Research on Effect of Wind Power Accommodation by Synergistic Operation Based on Electric Boiler and Heat Accumulator

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Abstract. With rapid development of wind power, on the one hand it reduces our reliance on fossil fuels and reduces environmental pollution, but on the other hand causes various issues related to power grid restructuring. Lots of wind power curtailment is one of these problems for high proportion of the generating capacity of northeast China based on combined heat and power (CHP) units whose cannot flexibly response to the peak regulation of power grids. Therefore the paper discussed economic benefits of accommodating wind power based on electric boilers and heat accumulators with CHP units. Electric boilers can directly consume curtailment wind power to supply heat during low load periods and thus mitigate the heat supply stress of CHP units. Heat accumulators can store heat during high load periods and supply heat during low load periods and decouple the constraint of forced power output determined by heat of CHP units. From analysis some factors such as average operation hours per year of electric boilers and heat-to-electric ratio of CHP units obviously influence economic benefits.

Introduction

Wind power as important resource solving energy and environmental issues becomes more important with rapid development of wind power industry in recent years. The Three North (North, Northeast and Northwest China) are major areas of wind power development and have 80% of the total installed wind power capacity[1]. On the one hand wind resources are concentrated in large scales and most of these areas are located at the end of the power grid and are far away from the load center, on the other hand wind power accommodation is not enough by local loads and export capacity construction of the power grid lagged. Lack of the peak regulation ability of power system is one of the most important causes of tremendous wind power curtailments. In these areas the power supply structures are single and adjustable power supplies like pumped storage and gas power stations are less than 20%. In particular, during winter, the ability of load regulation is limited because of the large proportion of heating units. Combined heat and power (CHP) units operating in the mode of forced power output determined by heat in order to meet the demand of heat load will further decrease the peak regulation ability of CHP and increase contradiction of lack of the peak regulation ability of the system. It causes lots of wind power curtailment. Wind power curtailment is mainly concentrated in North, Northeast, and Northwest China with over 10% curtailment ratio.

The domestic and foreign scholars proposed lots of measures in order to improve wind power accommodation. In [2,3], Heat accumulator technology and energy alternative technology are in focus considerable. In [4], heat pump technology used to increase wind power accommodation at the supply side. In [5], electric boilers used to increase wind power accommodation at the supply side. In [6], by installing an electric boiler in the thermoelectric plant can decouple the constraint of forced power output determined by heat and improve wind power accommodation. Heat accumulator technology was used to improve peak-load regulation ability of cogeneration unit in [7].

Achieving benefits and costs of the system that include electric boiler and heat accumulator for CHP units is important for power grid where a relatively high wind power capacity and CHP units are
installed. The benefits and costs of the system for wind power accommodation in an actual power grid is analyzed as an example.

**Thermoelectric Characteristics of CHP Units**

Heating mode of CHP units and regional boilers operating collectively is adopted in winter heating period. Because of inefficiency and high pollution of regional boiler, heating mode of CHP becomes popular. CHP units include backpressure units and extraction condensation units. Coupling relation between electric power output and heating power output is called thermoelectric characteristics.

For backpressure units, backpressure exhaust of turbines transfer heat with heat supply network by heat exchanger and achieve supply heat for heat loads by heat supply network. Its’ heating power and electric power present approximately coupling relation. Electric power of CHP units are decided by heating power and heat-to-electric ratio is confirmed. Backpressure units have not regulating capacity in order to meet heat load demands in heating period.

For extraction condensation units, a part of steams as heat source are extracted from intermediate pressure cylinder and low pressure cylinder of turbines for supplying heat. Heat-to-electric ratio of turbines are adjusted by accommodating steam extraction under the conditions of satisfying operation, therefore the relation of heating power and electric power can be commonly presented operating region. Electric power can be adjusted within limits for some heating power. When heat loads become higher, steam extraction increasing results in reducing adjustable range of electric power.

**Wind Power Accommodation Mode Based on Electric Boilers and Heat Accumulators for CHP Units**

Many thermal power units of the three North (North, Northeast and Northwest China) are CHP units. When electric loads are valley loads in winter night, heat loads are peak loads. If CHP units adopt the mode of forced power output determined by heat, forced power output of CHP units are high and peak-load regulation ability are small. This moment wind power curtailment is occurring if wind power output are large.

Power system and thermodynamic system are connected by CHP units in mains side. Since CHP units have thermoelectric characteristics constraint of forced power output determined by heat, it limits electric power. If CHP units can accommodate tremendous wind power curtailment by reducing forced power output result from forced power output determined by heat, insufficient heat supply of CHP units need be compensated. Since supply of heat by using electric boilers make high quality electric energy become low quality heat energy, electric boilers try to use wind power curtailment. If electric boilers supply heat without heat accumulator, electric loads of electric boilers are decided by heat loads and peak-load regulation ability of electric boilers are low. Therefore the project is composed that compensating supply heat and decoupling the constraint of forced power output determined by heat by configuring large electric boiler and heat accumulator for CHP units in the paper. The project can improve regulating capacity of CHP units.

Synergistic operation mechanism of electric boiler and heat accumulator for CHP of accommodating wind power curtailment is followed: When wind power output is small but electric loads are large, CHP units produce heat energy and heat accumulators store heat energy. When wind power output is large and wind power curtailment appear, on the one hand electric boilers that installed in CHP plant supply heat by consuming a part of wind power curtailment and electric power of CHP units are reduced by reducing heating power of CHP units, on the other hand electric power output of CHP units are further reduced by supplying heat of heat accumulators. The on-grid spaces of wind power are increased to accommodating wind power curtailment by reducing electric power output and lack of supply heat are compensated by electric boilers and heat accumulators. Accommodating curtailed wind power effectively is achieved with ensuring heating level. The principle of accommodating wind power curtailment is showed in Figure 1.
Economic Benefits of Wind Power Accommodation Based on Electric Boiler and Heat Accumulator

Costs Analysis of the Project
The costs consist of initial construction costs, operating and maintenance costs of electric boilers and heat accumulators. Initial construction costs consist of original equipment cost, construction cost and installation cost etc. and are calculated refer to existing projects. Maintenance costs consist of energy cost, operating personnel cost and quick-wear parts cost etc. and are calculated by a certain proportion according to initial construction costs.

Supposing capacity of electric boilers is $E_{BC}$, capacity of heat accumulators is $H_{AC}$, construction cost per unit of electric boilers is $E_{Bu}$, construction cost per unit of heat accumulators is $H_{Au}$, service life of electric boilers and heat accumulators are both $N$. In consideration of using curtailed wind power to supply heat for electric boilers, short-term cost of electric boilers is 0. Operating and maintenance costs of electric boilers and heat accumulators are respectively calculated by a certain proportion $\alpha$ and $\beta$. The total costs $C$ per year of electric boilers and heat accumulators is:

$$C = C_{EB} + C_{EB} + C_{EB} + C_{EB}$$

Benefits Analysis of the Project
According to the principle, benefit sources of accommodating curtailed wind power by electric boilers and heat accumulators include three parts: The first part is coal saving benefits of reducing consumption of coal by decreasing electric power of CHP units because of electric boilers supplying a part of heat instead of CHP units. The second part is coal saving benefits of reducing coal consumption by decreasing electric power of CHP units because of heat accumulators supplying a part of heat instead of CHP units. The third part is having a share in benefits of on-grid wind power owing to improving level of curtailed wind power by electric boilers and heat accumulators.

The first part benefit: saving consumption of coal per year $Q_{EB}$ by configuring electric boilers in combined heat and power plant:

$$Q_{EB} = 0.1228 \frac{C_{EB} \beta_{EB} (1 + \gamma_{CHP})}{\beta_{CLP} \gamma_{CHP}}$$

Figure 1. Diagram of accommodating wind power curtailment by combined heat and power plant.
Where $\beta_{EB}$ is heat production efficiency of electric boilers, $\beta_{CHP}$ is fuel efficiency of CHP units, $\gamma_{CHP}$ is heat-to-electric ratio of CHP units, $h_{EB}$ is average operation hours per year of electric boilers.

If the price of standard coal equivalent is $\nu$, coal saving benefits of electric boilers in combined heat and power plant:

$$B_{EB} = 0.1228 \frac{CEB\beta_{EB}(1 + \gamma_{CHP})}{\beta_{CHP}\gamma_{CHP}} h_{EB}$$

(3)

The second part benefit: when curtailed wind power that are accommodated by CHP is $W_W$, saving consumption of coal[3] is:

$$Q_{HA} = 0.1228 \frac{\beta_{EB}(1 + \gamma_{CHP})}{\beta_{CHP}(\beta_{EB} + \gamma_{CHP})} W_W$$

(4)

In view of increasing accommodation of curtailed wind power by supplying heat of heat accumulators similar to electric boilers, saving consumption of coal by heat accumulators increasing accommodation of curtailed wind power is calculated by formula (4). Coal saving benefits of heat accumulators per year:

$$B_{HA} = 0.1228 \frac{\beta_{EB}(1 + \gamma_{CHP})}{\beta_{CHP}(\beta_{EB} + \gamma_{CHP})} W_W$$

(5)

The third part benefit is environmental benefit: the environmental benefit is associated with the external and social benefit evaluations compared with the economic benefit based on coal costs in this system. The extra wind power accommodated by the power grid will replace a certain amount of thermal power generation. We define the reduction in pollutant and $CO_2$ emissions as the environmental benefit.

The environmental benefit of this project is based on $Q_{EB}$ and $Q_{HA}$ increasing (coal consumption decreasing) after the project is implemented. The environmental benefit evaluation model is given by:

$$B_{EH} = (Q_{EB} + Q_{HA}) \times \mu + (Q_{EB} + Q_{HA}) \times e_c \times \epsilon$$

(6)

Where $\mu$ is the pollutant emission cost per ton of coal, $e_c$ is the $CO_2$ emissions per ton of coal, and $\epsilon$ is the carbon emission cost.

The total benefits $B$ per year of electric boilers and heat accumulators is

$$B = B_{EB} + B_{HA} + B_{EH}$$

(7)

Example Analysis

A 300MW extraction condensation unit is as research subject in North China in the paper. Capacity of electric boilers is 10MW. Construction cost per unit of electric boilers is 1 million Yuan/MW. Capacity of heat accumulators is 20MW. Construction cost per unit of heat accumulators is 03 million Yuan/MW. Maintenance costs ratio of electric boilers and heat accumulators are respectively 1% and 2%. Service life are both 20 years. Heat production efficiency of electric boilers is 99%. Fuel efficiency of CHP units is 0.7 because of operating under backpressure condition or minimum condensing condition for CHP during curtailed wind. Heat-to-electric ratio of CHP is 1 and 2 respectively. Depreciations ratio is 5%. Average operation hours per year of electric boilers is 300h and 400h respectively. Coal price is 500 Yuan/t and amount to 715 Yuan/t of the price of standard coal equivalent. Pollutant emission cost per ton of coal $\mu$ is 80 Yuan/t. $CO_2$ emissions per ton of coal $e_c$ is 2.6 t. Carbon emission cost $\epsilon$ is 25 Yuan/t. Where initial construction costs(million Yuan)-IC, Maintenance costs(million Yuan)-MC, Curtailed wind power consumption(GWh)-CC, Power reduction(GWh)-PR, Coal saving(t)-CS, Benefits of coal saving(million Yuan)-BCS,
Accommodation wind power curtailment(GWh)-AC, Pollutant emission cost reducing(million Yuan)-PER, Carbon emission cost reducing(million Yuan)-CER, Electric boilers & Heat accumulators-EB&HA, Comprehensive profits(million Yuan)-CP.

Table 1. Analysis of costs and benefits.

| Items          | Electric boilers | Heat accumulators | The total costs per year/C | The total benefits per year/B |
|----------------|------------------|-------------------|---------------------------|-----------------------------|
|                | IC               | MC                | T                         | Electric boilers            | Heat accumulators | EB & HA | T         |
|                |                  |                   |                           | CC | PR | CS | BCS | AC | CS | BCS | PER | CER | CP |
| $h_{1, h} = 300 h$ | $\gamma_{err} = 2$ | $50$              | $10$                      | $30$ | $12$ | $102$ | $3$ | $1485$ | $782$ | $55.9$ | $13.5$ | $2352$ | $168$ | $25.1$ | $20.4$ | $26.9$ | $167.4$ |
| $h_{2, h} = 400 h$ | $\gamma_{err} = 2$ | $50$              | $10$                      | $30$ | $12$ | $102$ | $4$ | $1980$ | $1042$ | $74.5$ | $13.5$ | $2352$ | $168$ | $27.2$ | $22.1$ | $29.2$ | $189.7$ |
| $h_{3, h} = 400 h$ | $\gamma_{err} = 1$ | $50$              | $10$                      | $30$ | $12$ | $102$ | $4$ | $3960$ | $1389$ | $99.3$ | $13.5$ | $2352$ | $168$ | $29.9$ | $24.3$ | $32.2$ | $219.6$ |

Conclusion

The results of the paper indicate that installing electric boiler and heat accumulator for CHP units can increase wind power accommodation and there are significant benefits of coal saving by using wind power to supply power and heat instead of CHP units. Since some factors such as average operation hours per year of electric boilers $h_{EB}$ and heat-to-electric ratio of CHP units $\gamma_{CHP}$ dramatically influence economic benefits of the project, the project has priority to be applied to the conditions of large curtailed wind power, long curtailed wind time and small heat-to-electric ratio of CHP units.

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