no isolated nodes or isolated islands. Therefore, this transmission network topology is connected. The transmission network represented by scheme 5 contains 24 branches. The power flow of each branch in scheme 5 is showed in table 2.

| Branch | $E(P_1)$ | $\sigma(P_1)$ | $E(P_1) + \lambda \sigma(P_1)$ | $E(P_1) + \lambda \sigma(\lambda P_1)$ |
|--------|------------|---------------|---------------------------------|------------------------------------|
| 1      | 108.3      | 6.1           | 94.7                            | 121.9                              |
| 2      | 80.8       | 6.1           | 67.2                            | 94.4                               |
| 3      | 59.4       | 12.3          | 31.9                            | 86.9                               |
| 4      | 57.9       | 10.4          | 34.6                            | 81.2                               |
| 5      | 36.7       | 7.3           | 20.4                            | 53.0                               |
| 6      | 22.8       | 7.3           | 6.5                             | 39.1                               |
| 7      | 118.7      | 12.7          | 90.3                            | 147.1                              |
| 8      | 67.4       | 15.0          | 33.9                            | 100.9                              |
| 9      | 39.6       | 3.1           | 32.7                            | 46.5                               |
| 10     | 109.2      | 4.9           | 98.2                            | 120.2                              |
| 11     | 43.6       | 14.7          | 10.7                            | 76.5                               |
| 12     | 103.4      | 1.7           | 99.6                            | 107.2                              |
| 13     | 74.3       | 9.3           | 53.5                            | 95.1                               |
| 14     | 70.9       | 11.5          | 45.2                            | 96.6                               |
| 15     | 47.1       | 7.1           | 31.2                            | 63.0                               |
| 16     | 57.9       | 6.5           | 43.4                            | 72.4                               |
| 17     | 118.3      | 9.4           | 97.3                            | 139.3                              |
| 18     | 156.6      | 6.5           | 142.1                           | 171.1                              |
| 19     | 96.6       | 11.4          | 71.1                            | 122.1                              |
| 20     | 93.1       | 9.8           | 71.2                            | 115.0                              |
| 21     | 40.4       | 1.5           | 37.0                            | 43.8                               |
| 22     | 86.0       | 1.7           | 82.2                            | 89.8                               |
| 23     | 73.9       | 8.6           | 54.7                            | 93.1                               |
| 24     | 126.1      | 9.5           | 104.9                           | 147.3                              |
It can be seen from table 2 that the power flow of each branch in scheme 5 satisfies the power flow constraints as formula (4). It proves the feasibility of the planning model of the transmission network with wind power generation and the effectiveness of the optimization algorithm MOEDA.

6. Conclusion

In this paper, the transmission network with wind power generation is planned based on MOEAD through testing a 18-node transmission network. The planning model of the transmission network including two objective functions (minimum branch line construction cost and the minimum system network loss cost) is established. During solving the planning schemes, a repair strategy is applied in the optimization algorithm MOEAD to repair individuals and increase the number of feasible individuals. In addition, the probabilistic power flow method is implemented. The feasibility of the MOEAD optimization algorithm in solving the problem of transmission network planning with wind power generation is verified, and the economy of the transmission network planning is improved.

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