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AN ALTERNATIVE OPTIMISATION MODEL FOR RESERVE CAPACITY OF POWER SYSTEM CONSIDERING COORDINATIVE AGGREGATION OF LARGE-SCALE RENEWABLE ENERGY

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Abstract

In the new energy environment, the uncertainty of load demand and new energy power generation has put forward higher requirements for reserve capacity, and the collaborative aggregation of new energy and reserve alternation are increasingly receiving attention. The idea of this article is to alternate coal-fired generators with photovoltaic power generation systems and collaborate with other types of power generation units to achieve optimal alternation of reserve capacity in the power system. Using the expected energy not supplied (EENS) and operating cost to construct a comprehensive alternative benefit evaluation index, and taking its minimum value as the objective function, an optimisation model for the alternation of reserve capacity in the power system is constructed. The piecewise linear theory is used to linearise the objective function with quadratic characteristics, and the branch and bound algorithm is used to solve the nonlinear integer programming problem constructed in this paper. Taking the IEEE-30 system as a simulation example, the calculation results show that alternating coal-fired generators with photovoltaic power generation systems in reserve services can increase comprehensive alternation benefits and reduce reserve capacity.

Key Words

Power systems, reserve capacity, coordinative aggregation of renewable energy, optimisation alternation, the expected energy not supplied, nonlinear integer programming

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1. Introduction

In the new energy environment, the share of photovoltaic power generation and wind power is constantly increasing, and coal-fired generators are gradually withdrawing. The emergence of new features and structural changes in new power systems have made the demand for fast reserve services increasingly urgent. The uncertainties of load demand and new energy generation increase the difficulty and complexity of reserve assessment and configuration in new power systems, and also put forward higher requirements for reserve capacity. The output power of a single photovoltaic power generation system and a wind power plant is relatively small, but their aggregation increases the power capacity and has an impact on the operation and control of the power system. With the increasing scale of new energy capacity, the collaborative aggregation and reserve alternation of new energy are receiving increasing attention [1]–[19].

Many scholars have carried out fruitful research work and achieved gratifying results. For example, using the sequence operation method to describe the uncertainties of the output power of photovoltaic power generation system and wind-driven generators, a unit commitment model integrating economy and reliability is established; Taking the minimum generation cost and outage loss as the objective function and combined with relevant constraints, an optimal allocation method of reserve capacity based on DPSO-BCC algorithm is proposed [20]; Considering the participation of generators and interruptible loads in reserving operation, the reserve capacity is optimised by using stochastic genetic algorithm [21]; Based on the traditional reliability indicators, three indicators are proposed to evaluate the reserve capacity [20, 21].

As a traditional source of reserve capacity, traditional generators have always played an important role in the reliable operation of power system. With the proposal of “double carbon goal” [22], energy conservation and emission reduction, low-carbon transformation of energy and development of green energy have become the consensus of global energy development [23]. Many governments attach great importance to the development and utilisation of renewable energy. According to the statistics of the National Energy Administration, by the first half of 2021, the total installed capacity of photovoltaic power generation system in China has reached 268 million kW [24]. With the continuous expansion of the installed capacity of renewable energy, the aggregate power of power generation system using renewable energy is large. Due to the demand for reducing carbon emissions and limitations on the speed and capacity of traditional generators, there has been a trend for generators with renewable energy to alternate traditional generators as reserving sources. However, there is little research in this regard, especially the research on the alternation benefits of installed capacity of generators with renewable energy and the impact of new energy as reserving sources on the system. It is feasible and applicable for generators with renewable energy to alternate traditional generators to participate in reserving operation and has attracted more and more attention. However, the research in this field has been paid more and more attention, but there are few relevant studies and few results.

This article considers the significant demand for fast reserve in new power systems, the ability and mode of photovoltaic power generation systems to participate in reserve services under the uncertainties of load demand and new energy generation, and studies the optimisation problem of renewable energy generation systems aggregation and alternating coal-fired generators to participate in reserve services. On the basis of considering the aggregation of renewable energy, an optimisation model for the alternative configuration of reserve capacity in the power system is established, and the feasibility and technical effectiveness of photovoltaic power generation alternating coal-fired generators in reserve services are analysed.

2. Allocation Method for Reserve Capacity

The reserve capacity value of the coal-fired generator is determined according to the following formula [25]:

$$P_{\mathrm{TR}} = \max[\sum_{c=1}^{N_T} k_{TR1c}(P_{\mathrm{TN}c} - p_{Tc}P_{Tc}) \tag{1}$$

where k_{TR1c} represents the state variable of rotating reserve of coal-fired generator c, k_{TR1c}= 1 when it operates with an online reserve capacity, and k_{TR1c}= 0 when it operates without an online reserve capacity; $P_{\mathrm{TN}c}$ is the installed capacity of coal-fired generator c; p_{Tc} is the probability that the output power of coal-fired generator is greater than or equal to the rated power P_{Tc}.

According to the comparison value of response speed, installed capacity, operation failure rate and reserve benefit, the reserve capacity of the pumped storage generator, energy storage system, gas-driven generator, wind-driven generator and hydropower generator is determined successively from the remaining reserve capacity demand value of the whole power grid. The unified calculation formula is given as follows:

$$P_{\mathrm{xR}} = \min[\sum_{c=1}^{N_x} k_{xR1c}(P_{\mathrm{xN}c} - p_{xc}P_{xc}) \tag{2}$$

where x may refer to S, SEG, G, W and H, which, respectively, refer to the pumped storage generator, energy storage system, gas-driven generator, wind-driven generator and hydropower generator; and P_{yR} is the allocated reserve capacity.

3. Optimisation Model of Reserve Alternation

3.1 Evaluation Indicator of Alternation Benefit

Alternation means that the status of the new things alternates the status of the original things because of their own advantages in some aspects, and plays the same function as the original things. Considering the reliability and economy of system operation, and the evaluation indicator of reserve alternation benefit is determined [21]:

$$Z = \omega \frac{P_{\mathrm{EENS}}}{P_{EENS,o}} + (1-\omega)\frac{\frac{P_R}{P_{\max}}}{\alpha} \tag{3}$$

where Z is the evaluation indicator of reserve alternation benefit, the smaller the Z value, the better the comprehensive benefit; w is the weight factor of the ratio of reliability and economy. The greater the w value, the more emphasis on reliability, and the smaller the ω value, the more emphasis on economy; $E_{\mathrm{EENS},o}$ is the reference value of EENS indicator; according to the Technical Guidelines for Electric Power System (Trial)(SD131-84), α is the proportion of reserve capacity, usually 10% $\sim$ 20%; and $P_{\max}$ is the maximum load power.

3.2 Objective Functions

Considering that the photovoltaic power generation system alternates the traditional generator as the reserving power for supply sources, the total coal consumption for power generation and outage loss of the power system will be improved in theory. Taking the minimisation of the evaluation indicator of reserve alternation benefit as an objective function, considering the aggregation of photovoltaic power generation systems and alternating traditional generators to participate in reserving operation, an optimisation model of reserve capacity alternation of power system is constructed:

$$\begin{aligned} \min E &= \min(\Delta E_C) \\ &= \min \sum_{t=1}^{T} \left\{ \sum_{i=1}^{N} (a_i P_{T,i,t}^2 + b_i P_{T,,i,t} + c_i) \right. \\ &\quad \left. + \kappa(\mathrm{EENS}_{1,t} - EENS_{0,t}) \right\} \end{aligned} \tag{4}$$

where ΔE_C is the reserve alternation benefit.

The economic indicator of alternative benefits is:

$$\Delta E_C = \Delta E_{R,t} + \Delta E_S \tag{5}$$

where $\Delta E_{R,t}$ refers to the coal consumption cost of power generation provided by the traditional generator for the part of capacity where the photovoltaic power generation system alternates the traditional generators; ΔE_S represents the change of outage loss of photovoltaic power generation system alternating the traditional generators.

For the photovoltaic power generation systems alternating the traditional generators with the same capacity, if it is considered that the capacity of the photovoltaic power generation systems alternating the traditional generators is provided by the traditional generators, the coal consumption cost of the traditional generators in the t-th time period [25]–[31] may be expressed as:

$$\Delta E_{R,t} = \sum_{i=1}^{N} (a_i P_{T,i,t}^2 + b_i P_{T,,i,t} + c_i) \tag{6}$$

where a_i is the quadratic term coefficient $(\$/(MW)^2 \cdot h)$ of the coal consumption cost function of the traditional generator; b_i is the first-order term coefficient $(\$/MW \cdot h)$ of coal consumption cost function of the traditional generator; c_i is the constant term $(\$/h)$ of the coal consumption cost function of generating power of traditional generators; $P_{T,i,t}$ represents the output power of traditional generator in t-th time period; and N represents the number of traditional generators.

The changing value of the EENS indicator before and after alternation [24]:

$$\Delta E_S = \kappa(\mathrm{EEN}S_{1,t} - EENS_{0,t}) \tag{7}$$

where κ represents the penalty cost coefficient for load loss per unit power (kWh); $\mathrm{EEN}S_1$ and $\mathrm{EEN}S_0$, respectively, represent the EENS value before and after alternating the reserving operation of the traditional generator with the photovoltaic power generation system in the t-th time period. The mathematical expression [25] characterising the EENS value is formulated:

$$\mathrm{EEN}S_i = T \int_{C_t}^{C_t + x_{\max}} f(x)\mathrm{dx} \tag{8}$$

where i is a binary symbol of 0-1, $i = 1$ represents the alternative state, otherwise, it is a non alternative state; C_t is the total installed capacity of the power system; $x_{\max}$ is the maximum load power; $f(x)$ is the equivalent continuous load function, which is often used to describe the load curve; T indicates the operating period.

3.3 Constraint Conditions

1) Power balance constraint

The power balance may be expressed by the following formula:

$$\begin{aligned}
&\sum_{j=1}^{N_T} P_{T,j,t} + \sum_{i=1}^{N_{\mathrm{PV}}} P_{PV,i,t} + \sum_{i=1}^{N_H} P_{H,i,t} + \sum_{j=1}^{N_N} P_{N,j,t} \\
&+ \sum_{i=1}^{N_G} P_{G,i,t} + \sum_{i=1}^{N_W} P_{W,i,t} + \sum_{j=1}^{N_N} \Delta R_{T,j,t} + \sum_{i=1}^{N_{\mathrm{PV}}} \Delta R_{PV,i,t} \\
&+ \sum_{i=1}^{N_H} \Delta R_{H,i,t} + \sum_{i=1}^{N_W} \Delta R_{W,i,t} + \sum_{i=1}^{N_G} \Delta R_{G,i,t} \\
&= P_{L,t} + \Delta P_{L,t}
\end{aligned} \tag{9}$$

where $P_{T,j,t}$ represents the output power of the j-th traditional generator not alternated at the t-th time period; $\Delta R_{T,j,t}$ is the increase value of reserve capacity of traditional generator, $\Delta R_{H,j,t}$ is the increase value of reserve capacity of hydropower generator, $\Delta R_{N,j,t}$ is the increase value of reserve capacity of nuclear energy driven generator, $\Delta R_{G,j,t}$ is the increase value of reserve capacity of gas-fired generator, $\Delta R_{PV,j,t}$ is the increase value of reserve capacity of photovoltaic power generation system, and $\Delta R_{W,j,t}$ is the increase value of reserve capacity of wind-driven generator. $P_{L,t}$ represents the active power of the load power; N_T, N_H, N_N, N_G, N_{PV}, and N_W are the number of coal-fired generator, hydropower generator, nuclear energy-driven generator, gas-fired generator, photovoltaic power generation system and wind-driven generator, respectively.

2) Reserve capacity constraint

The output power of each type of generator shall be greater than the required reserve capacity:

$$P_{\mathrm{TR}} + P_{\mathrm{xR}} \geq P_R \tag{10}$$

where P_{TR} is the allocated reserve capacity of traditional generator; P_R is the reserve capacity required by the system.

3) Output power constraint of the generators

The output power of coal-fired generator and photovoltaic power generation system shall be less than its allowable maximum value and greater than the allowable minimum value:

$$P_{\mathrm{PV},i}^{\min} \leq P_{PV,i,t} \leq P_{\mathrm{PV},i}^{\max} \tag{11}$$

$$P_{T,j}^{\min} \leq P_{T,j,t} \leq P_{T,j}^{\max} \tag{12}$$

where $P_{PV,i}^{\min}$ and $P_{PV,i}^{\max}$, respectively, represent the minimum and maximum output power of the i-th photovoltaic power generation system; $P_{T,j}^{\min}$ and $P_{T,j}^{\max}$, respectively, represent the minimum and maximum output power of the i-th coal-fired generator.

4. Study Case

IEEE-118 system is taken as an study example, as shown in Table 1.

Figure 1(a) shows the daily aggregate power curve of photovoltaic power station group, which is the aggregate power of the photovoltaic power station group considering the aggregation characteristics [31], [32]. Figure 1(b) shows the daily load power curve. In the example, the real-time load power is taken from the daily load power curve.

Table 1
The Data in IEEE-30 System

Generator	P_{max}/p.u.	P_{min}/p.u.	a/\$/$(MW)^2 \ldots h$	b/\$/$MW \ldots h$	c/\$/h
1	1.2	0.4	0.152	38.54	786.80
2	1	0.25	0.106	46.16	945.63
3	0.6	0.15	0.028	40.40	1050.00
4	0.6	0.2	0.035	38.31	1243.53
5	0.3	0.1	0.021	36.33	1658.57
6	0.3	0.1	0.018	38.27	1356.66

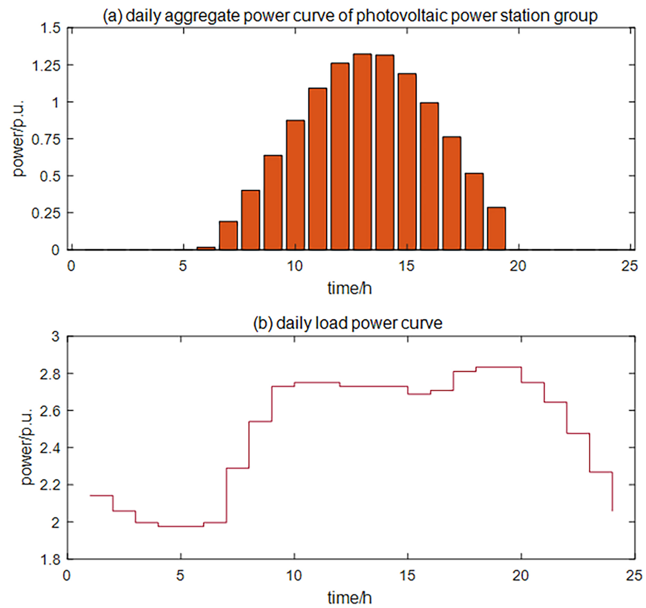

Figure 1. Daily aggregate power curve of photovoltaic power station group and load power curve.

Table 2
Optimisation Results for Different Scenarios

Scenario	P_R/p.u.	E/\$	P_{EENS}/p.u.	Z
Without PV	2.0249	171638.7084	0.1417	2.8540
With PV	2.5940	171196.5353	0.1400	3.5177

In simulation, the failure probability of all generators at different output power is set as $p_{\mathrm{GF}} = 0.02$, the number of linear segments is set as $m = 4$ and the weight factor as $w = 0.5$; The reference value of EENS indicator is set as $P_{\mathrm{EENS},o} = 0.15$; The reserve arrangement rate α is taken as 15%; The maximum load value is $P_{\max} = 2.834$.

When only six traditional generator supply power to IEEE-30 system, according to the alternative reserve optimisation problem established in Section 3.2, the following may be solved: total reserve demand $P_R = 2.0249$, economic benefit $E = 171638.7084$ and the EENS value $E_{\mathrm{EENS}} = 0.1417$, as shown in Table 2. According to (11), the comprehensive benefit evaluation indicator of reserve alternation may be calculated: $Z = 2.8540$. When the photovoltaic power generation system is a part of the system power supply, the energy supply percentage of traditional generator decreases. In the case of combined power supply of photovoltaic power generation systems and traditional generators, the reserve capacity of the system is $P_R = 2.5940$, which is 0.5691 more than that in the case without photovoltaic power generation systems providing reserving power; The EENS value is $E_{\mathrm{EENS}} = 0.1400$, which is slightly lower than that in the scenario without reserve power provided by photovoltaic power generation systems; The change value of coal cost and power shortage penalty cost is not obvious; Due to the increase of total reserve power, the comprehensive benefit evaluation indicator Z of reserve alternation increased from 2.8540 to 3.5177, which shows that the photovoltaic power generation system as an additional reserve power source supplies power to the system, and its comprehensive benefit is poor.

Table 3
The Optimisation Results

Alternating generator	P_R/p.u.	E/\$	P_{EENS}/p.u.	Z
6	2.2940	138654.247	0.1460	3.185
5	2.2940	131422.357	0.1460	3.185
4	1.9940	141388.975	0.1520	2.852
3	1.9940	146019.623	0.1520	2.852
2	1.5940	148504.394	0.1600	2.408
1	1.3940	152407.495	0.1640	2.186

From the perspective of economic benefits of reserve alternation, no matter how many capacity of the traditional generator is alternated by the photovoltaic power generation system, its value will decrease significantly, the maximum decrease may reach 40216.352\$, and the average decrease reaches 28572.527\$, as shown in Table 3.

5. Conclusions

Alternating the reserve service of coal-fired generators with photovoltaic power generation systems can reduce the comprehensive alternation efficiency and reserve capacity. Constructing an optimisation model for the alternation of reserve capacity in the power system can minimise the evaluation index values of comprehensive alternation benefits, which means minimising economic alternation benefits, minimising coal consumption costs for thermal power generation, and minimising changes in power outage losses.

In the scenario of "photovoltaic power generation system thermal power unit joint power supply," the power supply power of a single photovoltaic power generation system is small, and its impact can be ignored; After aggregation, the power supply of the photovoltaic power generation system is high, which can be used as an additional power source to participate in power supply services, which is beneficial for reducing the EENS value. However, the performance of other benefit indicators is not satisfactory.

In the scenario of "photovoltaic power generation system alternating coal-fired generators with different capacities," the higher the output power of the coal-fired generators alternated by photovoltaic power generation system, the smaller the value $Z$of comprehensive benefit evaluation index, and the better the comprehensive benefit; The impact of alternating coal-fired generators with photovoltaic power generation systems on the total reserve capacity is determined by the capacity of the alternated coal-fired generators. The larger the capacity, the greater the reduction in total reserve capacity required. In the example simulation calculation, the overall alternation efficiency of the photovoltaic power generation system alternating Unit 3 is the best, with a decrease in P_R, E, and Z value. The expected increase in low battery level is within the system's tolerance range.

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