An Improved Hybrid Planning Model for Wind Power Transmission Channels

LIU Zhuan¹, WANG Yi-zhe², LIU You-fei³, LIU Juan¹

¹State Grid Jiangxi Electric Power Research Institute, Nanchang 330096, China;
²State Grid Materials Co. LTD., Beijing 100120, China;
³State Grid Jiangxi Electric Power Co. LTD., Nanchang 330096, China

Email:zhuanliu@126.com

Abstract. Based on the principles of deterministic planning and probabilistic planning, this paper proposes a multi-scenario hybrid planning model for wind power transmission channels. The model turns transmission channel planning into mixed-integer programming. The model uses the commercial optimization software CPLEX to find an optimal planning scheme for wind power transmission channels. In addition, through the assessment by a test system based on the actual grid and the comparison with traditional planning models, the model proves to be effective and usable.

1. Introduction

In view of the large-scale integration of wind power into the electrical grid, the long distance between newly-built wind farms and load centers as well as the intermittent nature of wind power, the planning of wind power transmission channels becomes increasingly important. Traditional power planning methods are normally based on the N−a principle, which cannot appropriately deal with the uncertainties in the electrical grid [1]; the principle of probabilistic planning can better address the uncertainties in the electrical grid, yet it cannot replace the principle of deterministic planning but only provides some reference for the latter instead. Based on the principles of deterministic planning and probabilistic planning, and combining the merits of reliability planning and economic planning, this paper puts forward a multi-scenario hybrid planning model in order to get the optimal scheme that keeps a balance between reliability and economic efficiency in the planning of wind power transmission channels [2-11]. The model turns transmission channel planning into mixed-integer linear programming and uses the commercial optimization software CPLEX to compare the investment cost of the planning scheme with the benefits the scheme yields, so as to select the optimal one [6] [8-11].

2. Hybrid Planning Model

2.1. Objective function

The objective function of the hybrid planning model can be divided into two parts according to different situations. In order to evaluate the impact of N−1 fault on wind power, this paper defines the VLP (Value of loss of wind power, $/MWh) to monetize the loss of wind power, i.e. assess the
currency value corresponding to a unit of wind power loss. The value encompasses two parts: one is the loss of profits arising from insufficient generation of wind power, and the other is the added discharge costs. The objective function is as follows:

1) The first-stage objective function:

Maximize \( (1+r)^{-1} \left[ \sum_{v \in V} \sum_{d \in D} \left( \sum_{a \in A} \sum_{v \in V, d \in D} \lambda_{vd}^a \delta_{vd}^a d_{vd}^a \right) - \right. \)

\left. \sum_{v \in V, d \in D} \sum_{a \in A} \lambda_{vd}^a \delta_{vd}^a - \sum_{v \in V, d \in D} \sum_{a \in A} VLW_{vd}^a LW_{vd}^a \right] \right) - \sigma \sum_{(i,j) \in \Omega} C_{ij} p_{ij}\]

The constraints are as follows \([7]\):

\[
\begin{align*}
& s^a f^{da} + sf^a + g^a = d^a \quad \forall a \in \Omega_a \quad (2) \\
& f_{ij}^{da} - \gamma_0 \theta_{ij}^{a} (\theta_0^{a} - \theta_0^a) = 0 \quad \forall (i, j) \in \phi^0, \quad \forall a \in \Omega_a \quad (3) \\
& \left| f_{ij}^{da} \right| \leq n_{ij} \tilde{f}_{ij} \quad \forall (i, j) \in \phi^0, \quad \forall a \in \Omega_a \quad (4) \\
& \left| f_{ij}^a \right| \leq n_{ij} \tilde{f}_{ij} \quad \forall (i, j) \in \phi^0, \quad \forall a \in \Omega_a \quad (5) \\
& 0 \leq g^a \leq \bar{g} \quad (6) \\
& 0 \leq LW^a \leq \bar{g}_{wind} \quad (7) \\
& 0 \leq n_j \leq \bar{n}_j \\
& (i, j) \in \phi \\
& n_j \text{ is an integer} \quad (10)
\end{align*}
\]

This paper uses the forced outage rates (FORs) of lines as the probability of \( N - 1 \) fault. The constraints (2) to (9) are converted from the DC power flow model in order to satisfy the calculation requirements of CPLEX \([8]\).

The first-stage objective function is applied when the maximum load of the power system is less than or equal to the sum of the total installed capacity of the system except wind power and the maximum transmission capacity of the wind power transmission channels under the \( N - 1 \) principle.

In order to calculate the capital recovery factor \( \sigma \), it is assumed that the minimum life cycle of a new line is \( t \) years, so the capital recovery cycle is \( t \) years, and the discount rate in this life cycle is \( r \). Following is the expression:

\[
\sigma = \frac{r(1+r)^t}{(1+r)^t - 1} \quad (11)
\]

2) The second-stage objective function:

Maximize \([12]\):

\[
\begin{align*}
& (1+r)^{-1} \left[ \sum_{v \in V} \sum_{d \in D} \left( \sum_{a \in A} \sum_{v \in V, d \in D} \lambda_{vd}^a \delta_{vd}^a d_{vd}^a \right) - \right. \)

\left. \sum_{v \in V, d \in D} \sum_{a \in A} \lambda_{vd}^a \delta_{vd}^a - \sum_{v \in V, d \in D} \sum_{a \in A} VLW_{vd}^a LW_{vd}^a \right] \right) - \sigma \sum_{(i,j) \in \Omega} C_{ij} p_{ij}\]

The constraints are as follows \([7]\):

\[
\begin{align*}
& s^a f^{da} + sf^a + g^a + t^a = d^a \quad \forall a \in \Omega_a \quad (13)
\end{align*}
\]
\[ 0 \leq p \leq d \]  
\[ \text{Eq.}(3) \sim (10),(16) \text{ and } (19) \]  
(14)  
(15)

The second-stage objective function is applied when the maximum load of the power system is more than the sum of the total installed capacity of the system except wind power and the maximum transmission capacity of the wind power transmission channels under the \( N - 1 \) principle.

2.2. Expression of the \( N - 1 \) principle

The \( N - 1 \) principle requires the electrical grid to keep safe and stable operation when \( a \) components fail. In this principle, \( N \) refers to all the components of the electrical grid, and \( a \) denotes the redundancy of the grid. This paper mainly focuses on the \( N - 1 \) principle. It uses the max-flow/min-cut to express the \( N - 1 \) principle. That is, the flow of the transmission lines between the two parts of the electrical grid must be less than or equal to the max-flow/min-cut under the \( N - 1 \) principle[11], and following is the expression (16):

\[ f_{x\overline{x}} \leq P_t(X,\overline{X})_{N-1} \]  
(16)

In the above expression, \( f_{x\overline{x}} \) refers to the total flow of the lines in minimal cut sets between \( X \) and \( \overline{X} \), two parts of the grid, and \( P_t(X,\overline{X})_{N-1} \) refers to the maximum total capacity of the lines in minimal cut sets between \( X \) and \( \overline{X} \) under the \( N - 1 \) principle.

This paper uses the max-flow min-cut theorem to calculate the value of the maximum flow that can pass through the wind power transmission channels[11]. The total flow passing through the lines in minimal cut sets must be less than or equal to the maximum total capacity of the lines in minimal cut sets under the \( N - 1 \) principle. The expression is:

\[ P_t(X,\overline{X})_{N-1} = F_{N-1} \]  
(17)

Minimize \[ F_{N-1} = \sum_{(i,j)\in\rho} P_{ij} - \sum_{(i,j)\in\rho} P_{ijN-1} \]  
(18)

2.3. Expression of the reliability constraint

The constraint is as follows (19):

\[ \text{LOLE}_k < T \]  
(19)

In the expression, \( \text{LOLE}_k \) (hours/year) refers to the loss of load expectation for the bus \( k \); \( T \) (hours/year) is the threshold value of \( \text{LOLE} \) in the constraint.

\[ \text{LOLE}_k = \phi_k(x)|_{\lambda=\text{LOLE}_{k-1}} \]  
(20)

3. An Example for Calculation

In this paper, 500/220kV electrical grid in a certain province is used as an example and the commercial optimization software CPLEX is called by Matlab and YALMIP to perform the simulation. In the example, the structure of the electricity market is as follows: The system contains a certain number of generating units and electrical loads; both the supplier and the user of electricity give quotation on the electricity market to maximize their own interests; all route planning and construction are decided by a unified grid planning authority; the grid company is the operator of the electricity market and the transmission system. This paper uses the load growth with the probabilities of exceedance (POEs) of 10 %, 50 % and 90 % to simulate the load growth with high, medium, and low speed in the planning cycle.

Other assumptions in this paper are as follows:

1) The generation cost equation of generators is represented by a quasi-linear curve, which is divided into several regions, and each regional generator set has a boundary cost.
2) The bidding of the electrical load is determined by the bidding function of the load.

3) Within the planning cycle, the time step size for calculation is one year, and the planning cycle is ten years. The annual growth rates corresponding to POEs of 10%, 50% and 90% are 8%, 6% and 3% respectively.

4) The service life of new equipment is 25 years, i.e. the capital recovery cycle for new equipment is 25 years.

In order to test its superiority, the model is compared in this paper with a planning model based on the $N-1$ principle. Meanwhile, the severity index of power failure of the system (SI) is used to measure the impact of the two planning models on the reliability of the system.

Figure 1 shows the structure of a 500/220kV electrical grid in a certain province, and the maximum number of branches that can be built for each channel is 3. Table 1 illustrates the relevant data of each branch in the system. Table 2 shows the generating capacity of each generator set and the initial load of buses at the beginning of the planning horizon. The initial installed capacity of wind power is 500MW, which will increase by 400MW per year for the coming 10 years. Table 3 shows relevant parameters of the different scenarios. Table 4 lists the relevant parameters of the 19-bus test system.

![Figure 1 The 19-bus test system](image)

| The initial bus | Reactance (per-unit value) | Branch capacity (MW) | Construction cost ($10^5$) | The number of built branches | FORs |
|-----------------|---------------------------|----------------------|---------------------------|-----------------------------|------|
| 1-2             | 0.0374                    | 200                  | 60                        | 2                           | 0.0012 |
| 1-4             | 0.0010                    | 2000                 | 3100                      | 2                           | 0.0015 |
| 1-5             | 0.0435                    | 200                  | 150                       | 1                           | 0.0010 |
| 1-6             | 0.0259                    | 200                  | 100                       | 2                           | 0.0012 |
| 1-19            | 0.0258                    | 200                  | 60                        | 1                           | 0.0012 |
| 2-6             | 0.0218                    | 200                  | 150                       | 2                           | 0.0020 |
| 2-11            | 0.0233                    | 200                  | 200                       | 1                           | 0.0012 |
| 2-11            | 0.0233                    | 200                  | 200                       | 1                           | 0.0012 |
| 3-4             | 0.0218                    | 200                  | 300                       | 2                           | 0.0014 |
| 3-7             | 0.0162                    | 250                  | 100                       | 1                           | 0.0020 |
| 4-9             | 0.0200                    | 250                  | 90                        | 2                           | 0.0025 |
| 4-10            | 0.0256                    | 200                  | 120                       | 2                           | 0.0024 |
| 5-16            | 0.0210                    | 250                  | 120                       | 1                           | 0.0015 |
| 5-19            | 0.0162                    | 200                  | 100                       | 1                           | 0.0012 |
| 6-7             | 0.0200                    | 200                  | 310                       | 2                           | 0.0050 |
| 6-11            | 0.0256                    | 200                  | 300                       | 2                           | 0.0011 |
| 7-8             | 0.0210                    | 200                  | 200                       | 1                           | 0.0021 |
| 7-11            | 0.0117                    | 200                  | 200                       | 1                           | 0.0022 |
Table 2 Generators and demands location at the beginning of the planning horizon in 19-bus test system

| Bus No. | Name | Capacity (MW) | Supply price of electricity ($/MWh) |
|---------|------|---------------|------------------------------------|
| 14      | G1   | 330           | 25                                 |
| 18      | G3   | 300           | 27                                 |
| 19      | G5   | 500           | 21                                 |

| Load |
|------|
| Bus No. | Name | Load (MW) | Purchase price of electricity ($/MWh) |
|-------|------|----------|--------------------------------------|
| 1     | D1   | 60       | 40,38,36,34,32                       |
| 2     | D2   | 120      | 42,1,41,39,36,34                    |
| 3     | D3   | 60       | 44,2,42,40,39,36                    |
| 4     | D4   | 75       | 39,37,36,34,31                      |
| 5     | D5   | 100      | 40,38,36,34,32                      |
| 6     | D6   | 75       | 42,1,41,39,36,34                    |
| 7     | D7   | 70       | 44,2,42,40,39,36                    |
| 8     | D8   | 40       | 39,37,36,34,31                      |
| 9     | D9   | 65       | 40,38,36,34,32                      |
| 10    | D10  | 120      | 42,1,41,39,36,34                    |
| 11    | D11  | 100      | 44,2,42,40,39,36                    |
| 12    | D12  | 75       | 39,37,36,34,31                      |
| 13    | D13  | 40       | 40,38,36,34,32                      |
| 14    | D14  | 60       | 42,1,41,39,36,34                    |
| 15    | D15  | 60       | 44,2,42,40,39,36                    |
| 16    | D16  | 75       | 39,37,36,34,31                      |
| 17    | D17  | 45       | 40,38,36,34,32                      |
| 18    | D18  | 60       | 42,1,41,39,36,34                    |
| 19    | D19  |          | -                                   |

Table 3 Characteristic of the different scenarios

| Scenario No. | Proportion coefficient | Load coefficient | Wind power coefficient |
|--------------|------------------------|------------------|------------------------|
| 1            | 0.4                    | 0.35             | 0.5                    |
| 2            | 0.3                    | 0.50             | 0.45                   |
| 3            | 0.2                    | 0.80             | 0.40                   |
| 4            | 0.1                    | 1                | 0.35                   |

Table 4 Metrics for 19-bus test system

| The $N-a$ principle | N-1 | VCR ($10^3$/MWh) | r (discount rate) | T (hour/per) |
|---------------------|-----|------------------|------------------|--------------|
|                     |     | 0.001            | 6%               | 1000         |

The planning scheme is as follows:
When the annual growth rate of the load is 3%, the hybrid planning model requires two lines connecting Bus 1 with Bus 19 to be built in the fourth year and the sixth year, while the reliability planning model requires a line connecting Bus 1 with Bus 19 to be constructed in both the second year and the fourth year; when the annual growth rate of the load becomes 6%, the hybrid planning model requires a line connecting Bus 1 with Bus 19 to be constructed in both the fourth year and the fifth year and a line connecting Bus 16 with Bus 19 to be built in the seventh year, while the reliability planning model requires a line connecting Bus 1 with Bus 19 to be built in both the second year and the fourth year and a line connecting Bus 16 with Bus 19 to be built in both the sixth year and the tenth year; when the annual growth rate of the load reaches 8%, the hybrid planning model requires a line connecting Bus 1 with Bus 19 to be constructed in both the third year and the fourth year, a line connecting Bus 16 with Bus 19 to be built in the sixth year and two lines connecting Bus 5 with Bus 19 to be built simultaneously in the ninth year, while the reliability planning model requires a line connecting Bus 1 with Bus 19 to be built in both the second year and the fourth year, a line connecting Bus 16 with Bus 19 to be constructed in the fifth year and the eighth year, and two lines connecting Bus 5 with Bus 19 to be simultaneously built in the ninth year.

Tables 5, Table 6 show the social welfare surplus and the SI of the two planning models when the load growth rates are 3%, 6% and 8%.

| Table 5 Social Welfare Surplus (10’s) for 19-bus test system |
|-------------------|-------------------|-------------------|
| Load Growth Rate  | The Reliability Planning Model | The Hybrid Planning Model |
| 3%                | 81.39             | 82.82             |
| 6%                | 84.42             | 90.93             |
| 8%                | 81.53             | 88.32             |

| Table 6 SI (System Minute) for 19-bus test system |
|-------------------|-------------------|-------------------|
| Load Growth Rate  | The Model based on the N-1 Principle | The Hybrid Planning Model |
| 3%                | 0                 | 0                 |
| 6%                | 0                 | 16.34             |
| 8%                | 0                 | 72.36             |

4. Conclusion

Based on the environment of electricity market, this paper combines the advantages of deterministic planning and probabilistic planning and proposes a hybrid planning model for the channels of wind power integration by setting multiple constraints. This model takes the characteristics of wind power generation into consideration. Assessed by a test system based on the actual grid and compared with traditional planning models, this planning model proves to be applicable, flexible and economically effective, which increases the economic efficiency and accuracy of the planning of wind power integration channels and ensures the reliability of the electrical grid as well.

References

[1] L.L. Garver. Transmission network estimation using linear programming [J]. IEEE Trans. Power Appar. Syst., 1970, 89(7):1688-1697.
[2] W. Li. Risk assessment of power systems: models, methods, and applications [M]. IEEE Press and Wiley & Sons, 2005.
[3] Jun Hua Zhao, Z.Y. Dong, Peter Lindsay. Flexible transmission expansion planning with uncertainties in an electricity market [J]. IEEE Trans on Power Systems, 2009, 24(1):479-488.
[4] Y. Gu, and McCalley. Transmission expansion planning considering economic and reliability criteria [C]. Proc. IEEE PES General Meeting, July 22-26, 2012, San Diego, CA, USA.
[5] PAJ Fonseka, ZY Dong. A Price-based approach of generation investment planning in electricity market [J]. IEEE Trans on Power Systems, 2008, 23(4):1859-1870.
[6] Zhang Qian, Zhu Xue-ling, Huang Jun-hui. Mathematical model and forecasting method of load duration curve[J]. Electric Power, 2009, 42(9):49-53.
[7] Que Xun, Cheng Hao-zhong. A novel method of power network planning based on flexible constraints[J]. Automation of Electric Power System, 2000, 24(24):17-20.
[8] I. de J. Silva, M. J. Rider, R. Romero, A. V. Garcia, and C. A. Murari. Transmission network expansion planning with security constraints[J]. Proc. Inst. Elect. Eng., Gen. Transm. Distrib., 2005, 152(6):828-836.
[9] DU Chao, WANG Xi-fan, WANG Xiu-li. Electricity Market Based on Bilateral Block Bidding[J]. Automation of Electric Power Systems, 2014, 38(13):28-32.
[10] Xie Min, Zhong Jin, Wu Fu-li. Modified simplex method for economic evaluation of transmission expansion projects[J]. Automation of Electric Power Systems, 2006, 30(7):10-15.
[11] J. Choi, Trungtinh Tran, A. (Rahim) A. El-Keib. A method for transmission system expansion planning considering probabilistic reliability criteria[J]. IEEE Trans on Power Systems, 2005, 20(3):1606-1615.