A Collaborative Planning Model of Power Source Considering the Uncertainty of The New Energy and The Power Market

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Abstract. This paper studies the model of power system adapted to the new energy generation and power market environment. A collaborative planning model of power source considering the uncertainty of the new energy and the power market is proposed. The construction of coal-fired thermal power generating units, wind power generators and transmission lines are considered. At the same time, in view of the uncertainty of wind power generation and electricity market, considering from two perspectives: the randomness of wind power output and the use of geometric Brownian motion to predict electricity price. Finally, the example application of the IEEE 30-bus system shows that the model can effectively coordinate the construction scheme of power grid and power supply.

1. Overview

Power system planning plays an important role in ensuring the sustainable security, reliability, science and sustainable development of power grid. Scientific and reasonable power grid planning has great social and economic value. In recent years, with the rapid development of power system, power planning is facing new challenges. On the one hand, the large-scale access of new energy (such as wind power generation system, nuclear power system, etc.) brings many uncertainties to power grid planning (such as intermittent and randomness of power output). The traditional planning ideas and methods of power system will not be well suited to the requirements of power grid planning with large-scale new energy accessing to the system, and increase the difficulty of power grid planning. Some of the uncertainties can be classified as randomness, while others are more suitable for describing [1] with fuzziness. Some scholars [2-4] have considered some uncertainties of wind power generation from the perspective of randomness and fuzziness, but they do not take into account the uncertainty of power market, and the cost of each power station in the model is a continuous function of construction capacity. On the other hand, the imbalance between power grid planning and power supply planning is becoming more and more prominent [5]. For a long time, the study of power grid planning and power source planning has been separated, and the two kinds of planning problems have

their own main diversity. Literature [6][7] tries to combine power supply planning with power grid planning to some extent. Planning models are established from different perspectives, but most of them are based on traditional power grid planning models, in which the consideration of wind turbines or regulating units is added.

At the same time, the economic benefits of power grid planning depend on the situation of the electricity market largely. There are many uncertainties in the electricity market. The price of electricity and coal will fluctuate with the change of the electricity market. Therefore, how to consider the uncertainties of power market while studying power grid planning is a topic worthy to study. At present, there are few studies considering the uncertainty of power market in power grid planning.

Therefore, based on the above requirements, this paper will deeply study the power system planning model and method adapting to the large-scale grid-connected new energy generation and the power market environment. A network source collaborative planning model considering the uncertainties of new energy and electricity market is proposed. The model considers the construction of coal-fired thermal power generating units, wind turbines and transmission lines as a whole. It can optimize resources and maximize total revenue from a global perspective. According to the characteristics of thermal power plants, the construction cost of coal-fired power plants is a discrete function of capacity. At the same time, the model takes into account the uncertainty brought by wind power to the power system and the uncertainty of the power market, which accords with the development trend of the power system

2. Network source cooperative planning model

2.1. Basic concepts
In the past, power planning and power grid planning were often studied and practiced separately. Power grid planning is to determine the construction plan of transmission lines by establishing a suitable planning model and satisfying the requirements of various technical indicators and construction with the minimum cost to meet the transmission needs in the planning period. Power planning is to establish the optimal power planning model according to the actual power planning standard, in order to find the optimal construction scheme of various power units, and meet the power demand with the minimum cost.

The model proposed in this paper considers not only the coal-fired power generation, but also the construction demand represented by wind power generation. Combined with the stochastic characteristics of wind power generation and electricity market, the model further studies the randomness of wind power output and the uncertainty of market price.

In a word, the coordinated planning of power supply is to consider the power supply side and the power grid side comprehensively and make overall decisions on the construction of power grid lines, coal-fired units and wind turbines so as to achieve maximum economic benefits and realize the effective allocation of resources and efficient utilization of energy

2.2. Modeling
The goal of collaborative source planning is to maximize profits, which is a mathematical optimization problem. Including the revenue from electricity sales, the construction cost of new thermal power stations, the construction cost of new wind power stations, the construction cost of power grids, the operation cost of new wind power stations, the operation cost of existing wind power stations, the operation cost of new thermal power stations, the operation cost of existing thermal power stations, etc.

$$P_{total} = \sum_{t \in \Delta_T} p_{1,t} \left(\sum_{i \in \Delta_g} x_i Q_i H_{i,t} + \sum_{j \in \Delta_G} Q_j H_{j,t} + \sum_{i \in \Delta_h} \sum_{j \leq m} y_{i,j} C_j F_{i,t} + \sum_{j \in \Delta_H} C_j F_{j,t} \right) -$$

$$- \sum_{t \in \Delta_T} \left(\sum_{i \in \Delta_g} x_i R_i Q_i H_{i,t} + \sum_{j \in \Delta_G} Q_j R_j H_{j,t} + \sum_{i \in \Delta_h} \sum_{0 \leq j \leq m} y_{i,j} G_j C_j F_{i,t} + \sum_{i \in \Delta_H} C_i G_i F_{i,t} \right) - \qquad (1)$$

$$\sum_{t \in \Delta_T} \left(\sum_{i \in \Delta_h} \sum_{0 \leq j \leq m} y_{i,j} p_{2,t} C_j F_{i,t} + \sum_{i \in \Delta_H} C_i p_{2,t} F_{i,t} \right) - \sum_{i \in \Delta_g} x_i Q_i W_i - \sum_{i \in \Delta_h} \sum_{j \leq m} y_{i,j} K_j - \sum_{j \in \Delta_L} z_j L_j$$

In the formula (1), $p_{1,t}, p_{2,t}$ represents the predicted electricity price and coal price in the year I, x_i is a 0-1 variable which represents the construction of the candidate wind power station, Q_i, Q_j represents the construction capacity of the candidate wind power plant i and the existing wind power plant j respectively, $H_{i,t}, H_{j,t}$ represents the annual utilization hours of the candidate wind power plant i and the existing wind power plant j in the year t, $y_{i,j}$ is a 0-1 variable indicating the construction situation of the candidate thermal power plant i with construction capacity C_j, C_i, C_j indicate the construction capacity of the candidate thermal power station i and the existing thermal power station j respectively. The optional capacity set of a thermal power plant is $\{0, C_1, C_2, \ldots \ldots, C_m\}$, When the construction capacity is 0, it means no construction. $F_{i,t}$ and $F_{j,t}$ indicate the annual utilization hours of the candidate thermal power plant i and the existing thermal power plant j in the year t. R_i and R_j represent the generation and operation cost per unit power of the candidate wind power plant i and the existing wind power plant j respectively, G_j and G_i represent the generation and operation cost per unit power of the candidate heat power plant i and the existing heat power plant j respectively, K_j indicates the candidate thermal power plant j which the construction cost of construction capacity C_j, W_i represents the construction cost per unit capacity of the candidate wind power station i, z_j represents the number of construction loops of the candidate line j, L_j represents the single circuit construction cost of the candidate line j, P_{total} is the gross profit. Δ_T is the sets of planning years, Δ_h, Δ_H indicate the sets of candidate of heat power station and existing heat power station, Δ_g, Δ_G indicate the sets of candidate of wind power station and existing wind power station.

The variables of scalar function are constrained by each index in planning, mainly including the following categories:

(1) Power demand constraint: the sum of total power generation of all units shall not be less than the demand of target annual power consumption.

$$\sum_{i \in \Delta_g} X_i Q_i H_{i,t} + \sum_{j \in \Delta_\zeta} Q_j H_{j,t} + \sum_{i \in \Delta_h} \sum_{j \leq m} y_{i,j} C_j F_{i,t} + \sum_{j \in \Delta_H} C_j F_{j,t} \geq E_t \qquad (2)$$

E_t indicates the annual electricity demand of year $t \in \Delta_T$.

(2) Restriction on number of new wind power plants:

$$\sum_{i \in \Delta_g} X_i \leq X_{W,max} \qquad (3)$$

$X_{W,max}$ is the maximum number of new wind farms.

(3) Restrictions on the number of new coal-fired power plants:

$$\sum_{i \in \Delta_b, 0 < j \leq m} y_{i,j} \leq X_{f,max} \qquad (4)$$

$X_{f,max}$ is the maximum number of new coal fires.

(4) Total power investment constraints:

$$\sum_{i \in \Delta_s} X_i Q_i W_i - \sum_{i \in \Delta_h} \sum_{j \leq m} y_{i,j} K_j \leq I_{max} \qquad (5)$$

I_{max} is the upper limit of total investment in power construction.

(5) Annual maximum load constraint: the total capacity of all units shall not be less than the annual actual maximum load on the premise of ensuring a certain reserve margin.

$$\sum_{i \in \Delta_s} X_i Q_i + \sum_{j \in \Delta_c} Q_j + \sum_{i \in \Delta_h} \sum_{j \leq m} y_{i,j} C_j + \sum_{j \in \Delta_{\tilde{p}}} C_j \geq (1 + \varepsilon) P_{max} \qquad (6)$$

ε is the reserve coefficient, P_{max} is the actual annual maximum load.

(6) Constraints on total investment of transmission lines:

$$\sum_{i \in \Delta_L} Z_i L_i \leq I_{1,max} \qquad (7)$$

$I_{1,max}$ is the upper limit of total line construction investment.

(7) Constraints on variable value of thermal power plant construction:

$$\sum_{j \leq m} y_{i,j} = 1, i \in \Delta_h \qquad (8)$$

(8) Constraints on the number of construction cycles of a single candidate line:

$$0 \leq z_j \leq n_{j,max} \tag{9}$$

$n_{j,max}$ is the maximum number of construction cycles of line j.

(9) Generator set output constraint:

$$\sum_{i \in \Delta_g} X_i Q_i W_i - \sum_{j \in \Delta_h} \sum_{j \leq m} y_{i,j} K_j \leq I_{max} \tag{10}$$

I_{max} is the upper limit of total investment in power construction.

The above constraints are related to the investment amount of power supply and power grid, the number of line construction, annual load and annual power consumption. The role of circuit power flow constraints in power planning can not be ignored. The following constraints are the optimal power flow calculation constraints at the time of maximum annual load.

(10) Node power balance constraint:

$$\Phi_{i,in} - \Phi_{i,r} = \sum_{j=1}^{N} S_{j,i}(\Theta_j - \Theta_i) \tag{11}$$

$\Phi_{i,in}$, $\Phi_{i,r}$ are the input power and demand load of nodes i, Θ_j, Θ_i are the phase angle of node j and i, $S_{j,i}$ is the admittance of lines between nodes j and i.

(11) Wind power plant output constraints:

$$\Phi_{W,i} \leq Q_i \tag{12}$$

$\Phi_{W,i}$ is the output of wind power station i.

(12) Output restriction of coal-fired power generator:

$$\Phi_{f,i} \leq C_i \tag{13}$$

$\Phi_{f,i}$ is the Output of coal-fired power generator

(13) Node phase angle constraint:

$$\Theta_{j,min} \leq \Theta_j \leq \Theta_{j,max} \tag{14}$$

$\Theta_{j,min}$ and $\Theta_{j,max}$ are the upper and lower limits of node j phase angle.

(14) Upper limit constraint of line power flow:

$$|S_{j,i}(\Theta_j - \Theta_i)| \leq \Phi_{i,j,max} \tag{15}$$

$\Phi_{i,j,max}$ is the upper limit of line transmission power between nodes i and j.

This is a deterministic model. In order to establish the planning model of the actual load conditions, the randomness of wind power generation and the price of electricity market need to be considered.

3. A method of handing uncertainty

3.1. Market uncertainty

The value of electric power is shown by electricity price. Correct prediction of future electricity price level can maximize the benefits of power planning, which has certain guiding significance for the planning of power system. Due to the characteristics of electricity, the price of electricity is affected by the factors of science and technology, national policy and so on. In this paper, the price model of geometric Brownian motion [9] can better describe the price volatility, which has some advantages over the traditional regression method.

$\mu(t)$ is the power price of year t, λ is the expected rate of return of year t, σ is the standard deviation of the rate of return when selling electricity in $\mu(t)$, λ and σ are constant. The expression of the change of electricity price with time is:

$$d\mu(t) = \lambda\mu(t)dt + \sigma\mu(t)dz(t) \tag{16}$$

$z(t)$ is the *standard* Brownian motion, $dz(t) = \omega\sqrt{dt}$, ω obey the normal distribution, μ_0 is the initial electricity price, and according to the formula (15), the electricity price of year t is:

$$\mu(t) = \mu_0 \exp\left(\left(\lambda - \frac{\sigma^2}{2}\right)t + \sigma z_t\right)$$
$$E(\mu(t)) = \mu_0 \exp(\lambda t) \tag{17}$$
$$\text{var}(\mu(t)) = \mu_0^2 \exp(2\lambda t)(\exp(\sigma^2 t) - 1)$$

λ and σ can be *estimated* from the historical price data.

$$\lambda = \frac{1}{\Delta t} E\left(\text{In}\ \frac{\mu_{t+\Delta t}}{\mu_t}\right)$$
$$\sigma^2 = \frac{1}{\Delta t} \text{var}\left(\text{In}\ \frac{\mu_{t+\Delta t}}{\mu_t}\right) \tag{18}$$

Δ_t is the discrete time interval of electricity history price data. The price of coal can be calculated in a similar way

3.2. Uncertainty of wind power output
Under the *background* of the increasing penetration of new energy mainly based on wind power, there are many uncertain factors that cannot be ignored in power system planning, such as the randomness of wind power output point, the fuzziness of annual utilization hours of wind farms, the uncertainty of electricity price in power market, etc. On the basis of considering the uncertainty of electricity price and coal price in the power market, the randomness of wind power output is further studied, and the random measure constraint of wind power generation is added to improve the model.

In the model, the maximum load constraint of the power grid is considered, that is, the sum of the total capacity of all kinds of units in the power grid is not less than the actual load demand plus the necessary reserve margin. However, the wind turbine output has random characteristics, which cannot guarantee that the wind turbine can provide the same load as its installed capacity at the corresponding time. Therefore, it is necessary to provide random variables for the output of wind turbine.

Let's *set P* as the random variable of wind turbine output, and then its probability density function can be expressed as follow:

$$f_P(X) = \begin{cases} F(V_{\text{out}}) - F(V_{\text{in}}), X = 0 \\ \frac{k}{k_1 C}\left(\frac{X-k_2}{k_1 C}\right)^{k-1}\exp\left(-\left(\frac{X-k_2}{k_1 C}\right)^k\right), 0 < X < P_{\text{rate}} \\ F(V_{\text{out}}) - F(V_{\text{rate}}), X = P_{\text{rate}} \end{cases} \tag{19}$$

Using this random *variable*, the constraint (5) can be improved as follows:

$$\Pr\left(\sum_{i\in\Delta_g} X_i P Q_i + \sum_{j\in\Delta_C} P Q_j + \sum_{i\in\Delta_h}\sum_{j\leq m} y_{i,j} C_j + \sum_{j\in\Delta_H} C_j \geq (1+\varepsilon) P_{max}\right) \geq \alpha \tag{20}$$

α is the *confidence* level.

At this point, the model which considers the uncertainty of power market and new energy is established. This model can be realized by programming software based on GANMS.

4. Example analysis
In order to illustrate the implementation method and feasibility of the network source collaborative planning model proposed in this paper, IEEE 30 [10] node system is selected in this section for verification.

Table 1. Candidate power pack information

Serial number	Position	Power type	Optional capacity /MW	Construction cost /10K	Operation cost/10K/ （MW*h）
1	3	Coal electricity	160 210 320	320 550 680	0.03 0.035 0.04
2	8	Wind Power	50 120	150 380	0.003 0.003
3	13	Coal electricity	150 250	300 550	0.03 0.035

			350	700	0.04
			300	650	0.04
4	27	Wind Power	60	160	0.003
			110	360	0.003

4.1. Parameter description

Table 2 shows the planning results for each scenario, and table 3 shows the investment costs and benefits for each scenario.

Table 2. The planning results for each scenario

Scenario	Power supply construction	Power grid construction
Scenario 1	Unit 1(160MW), Unit 2(120MW),	10-22(1),27-28(2), 13-16(2), 16-18(3),13-19(3),27-29(2)
Scenario 2	Unit 1(210MW), Unit 3(150MW), Unit 4(110MW)	1-2(1),2-5(2),4-6(1),4-12(3),7-8(1),10-22(2), 3-4(2),15-13(1) ,16-17(1)

Table 3. Investment costs and benefits for each scenario

Scenario	Gross profit /10K	Power construction cost/10K	Power grid construction cost/10K	Operation cost/10K	Total cost/10K
1	3100	900	1300	1100	3300
2	3600	1250	350	1200	2800

The comparison of three scenarios further proves the significance of network source collaborative planning. Scenario 1 carries out power planning. Wind turbines are widely used in the planning due to their environmental protection characteristics, but the subsequent power grid planning requires a large power grid construction cost. The power grid construction cost of scenario 2 is far lower than scenario 1, and the comprehensive income of scenario 2 is better than scenario 1. One of the reasons for the high cost of power grid construction in scenario 1 is the weak transmission line of the node where the planned wind power plant is located. This shows that wind power has the advantage of operating costs, but the total profit of this scenario is still the lowest. In the power planning of scenario 2, the constraint of determining the new installed capacity is modified. The number of new units in the planning result is more than that of scenario 1, and the cost of power construction is also higher.

5. Summary

In this paper, the power system planning model and method for large-scale grid connection of new energy *generation* and power market are studied. This paper proposes a network source collaborative planning model considering the uncertainty of new energy and power market. Combined with the actual situation of Shanxi electric power, the model considers the construction of coal-fired thermal power generation unit, wind power generation unit and transmission line as a whole, which can realize the optimization of resources and the maximization of total revenue from a global perspective. At the same time, the model puts forward a method to deal with uncertainty from two aspects: the uncertainty brought by wind power to power system and the uncertainty of power market. The example shows that the network source collaborative planning model proposed in this paper can ensure the coordination and matching of power unit construction and power line construction, and make the optimal scheme from the overall perspective to maximize the benefit of network source construction.

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