Scheduling model of power system with renewable energy and transaction mode of direct electricity purchase by large consumers considering network security constraints

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Abstract: The policy of transaction mode of direct electricity purchase by large consumers will further reduce the power system scheduling space. When large-scale non-controllable wind turbines and photovoltaic power stations are connected to the system, the optimal scheduling of the system will face even more severe challenges. In order to analyse the impact of the direct purchase of large consumers on the system capacity of renewable energy, this paper proposes a scheduling model of power system with renewable energy and transaction mode of direct electricity purchase by large consumers considering network security constraints. By taking into account the network security constraints, this model can compute large power system and analyse the impact of the direct electricity purchase unit access node on renewable consumption capacity of the system. To illustrate the effectiveness of the proposed model, a real power system in a northern province of China is used in the case study. The consumed renewable energy is calculated and the reason for the wind and solar power curtailment is analysed. The influence of real-time price, contract size, and the unit access node of the direct electricity purchase on renewable energy consumption capacity of the system is analysed.

1 Introduction

On March 15, 2015, the ‘CPC Central Committee and State Council's Opinions on Further Deepening the Reform of the Electric Power System’ marked the start of a new round of power system reform that has drawn much attention from all sectors of society. The document proposes to establish a market-oriented mechanism to solve the problems in power development. The goal of the reform is to restore the attributes of electric power commodities and establishes an effective and competitive electricity market. As an important part of opening the sales side of the electricity market, the direct purchase of electricity policy is of extraordinary significance. Large users direct purchase of electricity will break the single-grid buyer's pattern and lay the foundation for the establishment of the more to buy and sell market structure. The implementation of direct purchase electricity policy promotes the sharing of market risk and the self-balancing of power supply side and load side [1]. With the accumulation of direct-purchase electricity operation experience, the threshold of ‘big users’ will continue to decrease until all users can purchase power directly [2]. The implementation of direct purchase requests the independence between transmission price and distribution price, and helps to establish a reasonable price formation mechanism [3].

When large-scale wind and solar units are integrated into the grid, some of the power generation output becomes uncontrollable. Due to the randomness and volatility of wind and sunshine, the power output of renewable units is unpredictable, the output of conventional units needs to be adjusted frequently to maintain the system balance, and the reliability of power supply is greatly reduced [4–7]. Large-scale renewable energy sources access not only adds a lot of new instability to the system operation, but also put forward higher requirements to the system economic scheduling problems [8].

In terms of the model and pricing mechanism of the large-user direct purchase transaction, [9] starts from the bidding algorithm of direct electricity purchase and gives three kinds of transaction methods and puts forward a fast solution of direct purchase model. [10] gives a new centralised matching transaction and promotes fair competition in the market. For power system dispatching aspects, [11] sets up a scheduling model with large-scale wind power and transaction mode of direct electricity purchase by large consumers. However, that model does not consider transmission line capacity constraints, which means it cannot compute large system.

This paper proposes a scheduling model with renewable energy and transaction mode of direct electricity purchase by large consumers considering network security constraints. Considering the grid security constraints makes possible analysing the renewable energy consumption ability of large power system more accurately than before. Moreover, we can find the weak part of the grid which limits the consumption of wind or solar energy and then reinforces the grid correspondingly.

2 Scheduling model with renewable energy and transaction mode of direct electricity purchase by large consumers

2.1 Objective function

The model's goal is maximising the profit of the power-generation companies. The objective function consists of three parts: the revenue from selling electricity to grid operators, the operation, start up, and shutdown costs of thermal units, and the penalty of curtailing wind and solar energy. It is formulated as follows:
The proposed formulation's constraints related to every generating unit, are formulated as follows:

$$\begin{align*}
    &c_{i,j} = a_i(p_{i,j}^N + p_{i,j}^Z) + b_i(p_{i,j}^N + p_{i,j}^H) + c_i v_{i,j}^N \\
    &c_{i,t}^l = \frac{\lambda_i - v_{i,t-1}^l + v_{i,t-1}^l - v_{i,t}^l}{2} \\
    &c_{i,t}^n = \frac{\lambda_i - v_{i,t}^n + v_{i,t}^n + v_{i,t-1}^n}{2}
\end{align*}$$

where $a_i, b_i, c_i$ are the coefficients of the quadratic production cost function of thermal unit $i$. $v_{i,t}^l$ is the binary state variable of thermal unit $i$. $c_{i,t}^{on}, c_{i,t}^{off}$ are start up and shutdown costs of thermal unit $i$.

### 2.2 Constraints of generating units

The proposed formulation's constraints related to every generating unit over the time span is described next.

i. **Generation Limit Constraints of Thermal Units:**

$$P_i^N \cdot v_{i,t}^N \leq P_{i,t}^N \leq P_i^N \cdot v_{i,t}^N$$

where $P_i^N$ is the capacity of thermal unit $i$ and $P_i^N$ is the minimum power output of thermal unit $i$.

ii. **Ramping Limit Constraints of Thermal Units:**

$$R_{i,t}^{N,down} \leq P_{i,t}^N - P_{i,t-1}^N \leq R_{i,t}^{N,up}$$

where $R_{i,t}^{N,up}, R_{i,t}^{N,down}$ are the limit ramp-up and ramp-down limit of thermal unit $i$.

iii. **Minimum Up and Down Time Constraints of Thermal Units:**

$$T_{i,t}^{N,on} \geq T_i^{N,U}$$
$$T_{i,t}^{N,off} \geq T_i^{N,D}$$

where $T_{i,t}^{N,on}$ is the number of periods thermal unit $i$ has been online prior to the shutdown in period $i$, $T_{i,t}^{N,off}$ is the number of periods thermal unit $i$ has been offline prior to the start up in period $i$. $T_i^{N,U}, T_i^{N,D}$ are the minimum online and offline operation times of the thermal unit $i$.

iv. **Generation Limit Constraints of Hydro Units:**

$$P_i^H \cdot v_{i,t}^H \leq P_{i,t}^H \leq P_i^H \cdot v_{i,t}^H$$

where $P_i^H$ is the capacity of hydro unit $i$ and $P_i^H$ is the minimum power output of hydro unit $i$. $v_{i,t}^H$ is the binary state variable of hydro unit $i$.

v. **Water Limit Constraints of Hydro Units:**

$$W_i \leq \sum_{t \in N} p_{i,t}^H \leq W_i$$

where $W_i, W_j$ are maximum and minimum water limits of hydro unit $i$.

vi. **Generation Limit Constraints of Wind and Solar Plants:**

$$0 \leq P_{i,t}^W \leq P_i^W$$

$$0 \leq P_{i,t}^S \leq P_i^S$$

where $P_i^W, P_i^S$ are the power output in the period $t$ of wind and solar plants $i$, and $P_{i,t}^W, P_{i,t}^S$ are the predicted power output in the period $t$ of wind and solar plants $i$.

### 2.3 Constraints of electrical power system

i. **Constraints of Power Balance:**

$$\sum_{i \in N_h} p_{i,t}^H + \sum_{i \in N_w} p_{i,t}^W + \sum_{i \in N_s} p_{i,t}^S = \sum_{j \in J} D_{j,t}$$

where $D_{j,t}$ is the electrical load of node $j$ in the period $t$.

ii. **Constraints of Spinning Reserve:**

$$\sum_{i \in N_h} p_{i,t}^H \cdot v_{i,t}^H + \sum_{i \in N_w} p_{i,t}^W \cdot v_{i,t}^W \geq (1 + r) \sum_{j \in J} D_{j,t}$$

where $r$ is the spinning reserve rate of the system.

iii. **Constraints of Line Capacity:**

$$-P_{l,t}^{line} \leq P_{l,t}^{line} \leq P_{l,t}^{line}, \quad \forall l \in \mathcal{L}$$

where $P_{l,t}^{line}$ is the capacity of line $l$, $L$ is the set of all transmission lines, and $P_{l,t}^{line}$, the power flow in the line $l$, is formulated as follows:

$$P_{l,t}^{line} = \sum_{j \in \mathcal{N}_l} G_{j,t} \left( \sum_{i \in \mathcal{N}_j} p_{i,t}^H + \sum_{i \in \mathcal{N}_j} p_{i,t}^W + \sum_{i \in \mathcal{N}_j} p_{i,t}^S + \sum_{i \in \mathcal{N}_j} p_{i,t}^H \right)$$

$$+ \sum_{i \in \mathcal{N}_j} p_{i,t}^H - D_{j,t}$$

where $G_{j,t}$ is the generation shift distribution factor of line $l$ and node $j$, $D_{j,t}$ is the electrical load of node $j$ in the period $t$ and $\mathcal{N}_j, \mathcal{N}_j^H, \mathcal{N}_j^W, \mathcal{N}_j^S$ represent the set of thermal units, hydro units, wind plants or solar plants $i$, which are connected to the node $j$.

iv. **Constraints of Tie Line:**

$$-F_{f} \leq \sum_{i \in \mathcal{N}_f} |P_{f}^{line}| \leq F_{f}$$

where $F_{f}$ is the transmission limits of the tie line $f$, $\mathcal{N}_f$ is the set of lines that are contained by the tie line.

Considering the grid security constraints makes possible analysing the renewable energy consumption ability of large power system more accurately than before. Moreover, we can find the
which is described as follows:

Non-direct purchase contract occupies a large proportion, enough to absorb the direct purchase contract constraints use of electricity constraints, weak part of the grid which limits the consumption of wind or solar energy and then reinforces the grid correspondingly.

2.4 Constraints of direct purchase contract

It is assumed that in the total load of large users, the load of direct purchase contract occupies a large proportion, enough to absorb the power output of direct purchase units in each period. Non-direct purchase load is still provided by the grid normal dispatch. The direct purchase contract constraints use of electricity constraints, which is described as follows:

$$\sum_{t \in T} P^N_{i,t} = Z^N_i$$  \hspace{1cm} (17)

where $Z^N_i$ is the direct purchase contract electricity of the thermal unit $i$.

3 Case study

3.1 Basic data of the test system

The case study is based on an actual power system in a province of north China. The total installed capacity of thermal, hydro, wind, and photovoltaic units are 29767, 1104, 2806.3, and 3972.3 MW, respectively. The forecasts of electric load are shown in Fig. 1. The predicat available wind power and solar power on a typical winter day are shown in Fig. 2.

Owing to two areas' ample transmission capacity, the areas are simplified as two nodes, node 1 and node 2. Then, the actual system is simplified as a 18-node system. The access location and total installed capacity of wind plants, and solar plants are illustrated in Fig. 3. Three tie lines are considered in the test system, and their transmission limits are 1200, 1300, and 1150 MW.

3.2 Set price curves and direct purchase unit access locations

Here, real-time electricity prices are used to calculate the revenue of non-direct purchase unit. A day's 24 h is divided into peak hours, flat hours, and valley hours: 0:00–6:00 for the valley hours, 10:00–15:00 and 19:00–21:00 for peak hours, the rest are flat hours.

The direct purchase contractual constraints are the constraint of electric energy, not the constraint of electric power, so the power-generation companies have the option in how to use the direct purchase of electric energy. Different direct purchase of electricity price setting will stimulate power generation companies to change the distribution of direct purchase electricity.

This paper selected three typical direct purchase electricity price curves to study the impact of the direct purchase price on the renewable energy consumption capacity of the system, the value of each electricity price curve is shown in Table 1. In Table 1, DP1, DP2, and DP3 represent direct purchase price 1, direct purchase price 2, and direct purchase price 3.

Due to the direct purchase, contract occupies the output of thermal power units, resulting in direct purchase units peak regulation capacity decreased significantly. In the meantime, power plants are more inclined to use direct-purchased energy when the maximum economic benefits of direct power purchase are obtained, which may conflict with the renewable energy consumption of the system. In order to fully analyse the impact of signing a direct purchase contract on the system, three typical locations, node 2, node 18, node 11, were selected in the grid, which represents the load centre, the generator centre, and the central node of the grid. For each node, two 300MW thermal units are set to sign the direct purchase contract with large consumers.

3.3 Basic renewable energy-consumption capacity of the system

Use the solver CPLEX to solve the model, and get the generation power of each unit and the curtailed renewable energy of each hour. The generated power of each type of units is shown in Fig. 4. The curtailed wind and solar energy of each hour are shown in Figs. 5 and 6.

In the early hours (from 2 o’clock to 6 o’clock), there is a larger amount of curtailed wind power and the rest of the day can almost fully absorb the wind power. The reason for curtailing the wind is that the wind power is very large at night, and the load of the area where the wind turbine mainly concentrates is small. Also, it is difficult for the other nodes to carry out the peak shaving support because of the tie line constraints. As for curtailing solar power, the tie line constraints are the dominant factor.

Curtailment rates of wind and solar energy of each node that accesses to the renewable units are shown in Tables 2 and 3.

It can be seen that there are differences in the curtailment of wind and solar energy at different nodes. At node 1, there are less...
wind and solar units and more hydro units whose peak regulation ability is very ample, so the wind and solar energy can be fully consumed. At node 2, there are lots of thermal units which in winter have to supply heat load and have poor peak regulation ability, therefore, some wind and solar energy are curtailed. At nodes 3–18, there are lots of wind and solar units and thanks to the tie line limits, lots of wind and solar energy are curtailed, especially in node 10.

### 3.4 Impact of different direct purchase price curves on renewable energy consumption

When direct purchase units are located separately at three nodes, each of which signed a 5000 MWh direct purchase contract, calculate the system's total profit and curtailment rates of wind and solar energy of each node at the different direct purchase price curve. Three different direct purchase price curves in Table 1 are selected. The results are shown in Table 4.

From Table 4, it can be seen that directly purchased price curves have a great impact on the system's renewable energy consumption capacity at node 11 and node 18. Compared to the non-direct purchase scene, the curtailed solar energy rate of DP1 greatly improves, the curtailed wind and solar energy rates of DP2 stay unchanged, and the curtailed wind energy rate of DP3 greatly improves. The reason is that DP1 has the highest price difference during the peak hours so the direct purchase energy tends to be used during the peak hours. During the peak hours, photovoltaic power output is very large and the distribution of direct purchase power squeezes the space for solar consumption, resulting in the increase of solar energy curtailment rate. DP2 has the highest price difference during the peak hours so the direct purchase energy tends to be used during the peak hours. During the peak hours, photovoltaic power output is very large and the distribution of direct purchase power squeezes the space for solar consumption, resulting in the increase of solar energy curtailment rate.

| Node | Direct purchase price curve | Curtailed wind energy/MWh | Consumed wind energy/MWh | Curtailed wind energy rate/% |
|------|------------------------------|---------------------------|--------------------------|----------------------------|
| 1    | 400                          | 0                         | 176.878                  | 0                          |
| 2    | 839.8                        | 0                         | 3713.5535                | 0                          |
| 4    | 30                           | 0                         | 132.6585                 | 0                          |
| 10   | 590                          | 500                       | 245.2759                 | 9.3874                     |
| 12   | 949.5                        | 0                         | 3666.5680                | 19.8177                    |
| 13   | 260                          | 0                         | 162.6792                 | 16.4240                    |
| 14   | 200                          | 140                       | 744.3900                 | 15.8301                    |
| 15   | 410                          | 0                         | 1812.9994                | 10.9277                    |
| 16   | 80                           | 0                         | 353.7560                 | 0                          |
| total| 2806.3                       | 2581.557                  | 12764.44                 | 16.8224                    |

| Node | Direct purchase price curve | Curtailed solar energy/MWh | Consumed solar energy/MWh | Curtailed solar energy rate/% |
|------|------------------------------|---------------------------|--------------------------|----------------------------|
| 1    | 400                          | 0                         | 176.878                  | 0                          |
| 2    | 839.8                        | 0                         | 3713.5535                | 0                          |
| 4    | 30                           | 0                         | 132.6585                 | 0                          |
| 8    | 353                          | 319.0941                  | 1241.8542                | 20.4423                    |
| 10   | 590                          | 746.7697                  | 1862.1808                | 28.6234                    |
| 12   | 949.5                        | 832.0733                  | 3366.5680                | 19.8177                    |
| 13   | 260                          | 188.8278                  | 960.8792                 | 16.4240                    |
| 14   | 200                          | 140                       | 744.3900                 | 15.8301                    |
| 15   | 410                          | 0                         | 1812.9994                | 10.9277                    |
| 16   | 80                           | 0                         | 353.7560                 | 0                          |
| total| 3972.3                       | 2228.919                  | 15336.39                 | 12.6893                    |
purchase contract brings economic benefits to the system. Different contract constraints of two units have a greater impact on the economic benefits of the system increase with the increase of direct purchase power. Squeeze the space for wind power, direct purchase price brings different economic benefits. DP1 has a higher price difference during the valley hours when wind power is very large, therefore the distribution of renewable energy consumption ability of the system. For node 2, the consumption capacity of the system.

In addition, compared to no direct purchase scene, direct purchase contract brings economic benefits to the system. Different direct purchase price brings different economic benefits. DP1 has the most economic benefits, DP2 has the least economic benefits.

| Node | Price curve | Total profit/$10^6 | Curtailed rate of wind power/% | Curtailed rate of solar power/% |
|------|-------------|-------------------|-----------------------------|-----------------------------|
| 2    | NDP         | 38.8440           | 16.8224                     | 12.6893                     |
|      | DP1         | 39.0739           | 16.8224                     | 12.6893                     |
|      | DP2         | 38.9627           | 16.8224                     | 12.6893                     |
|      | DP3         | 39.0013           | 16.8224                     | 12.6893                     |
| 11   | NDP         | 38.8440           | 16.8224                     | 12.6893                     |
|      | DP1         | 39.0490           | 17.5202                     | 18.3304                     |
|      | DP2         | 38.9576           | 16.8224                     | 12.6893                     |
|      | DP3         | 38.9898           | 18.9066                     | 12.8368                     |
| 18   | NDP         | 38.8440           | 16.8224                     | 12.6893                     |
|      | DP1         | 39.0384           | 17.4125                     | 19.7384                     |
|      | DP2         | 38.9556           | 16.8224                     | 12.6893                     |
|      | DP3         | 38.9823           | 18.5385                     | 12.8300                     |

Table 4: Total profit and curtailment rates of wind and solar energy of each node at different direct purchase price curve

Table 5: Total profit and curtailment rates of wind and solar energy of each node at different direct purchase contract size

| Node | Direct purchase electricity/MWh | Total profit/$10^6 | Curtailed rate of wind power/% | Curtailed rate of solar power/% |
|------|---------------------------------|-------------------|-----------------------------|-----------------------------|
| 2    | 4000                            | 38.9828           | 16.8224                     | 12.6893                     |
|      | 5000                            | 39.0013           | 16.8224                     | 12.6893                     |
|      | 5500                            | 39.0105           | 16.8224                     | 12.6893                     |
|      | 6000                            | 39.0173           | 16.8224                     | 12.6893                     |
| 11   | 4000                            | 38.9734           | 16.8525                     | 12.8368                     |
|      | 5000                            | 38.9899           | 18.9066                     | 12.8386                     |
|      | 5500                            | 38.9999           | 18.9066                     | 12.8386                     |
|      | 6000                            | 39.0021           | 18.9066                     | 12.8386                     |
| 18   | 4000                            | 38.9666           | 16.8224                     | 12.8300                     |
|      | 5000                            | 38.9883           | 18.5385                     | 12.8300                     |
|      | 5500                            | 38.9883           | 18.5385                     | 12.8300                     |
|      | 6000                            | 38.9902           | 19.1316                     | 15.3905                     |

4 Conclusion

This paper proposes a scheduling model with renewable energy and transaction mode of direct electricity purchase by large consumers. Considering the network security constraints, this model can compute large power system and analyse the impact of the direct electricity purchase unit access node on renewable consumption capacity of the system. The results of the case study show that in node 2 which has large load, a large number of thermal and hydro-generating units and ample transmission lines, a small number of units signed direct purchase contracts have little effect on the curtailment rate of wind and solar energy. On the contrary, node 11 and node 18 has little load, a large number of renewable generating units and inadequate transmission lines. A small number of units signed direct purchase contracts will increase the curtailment rate of wind and solar energy greatly. Since direct purchase units tend to use the direct purchase price electricity when the difference between the direct purchase price and the grid power price is the largest, adjusting the direct purchase price curve can guide the direct purchase unit to use the most direct purchase power at a specific time, which has different impacts renewable energy consumption ability of the system. At the node 8 and node 11, using DP 1 whose price difference is largest in the peak hours will result in an increase of the curtailment rate of solar energy. Using DP 2 whose price difference is largest in the flat hours will have little effect on renewable energy consumption. Using DP3 whose price difference is largest in the valley hours will result in an increase of the curtailment rate of wind energy. To reduce this adverse effect, DP 2 can be adopted in these areas, the economic benefits of direct purchase are sacrificed properly, and the direct purchase unit is guided to deviate from the period of renewable energy generation so as to avoid the curtailment of wind and solar energy.
5 Acknowledgments
This work was supported in part by the National Key R&D Program of China (2017YFB0902200), in part by the State Grid Science and Technology Program ‘Simulation technology research on multi-trading concurrent operation and trading platform adapting to electricity retail-side deregulation’ under Grant DZN17201700175.

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