Research on Collaborative Planning Technology of New Energy Power System

JiaoJiao Deng¹, LinNa Zhang², XuXia Li¹, Jia Li¹ and XiaoMing Zheng¹, *  
¹Economic and Electrical Research Institute of Shanxi Electrical Power Company of SGCC, Planning Review Center, Taiyuan, Shanxi, China  
²Shanxi Electrical Power Company of SGCC, Development Planning Department, Taiyuan, Shanxi, China  
* Corresponding author: zhengxiaoming@sx.sgcc.com.cn

Abstract. In this paper, the collaborative planning technology of new energy power system was intensively studied, and the model of collaborative planning of new energy power system was established after considering the power structure, power distribution, coordination and optimization of power grid, limited resources, peak load regulating of power system and access of new energy. The results of numerical examples show that this model can guarantee the safe and stable operation of the power system, reduce the cost of investment, and improve the capacity of the power system to absorb new energy.

1. Introduction  
In recent years, China’s new energy, represented by wind power and photovoltaic power, has developed rapidly, and power structure in some regions has gradually developed from a simple structure dominated by thermal power to a multiple pattern of including multiple types of power sources, such as thermal power, hydropower, nuclear power, wind power and pumped-storage power. How to coordinate the operation of all kinds of power sources and how to plan the coordinated development of all kinds of power sources and the power grid is a new challenge in the current power planning in production practice. China has a vast territory, but the distribution of energy and load is very uneven. In terms of power planning, the influence of transmission constraints on power distribution and the economic cooperation between power supply and transmission network should be considered, so that the planning scheme of the power grid is reasonable and economical. Therefore, when the power planning work is being conducted, the power structure, power distribution, power network coordination and other problems cannot be ignored, and all these problems are closely related to each other.

The traditional planning method of power grid is mainly based on the maximum load [1] or the selection of specific operation mode [2]. It aims to find the best scheme of power grid expansion [3] on the basis of meeting the requirements of load transmission. In the process of programming solution, the traditional programming method cannot take into account the uncertain factors in the power system. With the large-scale development of wind power and the generation of other new energy in recent years, the access of large-scale new energy will inevitably inject more uncertainty into the power system [4].

At present, the planning methods of transmission network that take into account the uncertainty of new energy can be mainly divided into two categories: the grid planning methods based on uncertainty mathematical method and the grid planning methods based on multi-scenario technology [5]. The power grid planning methods based on uncertainty mathematical methods include: the planning methods based
on probability theory, which describes and deals with the uncertain factors in the future environment using probability [6]; and the planning methods based on fuzzy mathematics, the application of fuzzy theory solves the problems of subjective factors and incomplete data in the planning of transmission network. In literature [7], a fuzzy model of wind speed which uses triangular fuzzy number and trapezoidal fuzzy number to describe the uncertainty of wind speed was proposed. The planning methods based on the blind number theory [8], although the direct distribution of power flow of lines and cost can be obtained and the actual situation of the site can be reflected in a more detailed and comprehensive way through this method, the correlation between various factors are not considered, and its calculation amount would greatly increase with the increase of the dimension of blind numbers.

Most of the studies of evaluation index of large-scale new energy accessing transmission system planning schemes only focused on some aspects, without forming a complete evaluation index system. In literature [9], the influence of wind power integration on power grid was analyzed, and a comprehensive evaluation flow chart for the connection scheme of wind farm grid was established. In literature [10], three new evaluation indexes of coal saving, water saving cost and reliability benefit were put forward. In literature [11], a new indicator of photovoltaic power integration was put forward, and AHP and information entropy theory were used to conduct an overall evaluation of the grid evaluation scheme to get the optimal planned scheme. In literature [12, 13], the grid-connection of photovoltaic power generation was studied from the aspects of voltage, network loss and environment. In literature [14], a multi-level and multi-objective economic evaluation system for photovoltaic systems was proposed, and the corresponding evaluation methods were introduced.

Therefore, based on the above requirements, this paper will intensively study the collaborative planning technology of new energy power system, and establish a power planning model that adapts to the current development of power system by considering such factors as power structure, power distribution, coordination and optimization of power network, resource constraints, peak load regulating of power system and the access of new energy. The work of this paper includes putting forward the cooperative planning model of new energy power system, designing the constraint conditions, and realizing the collaborative planning of power grid. The example results show that the collaborative planning model of new energy power system proposed in this paper can adapt to the current development of power system and realize the sustainable development of power grid.

2. Collaborative planning model of new energy power system

2.1. Target function
The objective function of the planning and optimization in this paper is to get the minimum total cost of investment and operation, namely:

\[
\min c = h + x
\]  

(1)

Where, h and x represent investment cost and operation cost respectively. The specific calculation formula is as follows.

2.1.1. Investment costs
Assuming that the static investment of generator unit u is v (if unit u has been put into production before the planning period, then v=0), the depreciation life is n, and the discount rate is i, then the equal annual value of investment of unit u is

\[
\alpha(u) = \frac{i(1+i)^n}{(1+i)^n-1},
\]

and the matrix of equal annual value of power supply investment is defined as GU \{\{u\}\}, GU [u]=\alpha(u). The matrix of equal annual value GL \{\{1\}\} of power grid investment is similarly defined.

The time-adjusted power supply investment after project reset and deduction of residual value is:

\[
\varphi(u) = \sum_{y \in \{y\}} (1+i)^{-y} M[u, y]G_G[u]
\]

(2)
The matrix of dynamic time-adjusted power supply investment is defined as \(H_U\left\{u\right\}\), \(H_U=\varphi[u]\). The matrix of dynamic time-adjusted power grid investment is defined similarly as \(H_L\left\{l\right\}\). The dynamic investment of the whole system is:

\[
h = \sum_{u \in \left\{u\right\}} H_U[u] + \sum_{l \in \left\{l\right\}} H_L[l]
\]  

(3)

2.1.2. Annual operating costs

(1) Electricity cost

According to the above definitions of unit operation characteristics, the matrix of operating cost is \(V\{n, \{k\}\}\), and \(V[n, k]\) is the unit electricity cost of node-\(n\) type-\(k\) unit. The matrix of electricity cost is \(X_C\{\{y\}\}\), where \(X_C[y]\) is the electricity cost in year \(y\), thus:

\[
X_C[y] = \sum_{n \in \left\{n\right\}} \sum_{k \in \left\{k\right\}} E[n, k, y]V[n, k]
\]  

(4)

(2) On-off cost

On-off cost \(V'\{\{k\}\}\), where \(V'[k]\) is the On-off cost per unit capacity of type-\(k\) units; The on-off cost matrix is \(X_C\{\{y\}\}\), where \(X_C[y]\) is the on-off cost of the year \(y\), so:

\[
X_x[y] = \sum_{n \in \left\{n\right\}} \sum_{k \in \left\{k\right\}} \sum_{d \in \left\{d\right\}} \sum_{e \in \left\{e\right\}} A[d, e]Q[n, k, y, d]V[n, k]
\]  

\[
X_x[y] = \sum_{n \in \left\{n\right\}} \sum_{k \in \left\{k\right\}} \sum_{d \in \left\{d\right\}} A[d, e]
\]  

(5)

(3) Total operating costs

The matrix of total operating cost is \(X\{\{y\}\}\), where \(X[y]\) is the total operating cost of the year \(y\), including on-off costs and operating costs:

\[
X[y] = X_C[y] + X_x[y]
\]  

(6)

(4) Time-adjusted operating cost of the whole system

Time-adjusted operating cost of the whole system is:

\[
x = \sum_{y \in \left\{y\right\}} X[y](1+i)^{-y}
\]  

(7)

(5) Load shedding cost of wind turbine and power generation cost

\[
\sum_{y=1}^{k_c} \sum_{s=1}^{k_c} (C_{w,s,y}^{\text{Gen}})^T (P_{w,max} - P_{w,s,y}^d) + (C_{w,s,y}^{\text{Curtail}})^T P_{w,s,y}^d
\]  

(8)

2.2. Constraint conditions

2.2.1. Description of constraints related to planning decisions

In order to describe the investment decision of power supply and grid, the decision matrix and state matrix shall be first introduced, which will serve as the basis of the unified planning model.

(1) Investment decision matrix for the power plant

In the actual investment of power supply, it has the following properties:

The investment decision of power supply is whether to build or expand a power plant. For different power plants, the types of units put into operation, the number of units, the time span and the schedule of units put into operation are different.

There is a time coupling relationship between different periods of the same power plant. For example, the third phase must be put into operation after the second phase, and there will be a minimum interval between them, such as three years.

The investment in the new construction period and the expansion period of the power plant are not the same, and because of the time value of the capital, it is not suitable to use the average approach;
Due to the schedule of construction or the demand of policy, it is necessary to be able to specify the definite start year or the earliest start year or the latest start year of a certain period of power plant, or within a certain period of time.

In order to express the above requirements, in this paper, the concept of matrix of power investment decision was put forward, which is described in a mathematical way, as follows:

The matrix of investment decision \( M'\{\{p\}, \{y\}\} \) of the power plant is defined to meet the following requirements:

1) \( M'\{p, y\} \in \{0, 1\} \), if the No. \( p \) power plant is put into production in the first year, then \( M'[p, y]=1 \). Otherwise, \( \sum_{y \in \{y\}} M'[p, y] \leq 1 \quad \forall p \in \{p\} \)

2) If the earliest production year of the No. \( p \) power plant is \( y_0 \), then \( M'[p, y]=0 \quad \forall y < y_0 \).

3) For the case of multi-phase construction of the same power plant, it can be treated as two power plants, but it is required to meet the restriction of the interval year between them. For example, let two adjacent phases be phase \( p_1 \) and phase \( p_2 = p_1 +1 \). If the time interval is required to be at least \( y_0 \) year(s), the following conditions need to be met:

\[
\begin{cases}
M'[p_2, y] = 0 & \forall y_0 > y \geq 0 \\
M'[p_2, y] \leq M'[p_1, y-y_0] & \forall y \geq y_0
\end{cases}
\]  

(9)

4) If it is necessary to specify that the No. \( p \) power plant must be put into production in year \( y_0 \sim y_1 \), the equation of \( \sum_{y=y_0}^{y_1} M'[p, y] = 1 \) year \( y_1 \), the equation of \( \sum_{y=y_0}^{y_1} M'[p, y] = 1 \) shall be satisfied. Similar treatment can be done for specified year of production and to limit the latest year of production, etc.

All constraints for the investment decision of the power plant that meet the above requirements are combined and abbreviated as:

\[ \psi(M') \geq 0 \]  

(10)

(2) Matrix of unit state

The matrix of unit state \( M\{\{u\}, \{y\}\} \) is defined to reflect whether the unit is callable or not, which needs to be determined according to the matrix of investment decision of the power plant and the technical transformation and decommissioning schedule of old units. The structure is as follows:

1) If unit \( u \) has been put into production before the planning period, then \( M[u, y] = 1 \);

2) For unit \( u \) to be selected, if it is assumed that it belongs to power plant \( p \) and is put into production in year \( y_0 \) of this period, then

\[ M[u, y] = \sum_{x=1}^{y-y_0} M'[p, x] \]  

(11)

3) If unit \( u \) begins to retire in year \( y_0 \), then \( M[u, y] = 0 \quad \forall y \geq y_0 \)

The above structural process can be abbreviated as:

\[ M = \phi(M') \]  

(12)

The matrix of unit state \( M \) thus constructed has the following properties:

1) \( M[u, y] \in \{0,1\} \), and \( M[u, y] \) is a state variable representing whether the unit \( u \) is valid in year \( y \), that is, whether it can be called. For units that have not been put into production or have been retired in a certain year, the state is 0, otherwise it is 1;

2) Assume that the earliest construction year of unit \( u \) is \( y_0 \), then \( M[u, y] = 0 \quad \forall y < y_0 \);

3) Constraints on installation continuity: if unit \( u_1 \) and \( u_2 \) belong to the same power plant in the same phase, and the time of production is \( y_0 \) apart, the following conditions shall be met:

\[
\begin{cases}
M[u_2, y] = 0 & \forall y_0 > y \geq 0 \\
M[u_2, y] = M[u_1, y-y_0] & \forall y \geq y_0
\end{cases}
\]  

(13)
4) Minimum interval constraint of the same power plant in continuous period: if unit $u_1$ and $u_2$ belong to the first operational unit in the first and second phases of the same power plant respectively, and the time interval between the two phases is at least $y_0$, then the following conditions are satisfied:

$$
\begin{align*}
M[u_2, y] &= 0 \quad \forall y_0 > y \geq 0 \\
M[u_2, y] &\leq M[u_1, y - y_0] \quad \forall y \geq 0
\end{align*}
$$

The above properties show that the mathematical description method can completely express the complex situation of power investment decision. The matrix of investment decision of power plant is taken as the optimization object, and the matrix of unit state is constructed from the matrix of investment decision of power plant. In this way, not only the time coupling relationship between power investment can be described, but also the number of variables equal the number of power plants to be selected (the same power plant is regarded as different power plants in different periods) $\times$ the number of planning years. This method can greatly reduce the number of variables and reduce the scale of the optimization problem compared to the situation where the unit is simply the decision-making unit for optimization.

(3) Investment decision for power grid

Similarly, for the lines to be selected, the corresponding matrix of planning decision $N'\{\{g\}, \{y\}\}$ and state matrix of line $N\{\{l\}, \{y\}\}$ can be defined, and the constraint is:

$$
\xi(N') \geq 0
$$

$$
N = \phi(N')
$$

It is similar to the power section, so that will not be repeated here.

2.2.2 Constraints related to line construction

Constraints on the production status of the line to be built:

$$
U_y \leq U_{y+1}, \quad y = 1, 2, ..., Y - 1
$$

(17)

Constraint on the production time of the line to be built:

$$
u_{l,y} = 0, \quad y < y_{l_{\min}}, \quad l = 1, 2, ..., L_B
$$

(18)

Power balance equation of all scene nodes in all years within the planning period:

$$
A_F B_{B, s, y} + A_B B_{E, s, y} + W_{B} P_{E, s, y} + W_{F} P_{F, s, y} + W_{F} P_{F, s, y} = (D_{s, y} - D_{s, y}^e)
$$

(19)

Constraints on upper and lower limits of power flow of built lines in all years and in all scenes during the planning period:

$$
F_{E, \max} \leq B_E A_E^T \Theta_{s, y} \leq F_{E, \max}
$$

$$
y = 1, 2, ..., Y, \quad s = 1, 2, ..., S_y
$$

(20)

In all years and in all scenes during the planning period, the power flow equation can be added as a constraint condition for the lines to be built that have already been put into operation, and the power flow is restricted to 0 for the lines to be built that have not yet been put into operation:

$$
F_{B, s, y} - U_y B_{B} A_E^T \Theta_{s, y} = 0
$$

$$
y = 1, 2, ..., Y, \quad s = 1, 2, ..., S_y
$$

(21)

Constraints on upper and lower limits of power flow of the line to be built in all years and scenarios within the planning period:

$$
-F_{B, \max} \leq F_{B, s, y} \leq F_{B, \max}
$$

$$
y = 1, 2, ..., Y, \quad s = 1, 2, ..., S_y
$$

(22)
Maximum and minimum output limits of units in all years and all scenarios within the planning period:

\[
P_{h,\min} \leq P_{h,s,y} \leq P_{h,\max}
\]
\[
P_{n,\min} \leq P_{n,s,y} \leq P_{n,\max}
\]
\[
P_{c,\min} \leq P_{c,s,y} \leq P_{c,\max}
\]
\[
0 \leq P_{w,s,y} \leq P_{w,\max}
\]
\[
y = 1, 2, ..., \ Y \ , \ s = 1, 2, ..., \ S_y
\]

(23)

Load shedding constraints of all years and scenarios within the planning period:

\[
0 \leq D_{s,y}^d \leq D_{s,y}
\]
\[
y = 1, 2, ..., \ Y \ , \ s = 1, 2, ..., \ S_y
\]

(24)

2. 2. 3. Constraint for power standby

Power reserve ratio is the percentage of available capacity in a system minus the maximum load before it’s divided by the maximum load. The reserve ratio includes load reserve, accident reserve, maintenance reserve, etc. In planning decisions, this kind of constraints must first be guaranteed. The specific expression is as follows:

\[
\sum_{s \in S_y} M[u, y]Q_{n, k, y, d} y \geq (1 + R[u(y)])D_{u, y} \quad \forall y \in \{y\}
\]

(25)

2. 2. 4. Description of constraints related to system operation

1) Constraint for peak load regulation

For reflecting the problem of peak-load regulation of the system, the units that run every day can be divided into two kinds: under on-off operation and under non-on-off operation. The maximum output that can be achieved is the sum of the available capacity of these two kinds of the units, and the minimum output is the sum of the minimum output of the units under non-on-off operation. The constraint of positive and negative standbys must be satisfied, and the optimization of power supply structure must be achieved with the objective function.

The starting capacity matrix of \(Q[n, k, y, d]\) of lines under non-on-off operation is defined, where \(Q[n, k, y, d]\) is the starting capacity of the lines under non-on-off operation of type-k units at the node \(n\) on day \(d\) of year \(y\). Similarly, the startup capacity of the lines under on-off operation is defined as \(Q'[n, k, y, d]\).

For the types of units that are unable to be under non-on-off operation, the constraint condition that the output under on-off operation is 0 shall be satisfied:

\[
Q'[n, k, y, d] = 0 \quad \forall n \in [n], \ y \in [y], \ d \in [d], \ B[k] = 0
\]

(26)

Starting capacity must not be less than 0:

\[
Q[n, k, y, d] \geq 0 \quad \forall n \in [n], \ k \in [k], \ y \in [y], \ d \in [d]
\]

(27)

\[
Q[n, k, y, d] \geq 0 \quad \forall n \in [n], \ k \in [k], \ y \in [y], \ d \in [d]
\]

(28)

The sum of starting capacity must not be greater than the available capacity:

\[
Q[n, k, y, d] + Q'[n, k, y, d] \leq Q[n, k, y, d]
\]
\[
\forall n \in [n], \ k \in [k], \ y \in [y], \ d \in [d]
\]

(29)

Positive standby constraint:
2) Constraint for power balance and lines

The model of DC power flow is simple, the calculation is fast, and it is more accurate, which can reasonably reflect the distribution of power flow during the planning period. In this paper, this method was also used to calculate the power distribution of all typical periods of all typical days in the planning period, which requires that the power flow constraint of the planning network be satisfied, and the optimization of power distribution, power grid planning and coordinated planning of power grid are achieved with the objective function from the technical and economic aspects.

The output matrix P \{n, k, y, d, t\} is defined, where P[n, k, y, d, t] is the output of the lines under non-on-off operation on that day in the node-n type-k unit at the time t of day d in year y. Similarly, the output of the lines under on-off operation is defined as P’\{n, k, y, d, t\}. The following constraints need to be satisfied:

➢ Technical output constraint of unit:
For the kind of units under non-on-off operation, the output of all periods must be within the starting capacity and its minimum output range:

$$\sum_{n \in \{y\}} \sum_{k \in \{d\}} J[n,k]Q[n,k,y,d] \leq P[n,k,y,d,t] \leq Q[n,k,y,d]$$

$$\forall n \in \{y\}, d \in \{t\}$$

(32)

For the kind of units under on-off operation, the starting capacity during peak load period is P’. It’s similar to that of non-on-off operation:

$$J[n,k]Q[n,k,y,d] \leq P[n,k,y,d,t]$$

$$\leq Q[n,k,y,d]$$

$$\forall n \in \{y\}, d \in \{t\}$$

(33)

t represents the time of peak load

The on-off starting capacity of valley load must be 0, therefore:

$$P[n,k,y,d,t]=0$$

$$\forall n \in \{y\}, d \in \{t\}$$

(34)

t represents the time of valley load

The starting capacity is between 0 and P’ during on-off period, therefore:

$$0 \leq P[n,k,y,d,t] \leq Q[n,k,y,d]$$

$$\forall n \in \{y\}, d \in \{t\}$$

(35)

t \in \{t\} and is not the time of peak load/valley load

➢ Power balance:

$$\sum_{n \in \{y\}} \sum_{k \in \{d\}} Q[n,k,y,d] + \sum_{n \in \{y\}} \sum_{k \in \{d\}} Q[n,k,y,d]$$

$$\geq (1 + R_{y})D_{y}[y,d]$$

$$\forall y \in \{y\}, d \in \{d\}$$

(30)

Negative standby constraint:

$$\sum_{n \in \{y\}} \sum_{k \in \{d\}} J[k]Q[n,k,y,d] \leq (1 + R_{y})D_{y}[y,d]$$

$$\forall y \in \{y\}, d \in \{d\}$$

(31)
\[ \sum_{n \in \{n\}} \sum_{k \in \{k\}} Q(n, k, y, d, t) + \sum_{n \in \{n\}} \sum_{k \in \{k\}} Q'[n, k, y, d, t] = D[y, d, t] \quad \forall y \in \{y\}, d \in \{d\}, t \in \{t\} \]

- **Constraint for load flow:**

  Similar to the available capacity of the unit, the matrix of line transmission limit \( F_{M}\{l, y\} \) is defined, where \( F_{M}\{l, y\} \) is the transmission limit of line \( l \) in year \( y \), which is related to variable \( N \), and is abbreviated as \( F_{M} = \theta(N) \). The matrix of power flow of lines \( F\{l, \{y\}, \{d\}, \{t\}\} \) is defined, where \( F\{l, \{y\}, \{d\}, \{t\}\} \) is the power flow of line \( l \) at the time \( t \) of day \( d \) in year \( y \), which can be obtained from the calculation of DC power flow [11], and is related to the variables \( N, P, P' \) and is abbreviated as \( F = \sigma(N, P, P') \). Requirements to meet the constraints for load flow:

\[ -F_{M}[l, y] \leq F[l, y, d, t] \leq F_{M}[l, y] \quad \forall l \in \{l\}, y \in \{y\}, d \in \{d\}, t \in \{t\} \]  

2. 2. 5. **Consideration of random output characteristics of new energy**

In the traditional electric power planning, because the installed capacity of new energy units is small, and their proportion in system installed capacity is low, thus, this kind of units in power planning can be completely ignored. In recent years, with the increasing capacity of new energy, the proportion of its installed capacity in the system is increasing, and the influence on the reliability of the system and the balance of power and quantity is becoming more and more significant, which has become a non-negligible part of the power planning. At the same time, the new energy represented by wind power and solar photovoltaic power generation has the operation characteristics of randomness and uncontrollablleness, which bring great challenges to the peak load regulation of power system. Therefore, in the power planning under the new environment, it is necessary to consider the problem of cooperation after the new energy is connected with the conventional power supply.

In the power planning model proposed in this paper, the new energy is taken as one or several types of units, and some special treatments are carried out for the unit categories corresponding to the new energy in the model.

Let the set of corresponding category unit of new energy be \( \{k\} \). Because this kind of power supply has the running characteristics of randomness and uncontrollablleness, its influence on the system mainly displays in the constraint for peak load regulation. Therefore, the situation in which the output is opposite to the peak-valley difference of the load should be considered in the planning, that is, the situation in which the output is 0 at peak load and the situation in which the output is the maximum output at valley load. Set its operating characteristics as follows:

1. The unit cannot be under on-off operation: \( BV[k] = 0, k \in \{kr\} \);
2. The unit must be started: \( BS[k] = 0, k \in \{kr\} \);
3. The annual utilization hours of a unit are determined according to its resource characteristics. \( W[k] = 0 \). For example, the annual utilization hours of onshore wind power are generally determined according to 2000h. Set \( H_{w}[k] = 2000 \);
4. The minimum output ratios \( J[k] \) of all types of units are set as the maximum output ratios of the new renewable power at a certain confidence level, that is, \( J[k] = p_{a}, (P(p < p_{a}) = \alpha) \). Generally, \( \alpha \) is 95%~100%.

The reasons for the setting is as follows.

Since the unit could not be under on-off operation, it can be known that the on-off output of the unit is 0:

\[ Q[n, k, y, d] = 0 \quad \forall n \in \{n\}, y \in \{y\}, d \in \{d\}, B_{i}[k] = 0 \]

Meanwhile, change the corresponding constraint conditions as follows:
In the power balance, the peak load is considered as the output of 0, and the valley load is considered as the maximum output of the wind turbine at a certain confidence level. Namely, in the constraint condition, the following is true:

\[ P[n, k, y, d, t] = 0 \]
\[ \forall n \in \{n\}, y \in \{y\}, d \in \{d\}, \]
\[ t \in \{t, \forall D_x[y, d, t] = D_{X_x[y, d]}\} \]

\[ P[n, k, y, d, t] = \sum_{k[y, k]} J[k]Q_{M}[u, y] \]  \hspace{1cm} (38)
\[ \forall n \in \{n\}, k \in \{k\}, y \in \{y\}, d \in \{d\}, \]
\[ t \in \{t, \forall D_x[y, d, t] = D_{X_x[y, d]}\} \]

In the calculation of positive standby, the non-on-off starting capacity of the unit is considered as 0, that is, under the constraint of positive reserve.

\[ Q[n, k, y, d] = 0 \hspace{1cm} \forall y \in \{y\}, k \in \{k\} \]  \hspace{1cm} (39)

When calculating the negative standby, the starting capacity shall be considered according to its installed capacity. Since \( J[k] \) is set as the maximum output of the new renewable power at a certain confidence level, that is, when calculating the negative reserve, the full output of the new energy is considered.

If the constraints are set as stated above, in fact, the reverse peak load regulation of new energy is considered in load balance and constraint for peak load regulation. When the system is connected to large-scale new energy, the model can be used to consider planning more peak load regulation power to operate with new energy.

3. Collaborative planning model of new energy power system

3.1. Boundary conditions

In this paper, the year of 2015 was selected as the status quo year to carry out collaborative planning for the power system of a province in 2019. Boundary conditions of the calculating example are set as follows:

1) Status quo controllable power supply

The main technical and economic parameters of all types of power supply that have been put into production in the province above 500kV in 2015 are listed here.

| Type of power source | Capacity under production (MW) | Minimum technical output ratio | On-off cost (RMB/MW) | Minimum shutdown time |
|----------------------|--------------------------------|--------------------------------|---------------------|----------------------|
| Thermal power        | 27520                          | 50%                            | 1250                | 24h                  |
| Pumped storage       | 1200                           | 0%                             | /                   | /                    |

2) Planning new energy sources

According to the province’s 2019 new energy plan, by 2019, the province’s installed wind power capacity would reach 12,515MW and photovoltaic capacity would reach 7,769MW. In this example, in order to absorb new energy to the maximum, wind power and photovoltaic power plants are set as necessary power plants.
Table 2. Planned new energy capacity

| Type of power source | 2019 Planned Capacity (MW) |
|----------------------|-----------------------------|
| Wind power           | 12,515                      |
| Photovoltaic power   | 7,769                       |

(3) Power supply to be built

From 2015 to 2019, there are three planned coal power units to be built, with a planned capacity of 3,000 MW. The specific parameters are shown as follows.

Table 3. Power supply to be built

| Planned power plant | Planned capacity (MW) | Minimum technical output ratio | On-off cost (RMB/MW) | Minimum shutdown time |
|---------------------|-----------------------|--------------------------------|----------------------|-----------------------|
| Power plant 1       | 1200                  | 50%                            | 1250                 | 24h                   |
| Power plant 2       | 1200                  | 50%                            | 1250                 | 24h                   |
| Power plant 3       | 600                   | 50%                            | 1250                 | 24h                   |

(4) Current line status

In order to reduce the computational complexity, equivalent treatment is conducted here to the lines and the N-1 constraint. The line with the same starting and ending stations is equivalent to an N-loop line, whose equivalent N-1 transmission capacity is the sum of the original transmission capacity of the two lines divided by 2.

In 2015, there were 31 transmission lines in the province, with an average transmission distance of 81.21 km and a total designed capacity of 3,767 MVA.

(5) Lines to be built

There are four planned lines to be built from 2015 to 2019, and the specific parameters are shown as follows.

Table 4. List of lines to be built

| Electric transmission line | Transmission distance (km) | Design capacity (MVA) |
|----------------------------|-----------------------------|-----------------------|
| Line-32                    | 109.80                      | 4742.00               |
| Line-33                    | 140.66                      | 4742.00               |
| Line-34                    | 92.50                       | 4742.00               |
| Line-35                    | 27.97                       | 9990.00               |

(6) Net system load

In this example, the load input is the 8,760-hour load of the 500kV station in 2019. The bus load of the 500kV station is the net load, which is equal to the actual load minus the output of the wind and solar power stations. The maximum net load of the system is 21,996 MW, and the minimum net load is 6,224 MW.
3.2. Results of Collaborative Planning of Source Network

(1) Results of planned power supply

According to the results of planning calculation, the three thermal power units planned in 2019 do not need to be put into construction. The reason is that the maximum net load of the system above 500 kV is 21,996 MW, while in 2015, the capacity of thermal power units that have been put into operation and connected to the grid above 500 kV reached 27,520 MW, which can fully meet the demand of the maximum load. On the other hand, although the minimum net load of the system is only 6,224 MW, part of the units can be shut down by means of on-off optimization of unit commitment to make the minimum technical output of the system meet the requirements.

(2) Results of route planning

According to the results of planning calculation, new lines need to be built for the province’s power grid in 2019. The line planning and construction table calculated through the algorithm is shown in the following table. It can be seen that the construction line obtained through the planning algorithm is completely consistent with the actual construction line. Comparing the line planning capacity with the design capacity, although the line planning capacity is smaller than the design capacity, considering the N-1 principle and the inherent transmission capacity of 2,371 MVA of a single 500 kV line, the result of the planned line in this calculation example is basically consistent with the actual line design capacity. Taking Line-32 as an example, the planned capacity is 1,324 MVA, so the construction of one 2,371 MVA line can meet the demand of transmission capacity. However, considering the N-1 principle, it is necessary to build two 2371 MVA lines with a total of 4,742 MVA lines, which is completely consistent with the results of the actual construction of two loops.

(3) System cost

According to the planning algorithm in this paper, the fixed cost of power generation in this province is 0 yuan, the fuel cost of power generation is 20.461 billion yuan, and the fixed cost of transmission is 1.688 billion yuan in 2019. Among them, the fixed cost of power generation is the investment cost of power generation + the fixed operation and maintenance cost. Since there is no power generation construction project and the power generation operation and maintenance costs are ignored in this example, the fixed cost of power generation is 0. The fuel cost of power generation is composed of unit fuel cost + on-off fuel cost, with a net present value of 20.461 billion yuan in 2019. The fixed transmission cost includes the cost of line construction, and the net present value in 2019 is 1.688 billion yuan.
Table 7. Planning system costs

| Item costs                      | Cost of annual net present value |
|---------------------------------|----------------------------------|
| Fixed cost of generation        | 0                                |
| Fuel cost for power generation  | 20.461 billion                   |
| Fixed transmission cost         | 1.688 billion                    |

(4) Abandonment of wind power and photovoltaic power

According to the grid construction planning based on the algorithm in this paper, abandonment of wind power and photovoltaic power in the power system of this province will be as low as 2.44% and 2.43% respectively in 2019. Among them, the annual power generation capacity of wind power is 24.576 billion kWh, the annual power generation capacity is 25.191 billion kWh, the abandoned wind power capacity is 615 million kWh, and the annual photovoltaic power generation is 9.864 billion kWh. The annual generating capacity is 10.111 billion kWh, and the abandoned photovoltaic power is 246 million kWh. The annual generating capacity of coal power units above 500kV is 137.924 billion kWh, and the utilization hours are 5,011 hours.

Table 8. Abandonment of wind power and photovoltaic power

| Type of power generation technology | Planning period | Total installed capacity (MW) | Annual power generation (100 million kWh) | Utilization hours | Annual generating capacity (100 million kWh) | Abandon rate of electricity (%) |
|-------------------------------------|-----------------|-------------------------------|-------------------------------------------|-------------------|-------------------------------------------|---------------------------------|
| Coal power                          | 2019            | 27520                         | 1379.24                                   | 5011              | /                                         | /                              |
| Photovoltaic power                  | 2019            | 7769                          | 98.64                                     | 1269              | 101.10                                    | 2.43                            |
| Wind power                          | 2019            | 12515                         | 245.76                                    | 1963              | 251.91                                    | 2.44                            |

4. Conclusion

In this paper, an in-depth study of collaborative planning technology for new energy power system was conducted, and collaborative planning model for new energy power system was established. Taking the comprehensive economic benefits of the construction of power generating facilities and power grids as the goal, this paper considered constraints such as constraint for abandonment of new energy power, constraint for power supply planning, planned load level of the power grid, safe operating boundary condition of power grid, and power supply reliability level of power grid. With these efforts, it achieved the collaborative planning of power grid. The planning results show that the collaborative planning model of new energy power system proposed in this paper not only meets the security and stability of the power system, but also avoids repeated or inefficient investment and improves the power system’s absorption capacity of new energy.

Acknowledgements

This work was supported by Economic and Electrical Research Institute of Shanxi Electrical Power Company of SGCC (Grant No.: 520533200003).

References

[1] Samarakoon H, Shrestha R M, Fujiwara O. A mixed integer linear programming model for transmission expansion planning with generation location selection. International journal of electrical power & energy systems. 23(4), 285-293 (2001)

[2] Capuder T, Pandžić H, Kuzle I, et al. Specifics of integration of wind power plants into the Croatian transmission network. Applied energy. 101, 142-150 (2013)
[3] Zhang Xinsong, Yuan Yue. Expansion planning of transmission in deregulated electricity network with large wind farm market environment. Electric Power Automation Equipment. 2012, 32(4), 100-103.

[4] Lei Yazhou. Studies on wind farm integration into power system. Automation of Electric Power Systems 27(8), 84-89 (2003)

[5] Ma Tao. Power transmission network planning considering the comprehensive effect of wind power and load. Shandong University. 2014.

[6] Zhou Renjun, Xu Zhisheng, Yang Hongming. An Application of Multi-Attribute Fuzzy Optimal Selection to the Evaluation of Grid Planning. Journal of Zhengzhou University 26(2), 23-26 (2005)

[7] Hong Lucheng, Shi Libao, Yao Liangzhong, Masoud B, Ni Yixin. Fuzzy Modelling and Solution of Load Flow Incorporating Uncertainties of Wind Farm Generation. Transactions of China Electrotechnical Society 25, 116-22 (2010)

[8] Cheng Haozhong, Zhu Haifeng, Wang Jianmin, Chen Chunlin, Fang Lingfeng. Electric Power Networks Flexible Planning via the Blind Model (BM) of Unascertained Number. Journal of Shanghai Jiaotong University. 2003, 1347-50.

[9] Qian Ying. Research on Evaluation System of Grid-connected Scheme of Large Wind Farm Considering Uncertainty. North China Electric Power University. 2012.

[10] Li Jin. An Analysis Considering the Reliability Benefits of Wind Power Development Economy. Power & Energy 34(6), 657-660 (2013)

[11] Wang Wan, Zeng Bo, Liu Zongqi, et al. Comprehensive Evaluation Model of Photovoltaic Generation Grid-connected Planning and Its Application. Modern Electric Power 28(6), 82-86 (2011)

[12] Hoff T, Shugar D S. The value of grid-support photovoltaics in reducing distribution system losses. IEEE Transactions on Energy Conversion 10(3), 569-576 (1995)

[13] Ochoa L F, Padilha-Feltrin A, Harrison G P. Evaluating distributed generation impacts with a multiobjective index. IEEE Transactions on Power Delivery 21(3), 1452-1458 (2006)

[14] Shen Weixiang, Yang Zhigang. Research on comprehensive economic evaluation structure and method of photovoltaic system. Acta Energiae Solaris Sinica 17(1), 69-74 (1996)