Optimal scheduling of cogeneration microgrid with wind energy and energy storage devices

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Abstract. Aiming at the optimal scheduling of cogeneration microgrid, a microgrid structure including wind energy, energy storage device, solar thermal power station, gas turbine and waste heat boiler is proposed. Based on the uncertainty of wind power output and load forecasting, according to beta distribution wind power output and normal distribution load forecasting, the CHP microgrid optimal scheduling model of photothermal power station is established and solved by genetic algorithm. Finally, the minimum operation cost of the system under different confidence levels is discussed. The results show that the minimum operating cost of the system can be significantly reduced by adding wind power generation into the microgrid structure, and the relationship between the confidence level of load forecasting and the minimum operating cost of the system is studied.

Key words: photothermal power station; combined heat and power (CHP); beta distribution; day ahead scheduling.

1. Introduction
Modern high-speed development of energy economy has improved people's living standards, but also has a certain negative impact on the environment. With the increasing depletion of non-renewable energy and its environmental pollution, many countries turn their attention to renewable energy power generation technology. In recent years, China's wind power generation, solar power generation, nuclear power and other renewable energy power generation technology has been in rapid development, especially solar thermal power generation because its thermal storage device can still generate power after the sun goes down. Combined with combined heat and power (CHP) hybrid power generation mode, the utilization efficiency of energy can be greatly improved and the cost of power generation can be reduced.

At present, scholars at home and abroad have made a lot of academic achievements in the research on optimal scheduling of cogeneration. In reference [1], the operation optimization model of CHP microgrid with heat pump and energy storage device was proposed, which was solved by mixed integer programming method. It improved the economy of the previous CHP microgrid model, but did not consider the benefits of wind power. In reference [2], the comprehensive operation of wind, solar and hydro energy is studied by using improved POA algorithm. It is proved that cascade hydropower stations can effectively alleviate the output fluctuation of wind power and photovoltaic power, and play a good role in wind and solar energy consumption. However, the construction of cascade
hydropower stations is limited by geological conditions. In reference [3], a multiday stochastic scheduling model was established for photovoltaic thermal power plants and wind power generation, and the influence of key parameters such as prediction time length, heat loss coefficient of thermal storage devices and installed capacity on the model was discussed. However, the accuracy of the model was limited due to the point estimation method.

The uncertainty of wind power generation is one of the reasons that hinder the large-scale development of wind power generation. A lot of research has been done on how to solve this problem at home and abroad. In reference [4-6], beta distribution is used to predict actual wind power output, and it is proved that this distribution can describe wind power output more accurately.

Under the above background, this paper introduces wind energy and energy storage device into CHP microgrid of photothermal power station, and builds a microgrid day ahead optimal dispatching model including photothermal power station, gas turbine, electric energy storage device, heat storage device, waste heat boiler, wind power station, steam turbine, electric load and heat load. Considering the uncertainty of wind power output, beta distribution is used to describe the output. The time-sharing transaction price is used to calculate the transaction income of power grid. At the same time, the genetic algorithm is used to optimize the output of thermal power units and photovoltaic thermal power stations, so as to obtain the minimum generation cost of the system.

2. Structure and mathematical model of microgrid

2.1. CHP microgrid structure of solar thermal power station with wind energy and energy storage device

The day ahead optimal scheduling model of CHP microgrid is shown in Figure 1. In Figure 1, the micro gas turbine uses natural gas to generate electricity to meet the electrical load. The surplus electric energy can be sent back to the power grid. The waste heat discharged during the power generation process is sent to the waste heat boiler, which reclaims the heat and stores it in the heat storage device. The wind power station adopts wind power generation, and the surplus electric energy can be stored in the power storage device. Solar thermal power station uses solar energy for power generation, and the heat is directly transmitted to the steam turbine. The steam turbine unit generates electric energy. At the same time, the surplus heat of the light field can be stored in the heat storage device, and it is supplied to the steam turbine when the solar heat are insufficient.

![Fig.1 System structure of a micro-grid concluding CHP and solar-thermal power stations](image-url)
2.1.1. Model of photo thermal power station. Solar energy is collected by light field in photothermal power station. Part of solar energy is sent to thermal storage device for storage, and the other part is generated by steam turbine.

\[ P_t = \eta_c Q_t \]  

(1)

\( P_t \) is the electric power output by the steam turbine in the photothermal power plant at \( t \). \( Q_t \) is the thermal power input to the steam turbine in the photothermal power station at \( t \). \( \eta_c \) is the conversion efficiency from heat energy to electric energy in the steam turbine.

The heat storage device stores the heat from the light field and waste heat boiler, then supplies heat to the heat load. After meeting the heat load, the remaining heat energy is supplied to the steam turbine for power generation.

\[ Q_t = (1 - \varepsilon)Q_{t-1} + (Q_{c,t} - \frac{Q_{d,t}}{\eta_c} - \frac{Q_{d,t}}{\eta_d})\Delta t \]  

(2)

\( Q_t \) is the thermal energy storage capacity of the heat storage device at \( t \). \( \varepsilon \) is the loss coefficient; \( Q_{c,t} \), \( Q_{d,t} \) are the charging and discharging power of the heat storage at \( t \); \( \eta_c \), \( \eta_d \) are the charging and releasing efficiency respectively.

2.1.2. Gas turbine

\[ P_{en,i} = \eta_{en} \varphi_{gas} G_{en,i} \]  

(3)

\( P_{en,i} \) is the output electric power of gas turbine \( i \) at \( t \). \( \eta_{en} \) is the power generation efficiency; \( \varphi_{gas} \) is the corresponding calorific value of natural gas; \( G_{en,i} \) is the natural gas consumption.

2.1.3. Waste heat boiler. The waste heat boiler recovers the waste heat of the gas turbine and sends it to the heat storage device.

\[ Q_{re,i} = \eta_{re} (1 - \eta_{en}) \varphi_{gas} G_{en,i} \]  

(4)

\( Q_{re,i} \) is the heat power reclaimed by waste heat boiler; \( \eta_{re} \) is the waste heat recovery efficiency.

2.1.4. Energy storage device

\[ S_t^E = (1 - \lambda_E)S_{t-1} + (P_{c,t}^E - \frac{P_{d,t}^E}{\eta_d})\Delta t \]  

(5)

\( S_t^E \) is the storage capacity of electric energy at \( t \). \( \lambda_E \) is the loss coefficient of electric energy storage device; \( P_{c,t}^E \), \( P_{d,t}^E \) are the charging and discharging power of electric energy storage device; and \( \eta_c \), \( \eta_d \) are the conversion efficiency of charging and discharging power of electric energy storage device respectively.

3. Uncertainty of wind power output and load

3.1. Beta distribution of wind power output

Wind power output has output constraint in the actual production, however, the independent variable range of normal distribution is \((-\infty, \infty)\). Compared with normal distribution, beta Distribution shows better fitting, so the actual output of wind power is given by beta distribution.
P is a random variable obeying beta distribution, which represents the actual wind power output; \( \omega \), \( \nu \) are distributed parameters; and \( D(\omega, \nu) \) is a standardized function whose value can be uniquely determined according to \( \mu \) and \( \sigma^2 \).

\[
g(p) = \frac{p^{\mu-1}(1-p)^{\nu-1}}{D(\omega, \nu)}
\]

(6)

\[
D(\omega, \nu) = \int_0^1 p^{\mu-1}(1 - p)^{\nu-1} dp
\]

(7)

\[
\omega = \frac{(1-\mu)\mu^2 - \mu}{\sigma^2}, \quad \nu = \frac{1-\mu}{\mu} \omega
\]

(8)

3.2. Load uncertainty
One-dimensional normal distribution is used to describe the predicted values of electric and heating loads.

\[
f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}}
\]

(9)

4. Objective function

\[
\min f = p_c E_c - p_g E_g + P_{gas} G_{gas}^t + \eta_{gd} P_t + \eta_{gr} Q_t + \eta_{cd} \left( \sum P_{E}^t + \sum P_{E} \right)
\]

(10)

\( p_c, p_g \) are the time-of-use electricity price of the power grid; \( E_c, E_g \) are the price of natural gas; \( P_{gas} \) is the price of natural gas; \( P_{gas} \) is the power generation cost coefficient of the photovoltaic thermal power station; \( \eta_{gd} \) is the electricity energy purchased and sold by the power grid; \( \eta_{gr} \) is the heat output cost coefficient of the photovoltaic thermal power station; \( \eta_{cd} \) are the cost coefficient of the power storage device.

5. Constraints

5.1. Network constraints
At each moment, the sum of gas turbine power generation, wind power generation, photothermal power generation, power grid purchase and sale power is balanced with the electrical load

\[
\sum_{i=1}^n P_{en,i} + P_w + P_t + E_g - E_c = P_{LT}
\]

(11)

\( P_{LT} \) is the load at t.

5.2. Reserve capacity constraints for positive and negative rotation

\[
z_{it} = \sum_{i=1}^n \min(P_{rmax} - P_{rmin}, r_{it}) \geq P_{ct}
\]

\[
f_{it} = \sum_{i=1}^n \min(P_{rmin} - P_{rmax}, r_{it}) \geq P_{ct}
\]

(12)
$z_i$, $f_i$, $P_i^{\text{max}}$, $P_i^{\text{min}}$, $P_i^{\text{max}}$, $P_i^{\text{min}}$, $r_i^u$, $r_i^d$, $r_g^u$, $r_g^d$ are the positive and negative rotating reserve capacity of gas turbine $i$ during $T$. $P_i^{\text{max}}$, $P_i^{\text{min}}$ are the upper and lower limits of output of gas turbine $i$; $r_i^u$, $r_i^d$ are the maximum up and down ramp rates of unit $i$.

5.3. Output constraints

The operating output constraint of gas turbine is

$$P_i^{\text{min}} \leq P_i \leq P_i^{\text{max}}$$

(13)

The ramp rate constraint of gas turbine and solar thermal power generation is

$$\begin{cases} -r_g^u \leq P_{i(t-l)} - P_{i(t-l-i)} \leq r_i^d \\ -r_g^d \leq P_{g(t-l)} - P_{g(t-l-i)} \leq r_g^u \end{cases}$$

(14)

$r_g^u$, $r_g^d$ are the maximum up and down climbing rates of solar thermal power generation respectively.

5.4. Constraints on thermal storage system of photo thermal power station

The heat storage capacity is constrained as

$$C_{C_{\text{min}}}^{\text{ST,c}} \leq C_{C_i}^{\text{ST,c}} \leq C_{C_{\text{max}}}^{\text{ST,c}}$$

(15)

$C_{C_{\text{max}}}$, $C_{C_{\text{min}}}$ are the upper and lower limits of the heat storage system respectively.

The power constraint of heat storage and release is

$$\begin{cases} P_{C_i}^{\text{min}} \leq P_{C_i}^{\text{ST,c}} \leq P_{C_{\text{max}}}^{\text{ST,c}} \\ P_{C_i}^{\text{min}} \leq P_{C_i}^{\text{ST,f}} \leq P_{C_{\text{max}}}^{\text{ST,f}} \end{cases}$$

(16)

$P_{C_i}^{\text{ST,c}}$, $P_{C_i}^{\text{ST,f}}$ are the heat storage and release power of the heat storage system; $P_{C_{\text{max}}}$, $P_{C_{\text{min}}}$ are the upper and lower limits of the heat storage; $P_{C_{\text{max}}}$, $P_{C_{\text{min}}}$ are the upper and lower limits of the heat release.

The thermal storage system can not store and release heat at the same time

$$P_{C_i}^{\text{ST,c}} P_{C_i}^{\text{ST,f}} = 0$$

(17)

6. Example analysis

6.1. Example background

In this paper, the structure of a microgrid after grid connected operation is taken as an example for illustration and analysis. The microgrid structure is shown in Figure 1, the time-sharing transaction electricity price between microgrid and power grid is shown in Figure 2, the predicted value of wind power output is shown in Figure 3, the predicted value of electric load is shown in Figure 4, and the predicted value of thermal load is shown in Figure 5. Given: ① the dissipation coefficient of heat storage device is 0.00032, the recovery efficiency of waste heat boiler is 0.75, and the dissipation rate of steam turbine is 0.1; ② the reference of natural gas price and calorific value [7]; ③ the charging and discharging efficiency of heat storage device is 98%, the maximum heat storage capacity is 2000kW, and the minimum heat storage capacity is 60kW; ④ the thermal efficiency of steam turbine is 0.3774, and the power generation efficiency of gas turbine is 0.4; ⑤ the maximum capacity of power storage device is 150kW, the minimum capacity is 20kW, the charge discharge coefficient is 0.9 and the loss coefficient is 0.0001.
Fig. 2 Curves of time-of-use price

Fig. 3 Predicted values of hourly wind power outputs

Fig. 4 Predicted values of hourly electrical loads
6.2. Model solving
Genetic algorithm is easy to use and has strong adaptability to deal with multivariable and complex constrained power system optimal scheduling problems.

In this paper, the genetic algorithm with initial population size of 800, maximum population evolution generation of 500, mutation factor of 0.85 and crossover probability factor of 0.5 is used to optimize the microgrid system.

6.3. Result analysis
Figure 6 shows the daily scheduling power output at a confidence level of 0.80. The wind power output is high at the time from 1:00 to 10:00, and most of the surplus electric energy is sold to the grid in order to reduce the net cost of the system, then a small part is stored in the power storage device; when the wind power output is low at the time from 16:00 to 20:00, the output of the photothermal power station and the discharge of the power storage device make up for the problem of low output to a certain extent. At 10:00 and 16:00-22:00, the power generation of solar thermal power station, wind power and two gas generating units can not meet the power load, so we purchase electricity from the grid. The specific data are recorded in Table 1.

Figure 7 shows the power balance of day ahead optimal dispatching under different confidence levels. When the confidence level is 0.80, the generation cost of microgrid optimal dispatching model is the minimum, and when the confidence level is 0.95, the generation cost of the model is the largest. It can be seen that with the increase of confidence level, the system cost becomes higher.
Fig. 6 Optimal scheduling results of power

Fig. 7 Minimum cost under different confidence levels

Table 1. Power output of each equipment under different confidence levels

| Confidence interval | Electric load /kw | Generating power of gas generating unit 1/kw | Generating power of gas generating unit 2/kw | Generating power of solar thermal power station/kw | Generating power of wind power station/kw | Charging capacity of power storage device/kw | Discharge capacity of power storage device/kw |
|---------------------|-------------------|-----------------------------------------------|---------------------------------------------|-----------------------------------------------|------------------------------------------|-----------------------------|-----------------------------|
| 0.95                | 8786.0            | 1336.3                                        | 2526.9                                      | 814.3                                         | 4720.0                                   | 173.4                        | 119.2                       |
| 0.90                | 8786.0            | 1356.5                                        | 2696.6                                      | 814.3                                         | 4720.0                                   | 193.4                        | 114.7                       |
| 0.85                | 8786.0            | 1434.3                                        | 2437.0                                      | 814.3                                         | 4720.0                                   | 176.0                        | 123.3                       |
| 0.80                | 8786.0            | 1143.2                                        | 2562.6                                      | 814.3                                         | 4720.0                                   | 177.6                        | 127.2                       |

7. Conclusion

First of all, wind energy and energy storage devices are added to CHP microgrid to supply electric energy from solar thermal power station, electric energy storage device and wind power station. When the sum of the output of the above output units is lower than the electrical load, electricity is purchased from the grid to meet the electrical load; when the sum of the output units above is higher than the
electrical load, the power is sold to the grid, so as to reduce the operation cost of the system. The heat energy released by thermal storage device of solar thermal power station meets the heat load. When the heat supply is surplus, the heat will continue to be stored in the heat storage device. When the heat supply is insufficient, the use of natural gas and the waste heat of gas turbine are increased, so that more heat energy can be recovered from the waste heat boiler and transferred to the heat storage device to meet the heat load. The surplus electric energy produced by the gas turbine can be sold to the power grid to reduce the cost. Secondly, beta distribution is used to describe the uncertainty of wind power output more accurately, and the objective function of minimum generation cost of microgrid optimization scheduling is established and solved by genetic algorithm.

The results show that: (1) adding wind power generation to the microgrid structure can significantly reduce the minimum operating cost of the system, but wind power and solar thermal power plants both have uncertainty of their output, which should be combined with the application of natural gas power generation and energy storage devices; (2) in the case of different confidence levels of load forecasting, the lower the confidence level is, the lower the minimum operating cost of the system is; 3) the microgrid structure established in this paper can be used to reduce the minimum operating cost of the system and then the results show that the optimal dispatching model has a better effect on the operation economy. The renewable energy such as wind energy and solar energy is applied in this model, making it more environmental-friendly.

References

[1] Jia Lihu, Gao Yi, Ge leijiao, Tian Zhuang, Zhao Gaoshuai, Zhang Lai, Zhang Haining. A Two-Stage Optimal Scheduling Method for CHP Systems Considering the Uncertainty of Solar-Thermal Power Stations [J]. Electric Power Construction, 2020,41 (01): 64-70

[2] Zhang Xinshuo, Huang Weibin, Wang Feng, Ma Guangwen, Chen Shijun. Research on the Optimal Scheduling of Large Wind-PV-Hydro Hybrid Energy Complementary Power Generation System[J]. China Rural Water Conservancy and Hydropower, 2019 (12): 181-185 + 190

[3] Yang Zhipeng, Zhang Feng, Liang Jun, Han Xueshan, Xu Zhen. Economic Generation Scheduling of CCHP Microgrid With Heat Pump and Energy Storage [J]. Power System Technology, 2018,42 (06): 1735-1743

[4] Sun Xin, Fang Chen, Shen Feng, Ma Qun. An Integrated Generation-Consumption Unit Commitment Model Considering the Uncertainty of Wind Power[J]. Transactions of China Electrotechnical Society, 2017,32 (04): 204-211

[5] Jin Hongyang, Sun Hongbin, Guo Qinglai, Chen Runze, Li Zhengshuo. Multi-day Self-scheduling Method for Combined System of CSP Plants and Wind Power with Large-scale Thermal Energy Storage Contained[J]. Automation of Electric Power Systems, 2016,40 (11): 17-23

[6] Liu Xingjie, Xie Chunyu. Wind power fluctuation interval estimation based on beta distribution[J]. Electric Power Automation Equipment, 2014,34 (12): 26-30 + 57

[7] Deng Bin, Huang Shufeng, Jiang Yufei, Shen Ce, Liao Junhong, Guo Chuangxin. Operational Risk Assessment for Power System Considering Inherent Volatility of Wind Power [J]. East China Electric Power, 2013,41 (05): 986-990