Multi objective transmission network expansion planning considering wind power uncertainty and scenario reduction

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Abstract. Under the background of large-scale new energy grid connection, the selection of grid connection point affects the grid structure to be expanded. The intermittence of wind power and the correlation with load also affect the voltage and line safety of each node in the grid. In order to accurately describe the uncertainty factors such as wind power output, multi scenario stochastic simulation technology and reduction method are used to establish multi scenario to accurately describe multi-point wind power and load uncertainty; At the same time, a multi-objective transmission network expansion planning model considering the cost of investment, operation and reliability is established. The effectiveness of the model is verified by IEEE 30 bus simulation. It shows that the accuracy and rationality of transmission network expansion planning can be improved by scenario reduction.

1. Introduction

With the large-scale integration of new energy, the traditional power grid planning method does not consider the impact of wind power fluctuation on the grid operation cost, and the economy and flexibility of the optimal plan are insufficient. How to fully consider the uncertainty of wind power output and carry out the coordinated planning of transmission network and wind power has become the research focus of planning.

At present, the factors considered in the optimal planning of transmission network including wind farm include construction cost, operation and maintenance cost, environmental cost, social benefit, congestion cost and load loss cost. Among them, according to the different impacts on power grid. Reference [1] increases the minimum waste discharge based on the traditional objective. Reference [2] adds the load shedding loss caused by overload into the economic objective. Reference [3] considers the network congestion cost and power shortage risk cost caused by wind farm integration. Reference [4] considers the impact of wind power intermittency on voltage stability and increases static voltage stability index as the goal. The above research is to study the optimization of transmission network expansion under the condition of fixed wind farm location.

Transmission network optimization planning models include deterministic model and probabilistic model. The probabilistic model can consider the uncertainties of wind power output, load and market. The probability distribution characteristics of load and wind power output are considered in reference...
In addition, many uncertain factors are considered in the probabilistic model of wind turbine, which makes it difficult to solve the probabilistic model of future load because of many uncertain factors. The uncertainty model is transformed into a deterministic model, which greatly simplifies the calculation and is widely used.

For this reason, this paper proposes a transmission network expansion planning method considering wind power uncertainty and scenario reduction. Many operation scenarios are generated randomly by using multi scenario random simulation technology. The typical mode and operation time of various operation scenarios are reduced by scenario clustering. The investment, operation and reliability costs are taken as multi-objective and safety N-1 constraints are considered, realizing the collaborative optimization of wind power integration network and line expansion.

2. Modelling method of simulated operation scenarios

2.1. Probability model of random variables

(1) Load model

The researches show that: the load model can be described by normal distribution, with the predicted value as the mean value, and a suitable statistical value as the variance of load variation

\[ f(x) = \frac{1}{\sqrt{2\pi} \sigma_L} e^{-(x-\mu_L)^2/2\sigma_L^2}, \quad -\infty < x < \infty \]  

Where \( \mu_L \) and \( \sigma_L \) denote the predicted mean value and variance of load; the normal distribution model of load is \( N(\mu_L, \sigma_L) \).

(2) Random distribution model of power supply

According to a lot of research on wind speed probability distribution and photovoltaic in recent years, two parameter Weibull distribution is used to simulate wind speed probability density distribution. The relationship between wind turbine output and wind speed is approximately treated as a straight line.

3. Modelling of scene reduction

Based on the analysis of load and multi wind farm output characteristics, a multi-dimensional variable operation scenario is established by using clustering method. The operation scenario includes the output of each wind farm and the system load level, as well as the duration of the operation scenario. Suppose there are \( n \) wind farms in the system, then the \( R \) scenario \( SR \) is defined as the output of each wind farm, the load level and the duration of the scenario, as shown in (2).

\[ S_r = [P_{load}, W_{win1}, W_{win2}, \ldots, W_{winr}, t_r] \]  

where, \( P_{load} \) is the total load level in scenario \( r; \) \( W_{wini} \) is the output of the \( i \) wind farm in scenario \( r \), and the remaining sub variables represent the output of other wind farms in scenario \( r; \) \( t_r \) is the duration of scenario \( r \).

Using the load distribution function and wind speed probability distribution of each wind farm, combining with the relationship between wind turbine output and wind speed, the hourly system operation scenario is obtained, and a sample set \( S_0 \) containing 8760 operation scenarios is obtained, as shown in (3), which is a \( (n + 2) \times 8760 \) dimensional matrix. Considering the large amount of calculation required in the transmission network planning based on \( S_0 \), the 8760 operation scenarios are clustered to find a smaller subset to replace the set \( S_0 \), to reduce the amount of calculation.
$n$ wind farms and total load levels constitute an $n+1$ dimensional multidimensional space $V$. Each wind farm and total load represent the one-dimensional coordinate axis of multidimensional space $V$ respectively. Thus, the multidimensional space $V$ is divided into multi-dimensional subspace composed of any interval of each dimension. For example, the random distribution interval of the total load is $[P_{\text{min}}, P_{\text{max}}]$, and the sub interval is obtained by dividing the interval into $N$ equal parts.

$$P_{\text{load}} = \left\{ x \mid x \in (P_{\text{min}} + \frac{P_{\text{max}} - P_{\text{min}}}{N}(i-1), P_{\text{min}} + \frac{P_{\text{max}} - P_{\text{min}}}{N}i) ; i = 1, 2, ..., N \right\}$$

where $P_{\text{load}}$ represents the $i$-th interval in the total load dimension.

Similarly, since the output of $n$ wind farm is distributed in the interval $[\text{Win}_{\text{min}}, \text{Win}_{\text{max}}]$, $\text{N}$-bisection operation is also carried out for these $n$ intervals, and $\text{N}$ subintervals are obtained in each dimension of the $n$-dimensional space. $\text{Win}_{\text{min}}$ is used to represent the $k$-th sub interval of wind farm $n$. After the bisection operation of each dimension is completed, a multidimensional subspace $V_r$ is formed by taking any subinterval in each dimension. As shown in (5), this multi-dimensional subspace is used for clustering the scene set $S_0$ and placing the same running scenario. The center point $M_r$ of $V_r$ is used as the clustering center; and the sub interval is obtained by dividing the interval into $N$ equal parts.

$$V_r = \text{span}\{P_{\text{load}}, \text{Win}_{\text{min}}, \text{Win}_{\text{max}}\}; (i, j, k, ..., m = 1, 2, 3, ..., N)$$

$$M_r = \left[ P_{\text{min}} \left( \frac{2N-1}{2N} \right), ... , P_{\text{max}} \left( \frac{2N-1}{2N} \right), \text{Win}_{\text{min}} \left( \frac{2N-1}{2N} \right), ... , \text{Win}_{\text{max}} \left( \frac{2N-1}{2N} \right) \right]$$

Because the system contains $n$ wind farms, the number of multi-dimensional subspaces $V_r$ ($r$ is any value between 1 and $N$) is $N^{n+1}$. After the above steps, this section obtains the running scene sample set $S_0$, $N^{n+1}$ multidimensional subspace $V_r$ and the center point $M_r$ of each subspace. The clustering operation is as follows:

1) The center point $M_r$ of each subspace $V_r$ in multidimensional space is used as the clustering center;

2) Take the first $n+1$ elements from the $S_0$ to form an array $S_r$. Take the $i$-th row element $S_i = [P_{\text{load}}, \text{Win}_{\text{min}}, ... , \text{Win}_{\text{max}}]$ and calculate the Euclidean distance from the center point $M_r$ of each subspace $V_r$.

$$d(S_i, M_r) = (S_i(1) - M_r(1))^2 + ... + (S_i(n+1) - M_r(n+1))^2)^{1/2}$$

3) Assign $S_i$ to the subspace $V_r$ where the nearest center point is located.

$$S_i \in V_r$$

4) Repeat steps 1)-3) to complete the allocation of $S_i$. According to (6), count the number of elements $T_r$ of $S_r$ belonging to subspace $V_r$, then $r$ scenario duration is $T_r$. Finally, the $r$ running scenario after clustering operation can be obtained.

$$S_r \in [M_r, T_r]$$
4. Transmission network expansion planning model

When the wind farm is connected to the transmission network, the power injected into the system may be absorbed locally in the substation at the connection point, or transmitted to the remote load through the transmission grid, which increases the transmission power and system loss of the transmission network. At the same time, the correlation between the wind power and the load at the access point has a great impact on the system voltage. The multi-objective model of transmission network expansion planning is established by considering the factors such as expanded line cost, system annual operation loss, overload risk (expectation), reliability cost (overload power).

4.1. Objective function

1. Minimizing line investment costs

\[
\min f_1 = \sum_{i=1}^{LN} C_i \cdot L_i \cdot K_i, \quad i \in \Omega, i = 1, 2, ..., LN
\]

where: \( \Omega \) is the set of alternative amplification lines; \( LN \) is the number of alternative amplification lines; \( L_i \) is the length of the \( i \)-th alternative line when expanding; \( C_i \) is the average cost of the \( i \)-th line; \( K_i \) is an integer 0 or 1, 0 means that the \( i \)-line is not expanded, and 1 table shows the \( i \) line expansion.

2. Annual network loss cost of system

The cost of network loss should be considered when planning the plan of wind power merging point and grid expansion line.

\[
\min f_2 = \sum_{i=1}^{S} \left( \sum_{j=1}^{LN} P_{ij\text{loss}} \cdot T_i \right), \quad i = 1, 2, ..., N
\]

where, \( P_{ij\text{loss}} \) is the network loss power of line \( j \) in operation scenario \( i \), and \( T_i \) is the duration of scenario \( i \). If \( U_{ij} \) is 1, \( \cos \Phi \) is 0.95, and \( R_j \) is the resistance of line \( j \), the calculation method of \( P_{ij\text{loss}} \) is as follows:

\[
P_{ij\text{loss}} = \frac{P_g^2}{U_{ij}^2 \cdot \cos \Phi} \cdot R_j, \quad i = 1, ..., N; \quad j = 1, ..., LN
\]

3. Reliability cost

In traditional transmission network planning, N-1 check is required for each plan to ensure that the plan selected by optimal calculation meets the N-1 criterion. The contradiction between the high reliability plan formed by this criterion is the high redundancy network and high construction cost. Considering the investment risk and the benefit of power supply company caused by high investment in the market environment, and the probability of line accident outage is not high, so it is beneficial to reduce redundant lines and reduce investment by properly allowing overload in N-1 check.

\[
f_3 = \min \varepsilon
\]

where \( \varepsilon \) represents the sum of the overload power of the planning network in the planning level year.

\[
\varepsilon_{ij} = \begin{cases} 0, & |P_{ij}| \leq P_{j\text{max}}, j=1,2, ..., L; i=1,2, ..., S \\ |P_{ij} - P_{j\text{max}}|, & P_{ij} \geq P_{j\text{max}}, j=1,2, ..., L; i=1,2, ..., S \\ |P_{ij} - P_{j\text{max}}|, & P_{ij} \leq P_{j\text{max}}, j=1,2, ..., L; i=1,2, ..., S \\ \end{cases}
\]

\[
\varepsilon = \sum_{i=1}^{S} \left( \sum_{j=1}^{LN} \Delta \varepsilon_{ij} \right) \cdot T_i \quad i=1,2, ..., S; j=1,2, ..., L
\]

\[
\Delta \varepsilon \leq \Delta \varepsilon_{\text{max}}
\]

where: \( \Delta \varepsilon_{ij} \) represents the overload amount of \( j \) line when N-1 check occurs under scenario \( i \), the N-1 constraint in this section changes from a constraint that must be satisfied to the objective function of
overload energy in a horizontal year and the constraint limiting the maximum value of load shedding power rate under each operation scenario; \( T_i \) represents the duration of scenario \( i \), and \( \varepsilon \) represents the lines in a year of a certain plan. The total amount of overload electricity when the road is overloaded in different operation scenarios; \( L \) is the total number of lines in the system, and \( S \) is the number of divided scenarios.

4.2. Constraints
(1) Power flow constraints in normal operation
\[
\begin{align*}
B \theta_i &= \delta_{pi} \\
P_j &= B_{ij} \Delta \theta_j \\
|P_j| &\leq P_{jmax}
\end{align*}
\tag{17}
\]
where: \( B \) is the node admittance matrix of DC power flow system; \( \theta_i \) is the phase angle of each node in the \( i \)-th operation scenario; \( P_j \) is the active power flowing through \( j \) lines in the \( i \)-th operation scenario; \( \Delta \theta_j \) is the phase angle difference between the two ends of line \( j \) under \( i \) scenario; \( P_{jmax} \) is the maximum transmission active power of line \( j \).

(2) Security constraints under N-1 check
\[
\begin{align*}
B^k \theta_{i}^k &= \delta_{pi}^k \\
P_{ij}^k &= B_{ij}^k \Delta \theta_{ij}^k
\end{align*}
\tag{18}
\]
where: \( B^k \) is the node admittance matrix in case of fault; \( \theta_{ik} \) is the phase angle of each node in the \( i \)-th operation scenario under fault condition; \( \delta_{pi}^k, P_{ij}^k \) is the power angle and active power flowing through the line \( j \) in the \( i \)-th scenario under fault condition; \( \Delta \theta_{ij}^k \) is the phase angle difference of nodes at both ends of line \( j \) in the \( i \)-th scenario under fault condition.

5. Case study
Taking IEEE30 standard calculation example, wind farm output model is treated as negative load (PQ model) in steady-state power flow calculation. Assuming that the wind farm outlet meets the power factor of 0.95, the corresponding reactive power is arranged for the grid point. The annual average forecast value of the total load is 185MW, and the load model is the normal distribution model (0, 0.1287); the wind speed of wind farm follows Weibull distribution, and the alternative set and parameter setting of each wind farm are shown in Table 1, in which the alternative nodes of wind farm 1 are 3 and 4; those of wind farm 2 are 13 and 14; and those of wind farm 3 are 15 and 23.

| Table 1. wind farm parameters. |
|--------------------------------|
| Parameters                  | Wind farm 1 | Wind farm 2 | Wind farm 3 |
| v_c(m/s)                    | 2           | 2           | 3           |
| v_R(m/s)                    | 5           | 6           | 7           |
| v_Co(m/s)                   | 11          | 12          | 13          |
| Alternative merging outlets | 3, 4        | 13, 14      | 15, 23      |

Based on the above scenario clustering technology, the annual running situation of Monte Carlo sampling is simplified and a set of 144 running scenarios is obtained. The Pareto front obtained by differential evolution algorithm is shown in figure 1. TOPSIS is used to search the frontier of the optimal plan and select the optimal plan. Table 2 and figure 2 gives the specific information of the optimal plan, in which plan 1 is the optimal plan calculated by the program, and plan 2 is the economic plan selected according to the safest experience at the frontier of Pareto. Figure 2 shows the network wiring diagram of plan 1.
Table 2. Line expansion plan.

|           | Plan 1 | Plan 2 |
|-----------|--------|--------|
| Total line cost (10000 yuan) | 7400   | 8800   |
| Annual system loss (MW·h)     | 7.795×10³ | 6.647×10³ |
| Reliability cost (n-1)        | 8.59   | 0      |
| Line expansion plan           | 5-7, 4-12, 12-13, 15-18, 18-19, 23-24 | 1-3, 5-7, 4-12, 12-13, 15-18, 23-24 |
| Grid connection position of wind farm | (3, 13, 15) | (3, 13, 15) |

There is no overload in plan 2 under N-1 check, and the overload energy in horizontal year under N-1 check is 0, so the total cost of the line is higher. It can be seen from the column of expansion plan that the transmission line redundancy is expanded. Meanwhile, due to the large number of redundant lines, the network loss of plan 2 is better than that of plan 1. Moreover, the overload power of plan 1 is only 8.59mwh; the network loss of plan 1 is 1148 MWh more than that of plan 2, and the cost of plan 2 is 14 million yuan higher than that of plan 1; plan 1 takes into account both reliability cost and network loss cost under the premise of cost economy, so plan 1 is selected as the optimal plan.

6. Conclusion
In this paper, a coordinated planning method of network source considering wind power uncertainty and scenario reduction is proposed. Taking the cost of construction, operation and reliability as multiple objectives, and considering the security (n-1) constraint, the joint planning of wind power integration point and line expansion is realized. The multi scenario stochastic simulation technology and reduction method are used to establish multi scenario, and accurately describe the uncertain factors of multi-point wind power and load. It provides a reasonable basis for the planning of objective function.

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