Capacity Coordination Planning Model of wind solar storage hybrid power system

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Abstract. Based on the daily and monthly characteristics of wind power and photovoltaic output, the wind power / photovoltaic sequence model based on the daily and monthly characteristics is constructed. Considering the generation constraints, energy storage constraints, system power balance constraints and renewable energy consumption rate constraints of each unit, the coordinated optimization planning model of wind photovoltaic storage complementary power system capacity is constructed to determine the different renewable energy consumption rate fields The optimal capacity of wind power, photovoltaic and energy storage. The results show that the optimal installed capacity of wind power, photovoltaic power and energy storage is different under different scenarios of renewable energy consumption rate and tie line utilization rate, but the impact of energy storage capacity is small.

1. Introduction
With the continuous growth of energy consumption and the emergence of global problems such as resource shortage, environmental pollution and climate change, the mismatch of power supply and demand and the uncertainty of renewable energy output have led to the reduction of investment in renewable energy in some regions. Therefore, how to use the complementary characteristics of energy storage and multiple energy sources to carry out the capacity planning of power system covering wind power, photovoltaic, energy storage and other resources, to achieve safe operation of the system, and to improve the penetration rate of renewable energy is a key issue.

At present, there are many researches on wind power and photovoltaic capacity planning. Reference [1] proposed a system capacity planning method based on system operation and weather factors. Reference [2] analyzes the main factors affecting the system power generation, such as solar radiation intensity and wind speed, and plans the system capacity based on the average level of power generation resources. Based on the reliability and construction cost of wind solar hybrid power system, the capacity planning method of wind solar hybrid power system is studied in reference [3]. In reference [4], the capacity planning of various complementary power systems is studied by using statistical methods. In reference [5], the static comprehensive optimal capacity allocation of transmission capacity is studied by using time series analysis method.

To sum up, the existing studies lack of planning for multiple uncertainties of wind power and photovoltaic power, as well as restrictions on renewable energy consumption rate and tie line capacity ratio. Therefore, this study constructs a coordinated optimization planning model of wind solar energy
storage complementary power system to optimize the installed capacity of wind power, photovoltaic and energy storage.

2. Capacity coordination and optimization planning of wind photovoltaic storage hybrid power system

2.1. Optimization objectives
The ultimate goal of capacity coordination optimization planning model of wind solar energy storage complementary power system is to minimize the total investment cost. Therefore, the objective function is to minimize the investment cost of renewable energy units and energy storage system of wind power and photovoltaic units in the planning level year, as shown in formula (1).

Where, $E_{S}$ is the capacity of energy storage system, $W_{max}$ and $PV_{max}$ are the maximum generation capacity of wind turbine and photovoltaic respectively, $t$ is the planning period, and $C_{ES}, C_{W}$ and $C_{PV}$ are the investment costs of energy storage, wind power and photovoltaic respectively.

$$C_{ES} = C_{battery}S_{battery} + C_{inverter}S_{inverter}$$  \hspace{1cm} (1)

$$C_{W} = C_{w}S_{w}$$  \hspace{1cm} (2)

$$C_{PV} = C_{pv}S_{pv}$$  \hspace{1cm} (3)

In the formula, $C_{battery}$ and $C_{inverter}$ are the unit cost of energy storage battery and inverter, $S_{battery}$ and $S_{inverter}$ are the capacity of energy storage battery and inverter respectively, $C_{w}$ and $S_{w}$ are the unit cost and maximum generation capacity of wind turbine, and $C_{pv}$ and $S_{pv}$ are the unit cost and maximum generation capacity of photovoltaic generator set respectively.

2.2. Constraints
(1) Wind power constraints

$$0 \leq P_{t}^{w} \leq N_{w}P_{t}^{w}$$  \hspace{1cm} (4)

Where, $P_{t}^{w}$ is the optimal output of the wind turbine at the t moment, $N_{w}$ is its rated installed capacity, and $P_{t}^{w}$ is the rated output of the wind turbine at the t moment.

(2) Photovoltaic generation constraints

$$0 \leq P_{t}^{pv} \leq N_{pv}P_{t}^{pv}$$  \hspace{1cm} (5)

In the formula, $P_{t}^{pv}$ is the optimal output of the photovoltaic generator set at the t moment, $N_{pv}$ is its rated installed capacity, and $P_{t}^{pv}$ is the rated output of the photovoltaic generator set at the t moment.

(3) Charging and discharging constraints of energy storage

$$0 \leq \lambda_{t}^{c} + \lambda_{t}^{d} \leq 1$$  \hspace{1cm} (6)

In the formula, $\lambda_{t}^{c}$ and $\lambda_{t}^{d}$ are 0-1 variables, which represent the charging and discharging states of energy storage at the t moment.

$$0 \leq P_{t}^{esc} \leq \lambda_{t}^{c}P_{max}^{esc}$$  \hspace{1cm} (7)

$$0 \leq P_{t}^{end} \leq \lambda_{t}^{d}P_{max}^{end}$$  \hspace{1cm} (8)
In the formula, $P_{esc}^t$ and $P_{esd}^t$ are the charging and discharging power of the energy storage at the $t$ moment, and $P_{max}^{esc}$ and $P_{max}^{esd}$ are the maximum charging and discharging power of the energy storage at the $t$ moment.

$$0 \leq P_{esc}^t \leq S_{inverter}$$

$$0 \leq P_{esd}^t \leq S_{inverter}$$

Equations (10) and (11) respectively indicate that the charging and discharging power of the energy storage at the $t$ moment shall not exceed the rated power of the battery inverter.

(4) State of charge (SOC) constraints

$$E_{es}^t = E_{es}^{T-1} + \eta_{esc} P_{esc}^t \Delta T - \frac{P_{esd}^t}{\eta_{esd}} \Delta T$$

In the formula, $E_{es}^t$ and $E_{es}^{T-1}$ are the energy of the energy storage battery at the T-1 moment, and $\eta_{esc}$ and $\eta_{esd}$ are the charging and discharging efficiency of the battery respectively.

$$E_{max}^{es} \geq E_{min}^{es} \geq E_{t}^e$$

$$E_{min}^{es} = S_{battery SOC_{min}}$$

$$E_{max}^{es} = S_{battery SOC_{max}}$$

In the formula, $E_{min}^{es}$ and $E_{max}^{es}$ are the minimum and maximum power of the energy storage battery, and $SOC_{min}$ and $SOC_{max}$ are the minimum and maximum state of charge of the energy storage battery.

(5) System power balance constraints

$$P_{i}^{out} = P_{i}^{w} + P_{i}^{pv} + \lambda_{i}^{d} P_{i}^{esd} - \lambda_{i}^{r} P_{i}^{esc}$$

Where $P_{i}^{out}$ is the power of the transmission tie line.

(6) Renewable energy consumption rate constraint

$$\sum_{t \in T} (P_{i}^{w} + P_{i}^{pv} + P_{i}^{esd} - P_{i}^{esc}) \geq \eta \sum_{t \in T} (S_{w} P_{i}^{w} + S_{pv} P_{i}^{pv})$$

Where $\eta$ is the wind and light rejection rate.

3. wind power and photovoltaic time series model

Based on the establishment of wind power and photovoltaic output characteristic index, the wind power and photovoltaic output characteristics are fully explored, and the wind power / photovoltaic series modelling method based on daily characteristics and monthly characteristics is proposed. The multi scenario wind power and photovoltaic output series are constructed to describe the multiple uncertainties of wind power and photovoltaic output, and lay the foundation for the optimization of installed capacity planning.

3.1. Output characteristic index

Considering the daily and monthly characteristics of wind power and photovoltaic output, several wind power and photovoltaic output series curves are constructed based on Monte Carlo method to describe the uncertainty of wind power and photovoltaic.

(1) Probability distribution of daily maximum output
\[ f_{Q_{\text{max}}}(t) = \frac{\sum_t M_t \{ t \mid Q_{\text{max}}(n,t) \}}{\sum_t M_t \{ t \mid Q_{\text{max}}(n,t) \}} \] (17)

\( Q_{\text{max}}(n,t) \) is the maximum output on the nth day, and the maximum output occurs at the t time; 
\( M_t \{ t \mid Q_{\text{max}}(n,t) \} \) is the total frequency of the maximum output occurring at the t time in the statistical period.

(2) Probability distribution of daily minimum output

\[ f_{Q_{\text{min}}}(t) = \frac{\sum_t M_t \{ t \mid Q_{\text{min}}(n,t) \}}{\sum_t M_t \{ t \mid Q_{\text{min}}(n,t) \}} \] (18)

\( Q_{\text{min}}(n,t) \) is the minimum output on the nth day, and the minimum output occurs at the t time; 
\( M_t \{ t \mid Q_{\text{min}}(n,t) \} \) is the total frequency of the minimum output at the t time in the statistical period.

(3) Proportion of annual electricity consumption by month

\[ \eta_E = \frac{E_m}{E_y} \] (19)

Where \( E_m \) is the total electricity in the M month and \( E_y \) is the total electricity in the whole year.

(4) Distribution of annual daily maximum output

\[ f(Q_{\text{max}}) = \frac{\sum M_{Q_{\text{max}}}(Q_{\text{max}}(n,t) = Q_{\text{max}})}{\sum M_{Q_{\text{max}}}} \] (20)

\( \sum M_{Q_{\text{max}}} \) is the total frequency of all daily maximum output; 
\( M_{Q_{\text{max}}}(Q_{\text{max}}(n,t) = Q_{\text{max}}) \) is the total frequency of daily maximum output of \( Q_{\text{max}} \).

(5) Distribution of annual daily minimum output

\[ f(Q_{\text{min}}) = \frac{\sum M_{Q_{\text{min}}}(Q_{\text{min}}(n,t) = Q_{\text{min}})}{\sum M_{Q_{\text{min}}}} \] (21)

\( \sum M_{Q_{\text{min}}} \) is the total frequency of all daily maximum output; 
\( M_{Q_{\text{min}}}(Q_{\text{min}}(n,t) = Q_{\text{min}}) \) is the total frequency of daily maximum output of \( Q_{\text{min}} \).

### 3.2. Wind power / photovoltaic time series modelling

Based on the analysis of daily and monthly characteristics, the wind power / photovoltaic series modelling method uses Monte Carlo method to simulate multiple wind power and photovoltaic output series. The specific steps of this method are as follows:

1. Collecting and statistics of wind power and photovoltaic theoretical output data for many years, considering the existence of missing data and bad data and other abnormal data, it is necessary to clean and recover the abnormal data based on autoregressive integrated moving average (ARIMA);

2. The daily and monthly characteristics of wind power and photovoltaic output series are analysed, including the probability distribution of daily maximum and daily minimum output and the proportion of annual monthly electricity;

3. The daily maximum output and daily minimum output are obtained by sampling based on the distribution of annual daily maximum output and annual daily minimum output;

4. Based on the probability distribution of daily maximum output and daily minimum output, the occurrence time of daily maximum and minimum output is obtained by sampling;

5. After the daily maximum / minimum output value and occurrence time are determined, the wind power output value at other times is generated randomly by Monte Carlo method, and the proportion of
annual monthly electricity is; photovoltaic series is directly generated based on daily maximum output and typical daily curve.

The capacity coordination optimization model of wind photovoltaic storage hybrid power system established in this paper is a typical mixed integer linear programming model. Therefore, gams software is used to solve the optimization model to obtain the optimal capacity of wind turbine, photovoltaic generator set and energy storage system under different renewable energy consumption rates.

4. Example analysis

4.1. Example parameters
In this section, an energy demonstration system in northern China is taken as an example to evaluate the effectiveness of the proposed model and algorithm. The multi energy system has two 220kV substations, in which the photovoltaic power station and energy storage device are connected with substation a, and the wind farm is connected with substation B.

The parameter setting of the example is shown in table 1, and the parameter information is obtained based on reference [6]. Due to the limitation of renewable power generation data, this paper assumes that the time scale is one hour, and the maximum and minimum capacity of energy storage are 0 and 200 MWh, respectively.

4.2. Result analysis
The transmission capacity of the transmission line is set as a certain proportion of the total power generation of the system. After the installed capacity of wind power and photovoltaic power generation is initialized randomly, the abandoned power and energy storage capacity of renewable energy under different tie line capacity proportions are studied. The results are shown in table 1.

Table 1. Correlation between the ratio of tie-line capacity to total capacity and the reduction rate of renewable energy and energy storage

| Ratio of tie line capacity to total power capacity | 40%  | 45%  | 50%  | 55%  | 60%  |
|-----------------------------------------------|------|------|------|------|------|
| Renewable energy abandonment rate (%)         | 4.8  | 3.3  | 2.2  | 0.4  | 0.9  |
| Energy storage capacity (MW)                  | 137.65 | 136.88 | 135.3 | 133.2 | 130.9 |

It can be seen from the above figure that with the increase of tie line capacity in the total capacity, the energy storage capacity required by the system and the rejection rate of renewable energy are reduced. Because the difference of energy storage capacity in different scenarios is small, and the rate of renewable energy abandonment is not more than 5%, the proportion of tie line capacity to the total capacity is 40%.

Calculation of renewable energy abandonment rate under different wind power and photovoltaic power generation capacity ratio is shown in Figure 1. When the capacity ratio of wind power and photovoltaic power generation is 1, that is, when the capacity of wind power and photovoltaic power generation are both 300MW, the renewable energy power abandonment rate is the minimum, which is 4.5%, and the total investment cost is the minimum, which is 26439.97 yuan.
Figure 1. Correlation between the ratio of wind power to photovoltaic power generation capacity and renewable energy curtailment rate

In this multi energy system, the total capacity of renewable energy is 600 MW, the energy storage power is 46 MW, and the utilization rate of tie line transmission capacity is 40%. Gams is used to solve the optimal model, and the optimal capacity of energy storage, wind power and photovoltaic power generation is obtained. The results are shown in the table below.

Table 2. Results of case study

| index                                      | numerical value |
|--------------------------------------------|-----------------|
| Minimum total investment cost / yuan       | 26439.97        |
| Energy storage battery capacity / MW       | 137             |
| Wind power capacity / MW                   | 300             |
| Photovoltaic power generation capacity / MW| 300             |
| Renewable energy abandonment rate /%       | 4.5             |

From table 3, we can see that when the capacity of wind power and photovoltaic power generation is 300MW, the minimum total cost is 26439.97 yuan, and the capacity of energy storage battery is 137MW.

5. Conclusion
In this study, combined with the characteristics of wind power and photovoltaic power generation, the output model of wind power and photovoltaic power is constructed, and then the optimal economic installed capacity of wind power, photovoltaic and energy storage is given. Through the research, the following conclusions are obtained

(1) Based on the daily / monthly characteristics of wind power and photovoltaic output model, multiple wind power and photovoltaic output time series can be generated to meet the local wind and solar output characteristics and realize the description of multiple uncertainties of wind and solar power.
(2) In different scenarios of renewable energy consumption rate and tie line utilization rate, the optimal installed capacity of wind power, photovoltaic power and energy storage is different, but the impact of energy storage capacity is small.

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