Two-tier power planning considering capacity tariff compensation

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Abstract. Faced with a high proportion of new energy power systems in the future, thermal power units will become the main peaking power source, and the reasonable recovery of their capacity value will become a focus of attention. To plan the power supply structure while considering the capacity tariff of thermal units and support the development of low-carbon energy, this paper proposes a two-tier power supply planning model that coordinates the scenery-to-fire ratio with the capacity tariff and proposes a capacity compensation mechanism for thermal units based on the effective capacity. With the gradually increasing ratio of scenery to fire, the capacity tariff compensation for thermal power units will be on the rise, providing a reference for the coordinated development of power supply planning and power market under the high proportion of new energy.

Keywords- Power supply planning; capacity compensation; scenery-to-fire ratio.

1. Introduction

Driven by the low-carbon energy strategy, the share of renewable energy will gradually increase, and the randomness of its output makes the safe and stable operation of the power system challenging. The role of thermal power generation units, which are currently the most economical resource for frequency regulation and peaking due to their high stability and flexibility, will gradually transform from a power generation source to a regulating source. In the process of this transformation, the tariff mechanism for thermal power will also be improved to ensure the sustainable development of thermal power enterprises and to reflect their efficiency value. How to plan the power supply structure while considering the capacity tariff of thermal power units is important to support the development of low-carbon energy and ensure the safety and stability of the energy system.

With the changing role of thermal power, the single electricity market can only guarantee the recovery of marginal operating costs of thermal power units and cannot reflect the capacity value of thermal power units as a regulating power source. To ensure the long-term capacity adequacy of the power system and to provide an effective signal for investment in power generation, the adoption of a reasonable capacity compensation mechanism will be the way forward.

Capacity compensation mechanisms decouple capacity cost recovery from generation operation [5], locking in a portion of the revenue for unit investment in advance. The literature [6-8] systematically introduces and compares the existing capacity compensation mechanisms in foreign countries, mainly the scarcity tariff mechanism, capacity subsidy mechanism and capacity market mechanism, and argues the necessity of capacity compensation mechanism. The above studies all focus on the design of market mechanisms and do not consider the impact of capacity compensation mechanisms on the power supply structure or the timing of the introduction of capacity tariffs.

In summary, this paper proposes a method of power planning that coordinates the capacity tariff with the scenery-to-fire ratio for a period of rapid power structure change. Firstly, a capacity compensation mechanism for thermal power units based on effective capacity is proposed; a two-tier power planning model with a coordinated scenery-fire power supply and capacity tariff is established. The model is validated by simulation and the relationship between ratios and capacity tariffs is explored to provide a reference for the coordinated development of power planning and power market under the high ratio of new energy.

2. Design of Capacity Compensation Mechanisms

the capacity compensation mechanism in this paper is developed and mainly applied to thermal power units. By accounting for the capacity tariff and the compensation capacity of thermal power units, the recovery of

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generation capacity costs of thermal power units is achieved.

1) Capacity tariff

This paper mainly considers the investment cost depreciation charge of thermal power units as the basis for accounting for the capacity tariff and considers a certain rate of return on investment Q_i, and the unit capacity tariff λ_i^{cap} obtained is a floating range, the maximum value of which is affected by the return on investment and the unit investment cost.

$$Q_i = K_i^{\text{inv}} \frac{\sigma(1+\sigma)^{N^i}}{(1+\sigma)^{N^i}-1}$$

$$0 \le \lambda_i^{\text{cap}} \le (1+\eta_{\max})Q_i$$

Where: K_i^{inv} is the unit capacity investment cost of thermal power unit *i*; σ is the discount rate, generally 7%; N^i is the service life of the unit, generally 30 years; $\eta_{\max}$ is the maximum return on investment.

2) Compensation capacity

The compensation capacity in the capacity compensation mechanism of this paper is calculated based on the unit availability and the number of years in operation. The unit availability factor is calculated by first considering the unit fuel availability rate, plant power consumption rate, maintenance time share and forced outage rate. In addition, as the depreciation cost of units with different years of operation varies greatly, the product of the installed capacity of the unit and the availability factor and the year of operation correction factor is taken as the compensable capacity C_i^{com} of each unit.

$$C_i^{\text{com}} = C_i^{\text{g}} F_{1,i}(1-F_{2,i})(1-F_{3,i})(1-\varepsilon_i)F_{4,i}$$

where: C_i^{g} is the installed capacity of thermal unit *i*; $F_{1,i}$ is the fuel availability rate of thermal unit *i*; $F_{2,i}$ is a penalty factor proportional to the plant electricity consumption of thermal unit *i*; $F_{3,i}$ is a penalty factor proportional to the annual maintenance and repair time of thermal unit *i*; ε_i is the equivalent forced outage rate of unit *i*; $F_{4,i}$ is the correction factor of the commissioning life of thermal unit *i*. New units are taken as 1 and old units are converted according to the commissioning life.

3) Settlement method

The capacity compensation fee is collected from the customer side and settled monthly. The total revenue of a thermal power unit is equal to the sum of its electricity revenue and capacity revenue. The capacity compensation revenue received by thermal unit *i* is f_i^{cap}:

$$f_i^{\text{cap}} = \lambda_i^{\text{cap}} C_i^{\text{com}}$$

3. Two-tier model for power planning

3.1 Upper tier investment planning model

3.1.1 Objective function

The upper tier power investment planning model aims at the lowest annual total cost at the planning level, which includes the investment cost of new units, the annual fixed maintenance cost of units, the annual operating cost of the system and the capacity compensation cost. The objective function can be specifically expressed as:

$$\min F_1 = f^{\text{inv}} + f^{\text{fix}} + f^{\text{ope}} + f^{\text{cap}}$$

$$f^{\text{inv}} = \left(\sum_{i\in\Phi^{\text{g,new}}} K_i^{\text{inv}} C_i^{\text{g}} \alpha_i + \sum_{j\in\Phi^{\text{w,new}}} K_j^{\text{inv}} C_j^{\text{w}} \alpha_j + \sum_{k\in\Phi^{\text{pv,new}}} K_k^{\text{inv}} C_k^{\text{pv}} \alpha_k \right) \frac{\sigma(1+\sigma)^{N^{i,j,k}}}{(1+\sigma)^{N^{i,j,k}}-1}$$

$$f^{\text{fix}} = \sum_{i\in\Phi^{\text{g}}} K_i^{\text{fix}} C_i^{\text{g}} \alpha_i + \sum_{j\in\Phi^{\text{w}}} K_j^{\text{fix}} C_j^{\text{w}} \alpha_j + \sum_{k\in\Phi^{\text{pv}}} K_k^{\text{fix}} C_k^{\text{pv}} \alpha_k$$

$$f^{\text{ope}} = \sum_{s=1}^{S} f_s^{\text{ope}} \theta_s$$

$$f^{\text{cap}} = \sum_{i\in\Phi^{\text{g}}} \alpha_i \lambda_i^{\text{cap}} C_i^{\text{com}}$$

Where: $\Phi^{\text{g,new}}$, $\Phi^{\text{w,new}}$, $\Phi^{\text{pv,new}}$ denotes the set of new thermal wind power and photovoltaic units, respectively, and $\Phi^{\text{g,old}}$ denotes the set of existing thermal power units; K_i^{inv}, K_j^{inv}, K_k^{inv} denotes the investment cost per unit capacity of new thermal power unit *i*, wind power unit *j* and photovoltaic unit *k*, respectively; C_i^{g}, C_j^{w}, C_k^{pv} denotes the capacity of thermal power unit *i*, wind power unit *j* and photovoltaic unit *k*; $N^{i,j,k}$ denotes the service life of the units; $\alpha_{i,j,k}$ is a 0-1 variable, denoting the commissioning status of thermal power unit *i* and wind power unit *j* and photovoltaic unit *k*.

3.1.2 Constraints

1) Constraint on the size of installed capacity

$$\sum_{i\in\Phi^{\text{g}}} \alpha_i C_i^{\text{g}} \le C^{\text{g,max}}$$

$$\sum_{i\in\Phi^{\text{w}}} \alpha_j C_j^{\text{w}} \le C^{\text{w,max}}$$

$$\sum_{i\in\Phi^{\text{pv}}} \alpha_k C_k^{\text{pv}} \le C^{\text{pv,max}}$$

where: $C^{\text{g,max}}$, $C^{\text{w,max}}$, $C^{\text{pv,max}}$ represent the maximum installed capacity of thermal, wind and photovoltaic units, respectively.

2) Unit annual profit constraint

$$\begin{aligned}N_i &=\left(f_i^{\mathrm{buy}}+f_i^{\mathrm{cap}}\right)-\left(f_i^{\mathrm{inv}}+f_i^{\mathrm{fix}}+f_i^{\mathrm{g}}+f_i^{\mathrm{car}}\right)\\ &=\lambda^{\mathrm{g}}\sum_{s=1}^{S}\theta_s\sum_{t=1}^{T}\sum_{i\in\Phi^{\mathrm{g}}}P_{i,s,t}+\sum_{i\in\Phi^{\mathrm{g}}}\alpha_i\lambda_i^{\mathrm{cap}}C_i^{\mathrm{com}}-\sum_{i\in\Phi^{\mathrm{g,new}}}K_i^{\mathrm{inv}}C_i^{\mathrm{g}}\alpha_i\\ &\quad-\sum_{i\in\Phi^{\mathrm{g}}}K_i^{\mathrm{fix}}C_i^{\mathrm{g}}\alpha_i-\sum_{s=1}^{S}\theta_s\left(f_s^{\mathrm{g}}+f_s^{\mathrm{car}}\right)\geq 0\end{aligned}$$

$$\begin{aligned}N_{j,k}&=f_j^{\mathrm{buy}}-\left(f_j^{\mathrm{inv}}+f_j^{\mathrm{fix}}+f_j^{\mathrm{ren}}\right)\\ &=\lambda^{\mathrm{w}}\sum_{s=1}^{S}\theta_s\sum_{t=1}^{T}\sum_{i\in\Phi^{\mathrm{w}}}P_{j,s,t}-\sum_{j\in\Phi^{\mathrm{w,new}}}K_j^{\mathrm{inv}}C_j^{\mathrm{w}}\alpha_j\\ &\quad-\sum_{j\in\Phi^{\mathrm{w}}}K_j^{\mathrm{fix}}C_j^{\mathrm{w}}\alpha_j-\sum_{s=1}^{S}\theta_s\sum_{t=1}^{T}\sum_{j\in\Phi^{\mathrm{w}}}\rho^{\mathrm{pun}}\left(P_{j,s,t}^{\mathrm{f}}-P_{j,s,t}\right)\geq 0\end{aligned}$$

Where: $N_{i,j,k}$ denotes the net profit of thermal unit *i*, wind turbine *j* and photovoltaic unit *k* in the equivalent level year. λ^{g} , λ^{w} , λ^{pv} denote the feed-in tariffs of thermal power unit, wind power unit and photovoltaic unit, respectively.

In addition to the installed capacity constraint and the annual profit constraint, the upper-level model constraints also include the capacity tariff constraint, the carbon emission constraint, and the renewable energy quota constraint.

3.2 Lower-level optimization operation model

3.2.1 Objective function

The lower level optimization model uses the lowest daily operating cost as the objective function to optimize the output and start/stop of each unit. The daily operating costs include thermal unit operating costs, renewable energy abandonment penalty costs and carbon emission costs, and the decision variables are the generation capacity of each unit during a typical day. The objective function can be expressed as follows:

$$\min F_2=f^{\mathrm{g}}+f^{\mathrm{ren}}+f^{\mathrm{car}}+f^{\mathrm{cap}}$$

$$f^{\mathrm{g}}=\sum_{t=1}^{T}\left(\sum_{i\in\Phi^{\mathrm{g}}}u_{i,t}g_i\left(P_{i,t}\right)+\sum_{i\in\Phi^{\mathrm{g}}}u_{i,t}\left(1-u_{i,t-1}\right)S_i^{\mathrm{g}}\right)$$

$$g_i\left(P_{i,t}\right)=a_iP_{i,t}^2+b_iP_{i,t}+c_i$$

$$f^{\mathrm{ren}}=\sum_{t=1}^{T}\rho^{\mathrm{pun}}\left[\sum_{j\in\Phi^{\mathrm{w}}}\left(P_{j,t}^{\mathrm{f}}-P_{j,t}\right)+\sum_{k\in\Phi^{\mathrm{pv}}}\left(P_{k,t}^{\mathrm{f}}-P_{k,t}\right)\right]$$

$$f^{\mathrm{car}}=\sum_{t=1}^{T}\sum_{i\in\Phi^{\mathrm{g}}}\gamma^{\mathrm{car}}e_iP_{i,t}$$

Where: *t* denotes each operating period in a typical day; $g_i\left(P_{i,t}\right)$ denotes the generation cost function of thermal units, a_i , b_i , c_i denotes the generation cost coefficient of thermal unit *i*; $u_{i,t}$ denotes the start-up and shutdown of thermal unit *i* in time period t; S_i^{g} denotes the start-up and shutdown cost of thermal unit i; ρ^{pun} denotes the unit penalty cost of renewable energy abandonment; $P_{j,t}^{\mathrm{f}}$, $P_{k,t}^{\mathrm{f}}$ denotes the projected output of wind turbine *j* and photovoltaic unit *k* in time period *t*, respectively.

3.2.2 Constraint

1) Power balance constraint

$$\sum_{i\in\Phi^{\mathrm{g}}}P_{i,t}+\sum_{j\in\Phi^{\mathrm{w}}}P_{j,t}+\sum_{k\in\Phi^{\mathrm{pv}}}P_{k,t}=P_t^d$$

where: P_t^d denotes the amount of load in period *t.*

2) Operating constraints for all types of units

$$u_{i,t}\alpha_iP_i^{\mathrm{g,min}}\leq P_{i,t}\leq u_{i,t}\alpha_iP_i^{\mathrm{g,max}}$$

$$0\leq P_{j,t}\leq\alpha_jP_{j,t}^{\mathrm{f}}$$

$$0\leq P_{k,t}\leq\alpha_kP_{k,t}^{\mathrm{f}}$$

where: $P_i^{\mathrm{g,min}}$, $P_i^{\mathrm{g,max}}$ represent the minimum and maximum output coefficients of thermal power unit i, respectively.

4. Case Analysis

In this paper, the regional power supply structure data of a region is used as the initial value of the planning model. The existing thermal power units in the region are 900 MW, wind power units are 100 MW and photovoltaic units are 100 MW. the maximum load of the system in the planning level year is 2000 MW, where the thermal power units to be built have good flexibility and their minimum output is 0.3 of the rated capacity.

To study the impact of wind-fire power ratio on capacity compensation price, the change of wind-fire ratio was achieved by controlling the number of different units to be built in the simulation. The scenery-to-fire ratio is divided into three periods, namely the early stage of new energy development, the period of normal new energy development and the period of high proportion of new energy. The capacity compensation prices for different ratios of thermal units are shown in Table 1.

Table 1. Wind, light and fire ratios, and corresponding capacity compensation prices

	Wind, light and fire ratios	Average capacity compensation price Yuan/(kW·month)		Average power generation capacity MW·h/unit	
		New	Original	New	Original
The early stage of new energy development	1:3.5	17.42	0	12.37×10^5	2.291×10^6
	1:3	18.22	0.26	9.365×10^5	2.286×10^6
New Energy Normal Development Period	1:1.6	18.84	0.64	9.042×10^5	2.244×10^6
	1:1.38	20.66	2.63	7.288×10^5	2.226×10^6
High percentage of new energy period	1:0.68	23.68	3.28	4.727×10^5	2.048×10^6
	1:0.63	24.78	3.55	3.790×10^5	2.025×10^6

As can be seen from the table, at the early stage of new energy development, the system is more stable, and most of the electricity is provided by thermal units, which can obtain stable income in the electricity market, and therefore the capacity compensation cost required is smaller and some of the original older units do not require capacity compensation. With the increase in the proportion of new energy installations, the capacity compensation cost for both new and existing units has increased to a certain extent due to the increased proportion of new energy bringing more volatility and uncertainty to the system. To reduce wind and light abandonment, thermal units must reduce their output to ensure system balance and are unable to obtain sufficient power yield, and all units require some capacity compensation. With the continuous promotion of the double carbon target, the future will usher in a period of large-scale development of new energy sources, and the proportion of new energy installations will exceed that of thermal power units. More and more thermal units will be transformed into peaking power sources, generating much less electricity, and requiring much higher capacity compensation prices. In a comprehensive analysis, as the ratio of wind to fire continues to increase, the generation capacity of thermal units will be on a downward trend and the capacity compensation price for thermal units will be on an upward trend.

5. Conclusion

To adapt to the survival pressure brought by large-scale scenery access to thermal power units under the vision of high proportion of renewable energy development, this paper establishes a power planning model that reconciles scenery-to-fire ratios with capacity tariffs. Based on the above calculation results, it shows that: as the scenery-to-fire ratios continue to increase, the demand for capacity compensation tariffs for thermal power units will increase.

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