Optimal Capacity Design of Independent Micro-Grid System for High Proportion of Wind-Solar Combined Cooling Heating and Power System with Energy Storage

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Abstract. This paper researches the optimal capacity design of independent micro-grid system for wind-solar combined cooling heating and power system with energy storage, puts forward a dispatching method based on expert time-judge for dynamic control of wind-solar direct permeability and a hierarchical design based on energy storage module. Because of the uncertainty of wind-solar system, this paper adopts fuzzy parameters to describe the system constraints and clarify the opportunity constraints, then optimizes the capacity design on fuzzy constraints and particle swarm optimization, analyses the operation results of optimal capacity allocation under dispatching method and hierarchical design of energy storage.

1. Introduction
Based on actual situation of China’s energy supply and demand, the remote areas mainly develop diesel and gas power generation. The cost of power system is high and the reliability of system operation is low. Actually, most of the western regions are rich in renewable energy[1], which can be used to build renewable energy power generation system. Considering the cold and hot needs of users, an independent micro-grid system with multi-potential complementary renewable energy can be constructed.

This paper considers the independent micro-grid system for high proportion of wind-solar combined cooling heating and power system with energy storage[2-3] and this puts forward a dispatching method based on expert time-judge for dynamic control of wind-solar direct permeability to enhance the reliability of the system, a hierarchical design based on energy storage module to reduce the battery charge and discharge times, then, designs a dispatching strategy, get the optimal capacity of system configuration, and discusses the influence of high proportion of renewable energy penetration for a dispatching method.

2. System modelling

2.1. Joint Modeling of Wind and Photovoltaic Power Plants
From the single analysis of wind power and photovoltaic output, the wind power output has randomness, and the photovoltaic output has the phenomenon of work at day, stop at night. However,
from the wind and solar power combined output, the coupling characteristics of wind and solar complementary output force reduce the fluctuation of output to a certain extent and continuity of the output is guaranteed. Therefore, this paper regards wind and solar power combined output as a power source.

Due to the environment, climate, and other factors[4], the output of renewable energy is difficult to predict, so, the renewable energy output adopt fuzzy model. The actual value wind and solar power combined output is used as the fuzzy parameter to establish the fuzzy chance constraint[5], the risk is controlled by confidence level.

\[ R_{\text{w-pv}} = \omega_i P_{\text{forecast}} \]  

(1)

In the formula (1), \( \omega_i (i = 1,2,3,4) \) is the proportional coefficient, and \( \omega_i \in (0,1) \), \( P_{\text{forecast}} \) is the predicted value of the wind-solar power combined output.

2.2. Energy storage system modeling

In order to reduce the times of charge and discharge of battery, the energy storage system is divided into the charged and the discharge groups according to the operating status in real time.

The remaining capacity of the battery at \( t \) is related to the remaining capacity of the battery at \( t-1 \), the battery output during \([t,t-1]\) and the self-discharge amount per hour[6].

When the battery works, the remaining capacity at the time \( t \) is:

\[ S(t) = S(t-1)(1-\sigma) - \frac{P_t(t)}{\eta} \]  

(2)

In the formula (2), \( S(t) \) is the remaining capacity of the battery at the time \( t \), \( P_t(t) \) is the charging and discharging power of the battery at \( t \), \( \eta \) is battery efficiency, \( \sigma \) is the ratio of the battery per hour.

Upper and lower limits of battery pack capacity:

\[ S_{s\text{min}} \leq S_s(t) \leq S_{s\text{max}} \]  

(3)

Upper and lower limits of battery pack power:

\[ P_{s\text{min}} \leq P_s(t) \leq P_{s\text{max}} \]  

(4)

2.3. Modeling of Cooling Heating and Power System

The cooling and power system uses a micro gas turbine as the core device. As the gas turbine generates electricity, the discharged high-temperature flue gas is used for cooling, heating and supplying domestic hot water through a lithium bromide absorption chiller[7-8].

In the operation of independent micro-grid, in order to improve the utilization rate of renewable energy, this paper adopts the operation mode of “power determine heating (cold)”.

The upper and lower limits of the output of the combined cooling and heating capacity and power system:

\[ P_{t\text{min}} \leq P_t(t) \leq P_{t\text{max}} \]  

(5)

In the formula (5), \( P_t(t) \) is the output power of micro gas turbine.

The upper and lower limits of the climbing rate of the cooling heating and power system:

\[ R_t^{\text{down}} \Delta t \leq P_t(t) - P_t(t-1) \leq R_t^{\text{up}} \Delta t \]  

(6)

In the formula (6), \( R_t^{\text{down}}, R_t^{\text{up}} \) are up and down climbing power speed.

2.4. Clear Equivalence Class Conversion of System Fuzzy Opportunity Constraints

The constraint can be converted by clear equivalence class method, the system power balancing is:

\[ \text{Cr}\{P_{\text{w-pv}} + P_s + P_t - P_l = 0\} \geq \alpha \]  

(7)

In the formula (7), \( P_{\text{w-pv}} \) is the wind-solar power combined output, \( P_l \) is load power, \( \alpha \) is confidence level.

According to the clear equivalence class analysis method, the clear equivalence class of system power balance under trapezoidal fuzzy parameters is:

\[ (2 - 2\alpha)(\omega_3 P_{\text{w-pv}}^{\text{forecast}}) + (2\alpha - 1)(\omega_4 P_{\text{w-pv}}^{\text{forecast}}) + P_s + P_t - P_l \leq 0 \]  

(8)

In the formula (8), \( P_{\text{w-pv}}^{\text{forecast}} \) is the wind-solar predicted power combined output.

3. System dispatching strategy
The control system regulates wind farm and other subsystems through the control line, and changes the dispatching strategy through the line switch. Combined Power Generation System is shown in Fig 1.

![Combined Power Generation System](image)

**Figure 1.** Combined Power Generation System

3.1. **Expert time-judge**

Different electric users have different load characteristics. Under the premise of ensuring the reliability of the system, the use of renewable energy during peak hours will be realized, and the phenomenon of abandoning wind and solar power should be reduced. First, peak hours and valleys hours should be divided by expert time-judge in different situations [9].

This paper adopts the time-judge plan proposed by tariff policy. The peak period of electricity consumption is 10:00-15:00 and 18:00-21:00, and the electricity valley is 00:00-7:00 and 23:00-24:00, weekdays are 7:00-10:00, 15:00-18:00 and 21:00-23:00.

3.2. **Compound dispatching**

The compound dispatching refers to a dispatching method in which two single-type dispatching modes are alternately operated. The control system uses $S_s$ to determine which battery in the battery module is in a charging or discharging mode, thereby connecting the mode 1 and the mode 2, and the mode 1 refers to the wind-solar power priority input. The load is applied, and the direct penetration rate does not exceed the $\alpha\%$ of load; if there is more wind-solar power, the chargeable battery pack continues to be consumed; the remaining load is responsible for the combined heat and power supply system. Mode 2 means that the wind-solar power priority input, and the direct penetration rate does not exceed the $\alpha\%$ of load; the remaining load is supplied by the energy storage system and the cooling heating and power system. Determine the value of $\alpha\%$ according to peak, trough and time.

4. **System capacity optimization**

4.1. **Economy**

Total system construction cost measures economy $C$ [10]:

$$C = C_w + C_{pv} + C_s + C_{CHP}$$

(9)

In the formula (9), $C_w, C_{pv}, C_s$ and $C_{CHP}$ are the cost of wind power, photovoltaic, energy storage systems and cooling heating and power system, $\$. 

4.2. **Power supply reliability**

Load of power supply probability measures power supply reliability $LPSP$:

$$LPSP = \frac{\sum_{n=1}^{n_{max}} P_{lp}(n) \cdot 24/n_{max}}{\sum_{n=1}^{n_{max}} P_{ls}(n) \cdot 24/n_{max}}$$

(10)

In the formula (10), $n_{max}$ means equal time periods numbers; $P_{lp}(n)$ is the average abandonment power of the first time of the day, kW; $P_{ls}(n)$ is the average load of the first time of the day, kW.

4.3. **Renewable energy efficiency**
Abandonment rate measures renewable energy efficiency $A$:

$$A = \frac{\sum_{n=1}^{n_{\text{max}}} P_{a}(n) 24/n_{\text{max}}}{\sum_{n=1}^{n_{\text{max}}} [P_{w}(n)+P_{p}(n)] 24/n_{\text{max}}} \quad (11)$$

In the formula (11), $P_{a}(n)$ is the average abandoned wind power in the first time of the day, kW.

### 4.4. System capacity optimization model

Convert the above three objective functions into joint satisfaction single objective function [11]:

$$\min \{\mu\} = \min\{\alpha_1 \mu_1 + \alpha_2 \mu_2 + \alpha_3 \mu_3\} \quad (12)$$

In the formula (12), $\mu_1$, $\mu_2$ and $\mu_3$ are satisfaction degrees after normalization of $C$, $LPSP$ and $A$, $\alpha_1$, $\alpha_2$ and $\alpha_3$ the satisfaction weight chosen for preference based. The particle swarm optimization algorithm[12] is used to find the optimal solution of the system.

### 5. Case study

This paper selects a wind-solar combined cooling heating and power system with energy storage as the analysis object. Given the 24-hour predicted value of the capacity of a single wind turbine and the 24-hour predicted value of a single solar photovoltaic, the rated capacity of a single battery unit is 1.2 kWh and the rated power is 1.2 kW. The maximum capacity of the energy storage device is 30 kWh, the minimum capacity is 2 kWh, the initial capacity is 10 kWh, and the charging and discharging efficiency is 0.87. The discharge rate is 0.005. Given the upper and lower limit power and climbing rate of the cooling heating and power system, and the predicted value of the load for 24 hours, the confidence level of the system's fuzzy constraints is set at 75%. Fig 2 is 24h system load and actual output.

#### 5.1. System capacity optimization results

According to the different wind-solar direct penetration plans, the optimal capacity allocation of the system is obtained by the method of system optimization allocation strategy in Section 3. The operating results of the system under different direct permeability are obtained in Fig. 3.

![Figure 2. 24h system load and actual output](image)

![Figure 3. The operating results under different wind-solar direct permeability](image)

From the point of view of the system operation results following the load, with the increase of the wind-solar direct penetration, the system operation deviation becomes larger and larger. There are two reasons: first, the higher the wind-solar direct penetration, the smaller the capacity demand of energy storage, so the stable system output function of energy storage system can’t work; second, the increase of wind-solar direct penetration makes the residual load change more rapid, and the climbing power of CCHP system and energy storage system is limited, so the system is difficult to follow the load.

#### 5.2. The influence of direct permeability of wind and solar

The influence of direct permeability of wind and solar is shown in Table1.
Table 1. The influence of direct permeability

| Direct permeability | Economy | Reliability | Environment |
|---------------------|---------|-------------|-------------|
| \(\text{low} = 0.3\)  \\
| \(\text{norm} = 0.45\)  \\
| \(\text{high} = 0.75\)  | 1        | 0.17        | 0.5         |
| \(\text{low} = 0.2\)  \\
| \(\text{norm} = 0.35\)  \\
| \(\text{high} = 0.65\)  | 0.6      | 0.36        | 0.4         |
| \(\text{low} = 0.1\)  \\
| \(\text{norm} = 0.25\)  \\
| \(\text{high} = 0.55\)  | 0        | 0.39        | 0.3         |
| \(\text{low} = 0.3\)  \\
| \(\text{norm} = 0.45\)  \\
| \(\text{high} = 0.65\)  | 0.9      | 0.16        | 0.467       |
| \(\text{low} = 0.3\)  \\
| \(\text{norm} = 0.35\)  \\
| \(\text{high} = 0.65\)  | 0.3      | 0.26        | 0.433       |

Overall, with the increase of direct penetration of wind and solar power, the economy and environmental protection of the system are improved, while the reliability of power supply is reduced.

The economic improvement is due to the increase of direct wind-solar permeability, which makes fewer wind-solar input energy storage elements, the system's capacity demand for energy storage elements is reduced, and the load proportion of energy storage elements is reduced. At the same time, the increase of wind-solar permeability also reduces the output of the CCHP system, so the system cost is reduced and the system economy is improved. The improvement of environmental protection is mainly due to the improvement of utilization rate of wind photovoltaics.

The reasons for the decrease of power supply reliability are as follows: firstly, with the increase of wind-solar direct penetration, the charging and discharging time of energy storage system is prolonged, which leads to the increase of the probability of "load loss"; secondly, with the increase of direct penetration of wind and solar energy, the capacity demand of the system for the combined cooling, heating and power system decreases, so the system produces "power loss". The probability of load loss increase.

6. Conclusion
This paper researches the optimal capacity design of independent micro-grid system for wind-solar combined cooling heating and power system with energy storage, puts forward a dispatching method based on expert time-judge for dynamic control of wind-solar direct permeability and a hierarchical design based on energy storage module, combining with example simulation. The operation results of the optimal system capacity under different direct permeability of wind and solar are obtained, and the influence of direct permeability of wind and solar on the system capacity planning is analysed, which has the guiding significance of the independent micro-grid system for high proportion of wind-solar combined cooling heating and power system with energy storage plan.

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