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Unit Commitment under the Environment of Wind Power and Large-Scale Bilateral Transactions

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Abstract

Bilateral electric power contract is settled based on contract output curve. This paper considered the bilateral transactions execution, new energy accommodation, power grid security and generation economy, considering the executive priority of different power components to establish a multi-objective coordination unit commitment model. Through an example to verify the effectiveness of the model in promoting wind power consumption, guaranteeing trade execution, and improving power generation efficiency, and analyzed the interactions to each other among the factors of wind power, trading and blocking. According to the results, when wind power causes reverse power flow in the congestion line, it will promote the implementation of contracts, the influence of wind power accommodation to trade execution should be analyzed combined with the grid block, the results can provide reference for wind power planning.

Keywords

Bilateral Electric Power Contract, Unit Commitment, Wind Power Accommodation, Transaction Execution, Congestion

1. Introduction

Differs from foreign typical electric power market, electricity market in our country is still in the phase of transition from traditional scheduling to fully market. It is neither an American PJM full power centralized price bidding, nor the British market both generator and users to submit the output curve, due to both market power and planned power, and the lack of full power offer or increase or decrease offer for power balance, bilateral deals abroad to participate in the power balance method is not suitable for the current stage in our country.

Related researches have been carried out in our country as follows. Literature [1] analyzed the bilateral trade mode under wholesale competition market, according to the market target to propose the bilateral trade model, and the corresponding settlement algorithm is analyzed according to the different model. Literatures [2] [3] [4] [5] introduced the experience of foreign typical bilateral trade market mode from aspects of the bilateral transaction subjects, types, means of exchange and so on, a method is. Literatures [6] [7] [8] [9] [10] introduced the bilateral trade pricing, game model and trading strategy optimization problems. Literature [11] analyzed the bilateral trade trading mode, offer model and the model of deal-making, by using the model trading scheme simulation calculation is studied. The literature [12] introduced the bilateral trade practice carried out in the south power market. Overall, the study of the bilateral trade is more focused on the operation of the bilateral trade mode, it is lack of the study on bilateral electricity contract to participate in power balance.

This article put forward a unit commitment model, which would achieve the coordination of a variety of objectives, promoting wind power consumption, ensuring contracts execution, achieving different power components coordination, guaranteeing fairness among power plants.

2. Multi-Objective Coordinated Optimization Modeling Method

The unit commitment model needs to meet general requirements as follows: first, consider uncertainty of wind power and grid security to promote the accommodation of wind power; second, take transaction execution, generation economy and security into consideration, find the unit commitment that costs least meanwhile transaction executes the most and wind power consumption is ensured.

Using the confidence interval method to model the uncertainty of wind power uncertainty [13] [14], according to the wind power prediction and error distribution model to obtain wind power fluctuations confidence interval, take the upper and lower limits of interval as wind power extreme scenarios. The cost of wind power is not considered into the power generation cost, according to the wind power purchase policy, this article will give priority to ensure that wind power consumption, to achieve the above goal, wind power uncertainty model will be treated as constraints, given a confidence interval, wind power generation output within the interval can be consumed totally.

Establish bilateral electric power contract and Sangong contract respectively, thus the optimization results can directly reflect the implementation of different power components, obtaining bilateral perform curve and Sangong completion. According to the implementation priority of the contract, set the weight of the different components of power, to minimize the total contract reduction. At the same time, establish related constraints on bilateral electric power contract and Sangong contract, to ensure that all types of contract reduction taking into account of the fair implementation among power plants.

Contract completion rate related to power plants interests, through contract reduction factor to achieve the fair distribution of contract reductions among the power plants. When the bilateral transaction is an electric quantity contract, there is only one contract cutting factor for both bilateral and Sangong power, while the bilateral power contract is electric power contract, the bilateral and Sangong power will respectively use different cutting factors. The bilateral electric power contract cutting factor is shown in (1), Sangong contract cutting factor is shown in (2).

$$SX_i = \frac{HS_i}{\sum_i HS_i} \tag{1}$$

$$JX_i = \frac{HJ_i}{\sum_i HJ_i} \tag{2}$$

In Equation (1), SX_i is the bilateral electric power contract cutting factor for plant i; HS_i is the total amount of bilateral power for plant i; JX_i is the Sangong contract cutting factor for plant i; HS_i is the total amount of Sangong power for plant i.

Power generation enterprises want to maximize the transaction execution at the lowest cost, through the establishment of power generation economy goal, the optimization process will automatically find the optimal allocation of units, the better economy the unit will be given priority to power generation to complete its power plant contract, to ensure that the power plant complete the contract requirements at the lowest cost.

3. Objective Function

In order to balance the implementation of the contract and power generation economy, this paper used joint optimization of the contract adjustment and power generation cost, the priority of the two types of targets is coordinated by introducing the penalty factor M_1 and M_2, the objective function is shown as Equation (3).

$$\min \quad (W_1 \bullet \Delta S + W_2 \bullet \Delta J) \bullet M_1 + C(P) \bullet M_2 \tag{3}$$

In Equation (3), part of symbols expression is as follows:

$$\Delta S = \sum_{g=1}^{H} \sum_{t=1}^{T} P_{g,t,0} - \sum_{i=1}^{N} \sum_{t=1}^{T} P_{i,S,t} \tag{4}$$

$$\Delta J = \sum_{g=1}^{H} J_{g,0} - \sum_{i=1}^{N} \sum_{t=1}^{T} P_{i,J,t} \tag{5}$$

$$C(P)=\sum_{i=1}^{N} \sum_{t=1}^{T} (f_{i,t} + S_{Ui,t} + S_{Di,t}) \tag{6}$$

Equation (4) is the amount of bilateral transaction cutting, Equation (5) is the amount of Sangong contract cutting, Equation (6) is generation cost, including operation cost, start-up cost and downtime cost.

In the above equations, all the variables in the objective function are the values under the wind power prediction scenario. H is number of thermal plant; N is number of thermal unit; T is number of time intervals; W_1 is the execution weight of bilateral electric contract; W_2 is the execution weight of Sangong contract; M_1 is the penalty factor of contract reduction; M_2 is the penalty factor of generation cost; ΔS is the total amount of bilateral transaction reductions (MWh); ΔJ is the total amount of Sangong contract reductions (MWh); $P_{g,t,0}$ is the bilateral transaction output for plant g at time t(MW); $J_{g,0}$ is the quantity of Sangong contract for plant g (MWh); $P_{i,S,t}$, $P_{i,J,t}$ is the actual output corresponding to bilateral transaction and Sangong contract respectively for unit i at time t (MW); $f_{i,t}$ is the operation cost for unit i at time t; $S_{Ui,t}$, ${}_{Di,t}$ is the start-up cost and downtime cost respectively.

M_1 and M_2 are decided in accordance with the priority of transaction execution and power generation economy, when the contract execution is given priority, the order of magnitude of M_1 is much higher than M_2, otherwise, M_2 is much higher than M_1. W_1 and W_2 will be decided in accordance with the priority of different power components, when the bilateral power is given priority, W_1 will take a larger value, otherwise, W_2 will take a larger value, specific options need to be combined with relevant national policies and rules.

4. Constraints

According to "the worst feasible and the expect optimal" optimization principle, constraints consist of two parts: constraints under wind power prediction scenario and constraints under wind power extreme scenarios. The wind power prediction scenario is the desired operating condition, it is going to ensure the realization of wind power consumption, transaction execution, system operation safety and power generation economy under the desired operating conditions. The constraints under wind power extreme scenarios improve the reliability of unit commitment.

4.1. Constraints under Predicted Wind Power Scenario

Constraints under predicted wind power scenario including power balance, unit operation limits, constraints related to bilateral transactions and Sangong contracts, power flow and reserve requirements, etc., as follows:

$$\sum_{i=1}^{N} P_{i,t} + \sum_{j=1}^{W} P_{wj,t} = L_t \tag{7}$$

$$\Delta S_g = \sum_{t=1}^{T} P_{g,t,0} - \sum_{i\in N_g}\sum_{t=1}^{T} P_{i,S,t}, \quad g=1,2,\cdots,H \tag{8}$$

$$\Delta S_g = SX_g \bullet \Delta S \tag{9}$$

$$P_{g,t,0} - \sum_{i\in N_g} P_{i,S,t} \geq 0 \tag{10}$$

$$\Delta J_g = J_{g,0} - \sum_{i\in N_g}\sum_{t=1}^{T} P_{i,J,t} \tag{11}$$

$$\Delta J_g = JX_g \bullet \Delta J \tag{12}$$

$$P_{i,t} = P_{i,S,t} + P_{i,J,t} + P_{i,z,t},\quad i=1,2,\cdots,N \tag{13}$$

$$P_{i,\min} I_{i,t} \le P_{i,t} \le P_{i,\max} I_{i,t} \tag{14}$$

$$\boldsymbol{k}(\boldsymbol{P},\boldsymbol{I})=0 \tag{15}$$

$$\boldsymbol{y}(\boldsymbol{P},\boldsymbol{I}) \le 0 \tag{16}$$

$$\sum_{i=1}^{n} \left| A_{li} P_{i,in} \right| \le F_{l,max},\ l=1,2,\cdots b \tag{17}$$

$$\Delta J_g \ge 0, P_{i,S,t} \ge 0, P_{i,J,t} \ge 0, P_{i,z,t} \ge 0, \boldsymbol{I} \in (0,1) \tag{18}$$

In the above equations, H is number of thermal plant; N is number of thermal unit; T is number of time interval; $\boldsymbol{P}$ is thermal unit output column under predicted wind power, its element $P_{i,t}$ is the output of unit i at time t(MW); $\boldsymbol{I}$ is the operation state column of thermal units, its element $I_{i,t}$ is the operation state of thermal i at time t; $P_{wj,t}$ is the predicted power of wind farm j at time t(MW); L_t is load forecast at time t(MW); ΔS_g is bilateral transaction reductions of plant g(MWh); SX_g is bilateral transaction cutting factor of plant g; $P_{i,z,t}$ is other component of $P_{i,t}$ for unit i at time t(MW); N_g is all the units number of plant g; ΔJ_g is the Sangong contract reduction of plant g(MWh); JX_g is Sangong contract cutting factor of plant g; $P_{i,\max}$, $P_{i,\min}$ is the upper and lower limit of the output of unit i respectively (MW); n is number of node; b is number of branch; A_{li} is sensitivity factor of branch l to net power injection of node I; $F_{l,\max}$ is the upper limit of power flow for branch l(MW); $F_{i,in}$ is the net power injection of node i(MW).

Equation (7) is power balance constraint under predicted wind power scenario. Equation (8) is the expression of bilateral transaction reduction of plant g. Equation (9) is the relationship of bilateral transaction reduction between plant g and the total reductions all the system. Equation (10) is the actual bilateral output limit of plant g at time t, which can ensure the bilateral transaction reduction non-negative for plant g at time t, preventing the occurrence of the positive adjustment and negative adjustment offset each other during different periods of time, as is shown in **Figure 1**, constraint (10) will prevent the occur-

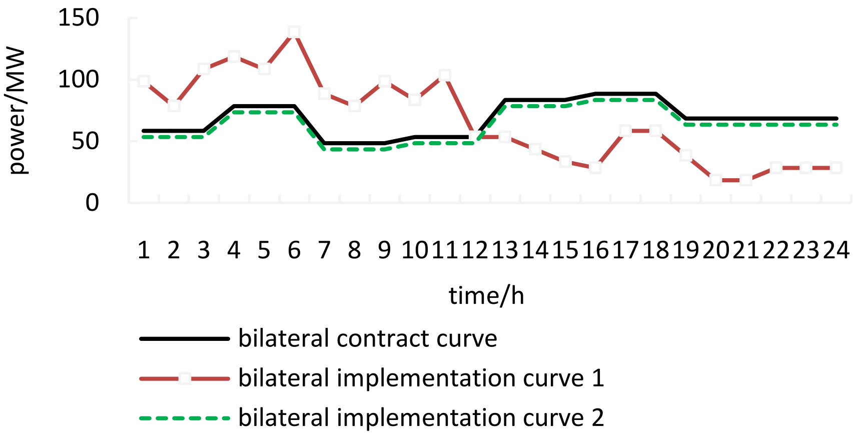

Figure 1. Comparison of two bilateral output curves.

rence of bilateral output curve 2, and control the output implementation like curve 1. Equation (11) is the expression of Sangong contract reduction of plant g. Equation (12) is the relationship of Sangong contract reduction between plant g and the total reductions all the system. Equation (13) is the expression based on various power components of unit output. Equation (14) is unit output limit constraint. Equation (14) is unit output limit constraint. Equality constraints (15) and inequality constraints (16) are common basic constraints, including thermal power unit start variables and outage variables related constraints, minimum on/off time constraints, up-regulation and down-regulation reserve constraints, climbing constraints. Equation (17) is power flow limit constraints. Equation (18) is variable limit constraint, $\Delta J_g \geq 0$ is contract reduction non-negative constraints of Sangong contract for plant g, which can prevent Sangong contract reduction is negative, and the bilateral transaction reduction is positive, resulting in Sangong reduction and bilateral reduction offset each other for power plant total contract reduction.

4.2. Constraints under Wind Power Extreme Scenarios

Constraints under wind power extreme scenarios is for considering the uncertainty of wind power, to improve the system ability to absorb random wind power, and does not involve the implementation of the transaction, this part constraints include the power balance constraint, the reserve constraint, the power flow constraint, the thermal power unit running limit constraint and the system up and down regulation constraints under the coupling wind power limit scenes.

$$\sum_{i=1}^{N} P_{i,t}^{s} + \sum_{j=1}^{W} P_{wj,t}^{s} = L_t \tag{19}$$

$$P_{i,\min} I_{i,t} \leq P_{i,t}^{s} \leq P_{i,\max} I_{i,t} \tag{20}$$

$$\boldsymbol{k}(\boldsymbol{P}^{s},\boldsymbol{I})=0 \tag{21}$$

$$\boldsymbol{y}(\boldsymbol{P}^{s},\boldsymbol{I}) \leq 0 \tag{22}$$

$$\sum_{i=1}^{n} \left| A_{li} P_{i,in}^{s} \right| \leq F_{l,max},\ l=1,2,\cdots b \tag{23}$$

$$dL_t^s = L_t - \sum_{k=1}^{W} P_{wk,t}^{s} \tag{24}$$

$$\sum_{i=1}^{N} [\, min\left\{P_{i,max} - P_{i,t-1}^{1}, R_i\right\} I_{i,t-1} I_{i,t} + P_{\mathrm{i},min} u_{i,t} - P_{i,min} v_{i,t}\,] \geq dL_t^2 - dL_{t\text{-}1}^1 \tag{25}$$

$$\sum_{i=1}^{N} [\, min\left\{P_{i,t-1}^{2} - P_{i,min}, D_i\right\} I_{i,t-1} I_{i,t} + P_{i,min} v_{i,t} - P_{i,min} u_{i,t}\,] \geq dL_{t-1}^2 - dL_t^1 \tag{26}$$

$$I \in (0,1),\ P_{i,t}^{s} \geq 0 \tag{27}$$

In the above equations, N is number of units; the superscript s represents the wind power extreme scenario, 1 is the upper limit of the confidence interval of the wind power, and 2 is the lower limit of the confidence interval, variable with the superscript s indicate that the variable is the value under the wind power extreme scenario s. $u_{i,t}$, $v_{i,t}$ is start-up variable and switch-off variable of unit i

at time t respectively; $P_{wj,t}^{s}$ is the output of wind farm j at time t under extreme scenario s(MW); $P_{i,t-1}^{1}$, $P_{i,t}^{1}$ is the output of thermal unit i at time $t-1$ and time t under upper extreme scenario 1 respectively(MW); $P_{i,t-1}^{2}$, $P_{i,t}^{2}$ is the output of thermal unit i at time $t-1$ and time t under lower extreme Scenario 2 respectively(MW); dL_t^s is the equivalent load at time t under extreme scenario s; dL_{t-1}^{1}, dL_t^1 is the equivalent load at time $t-1$ and t respectively under extreme scenario 1; dL_{t-1}^{2}, dL_t^2 is the equivalent load at time $t-1$ and t respectively under extreme Scenario 2; R_i, D_i is the climbing rate and descent rate of unit i respectively.

Equation (19) is power balance constraint under wind power extreme scenario s. Equation (20) is unit output limit constraint. Equality constraints (21) and inequality constraints (22) are common basic constraints, including thermal power unit start variables and outage variables related constraints, minimum on/off time constraints, up-regulation and down-regulation reserve constraints, climbing constraints. Equation (23) is power flow limit constraints. Equation (24) is the expression of equivalent load; Equation (25) is the system up-regulation capacity constraint, the left side indicates the system up regulation capacity from period $t-1$ to t, and the right side indicates that the system up-regulation capability needs to be higher than the equivalent load change when wind power across between the extreme scenes. Equation (26) is the system down regulation capacity constraint, the left side indicates the system down regulation capacity from period $t-1$ to t, and the right side indicates that the system down regulation capability needs to be higher than the equivalent load change when wind power across between the extreme scenes.

5. Example

According to the example, this paper studied the influence of the execution priorities of bilateral electric power contract and Sangong contract to the implementation of the contracts, studied the influence of the power flow restriction and wind power accommodation on the contract implementation, and verified the effectiveness of ensuring the fairness of contract implementation among power plants, verified the validity of the model.

5.1. Test System Description

The system is shown in **Figure 2**: thermal power installed capacity is 1200 MW, wind power installed capacity is 150MW, wind power accounts for 11%, the bilateral transaction size is 80% of electricity demand. Thermal unit parameters are shown in **Appendix Table A**, the bilateral electric power contract information of power plant is shown in **Appendix Table B**, wind power and system load forecast data is shown in **Appendix Table C**.

5.2. Running Results

Bilateral transaction cutting factors and Sangong contract cutting factors are calculated according to **Appendix Table B** as are shown in **Table 1**.

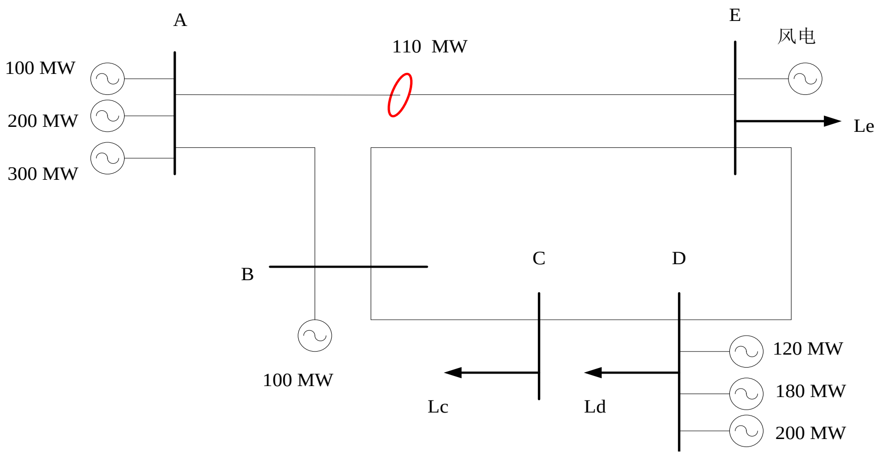

Figure 2. The test system.

Table 1. Cutting factors for power plants.

Power plant	Bilateral/MW*h	Sangong/MW*h	Bilateral cutting factors	Sangong cutting factors
A	6447	1611.75	0.5	0.5
B	1074.5	268.63	0.083	0.083
D	5372.5	1343.13	0.417	0.417

- The Impact of Execution Priority on Contract implementation.

According to the different execution priorities, the following two cases are studied to compare the impact of the execution priority on the results of the operation:

1) Case 1: Bilateral transactions are given priority, W_1 takes 4, W_2 takes 1, confidence interval takes 98%;

2) Case 2: Sangong contracts are given priority, W_1 takes 1, W_2 takes 4, confidence interval takes 98%;

Contract reductions and power generation costs of two cases are shown in **Table 2**, bilateral transaction implementation of Case1 is shown in **Figure 3(a)**, bilateral transaction implementation of Case2 is shown in **Figure 3(b)**.

- Unit Commitment, Generation Cost and Wind Power Accommodation Ability.

Under the premise of giving priority to the implementation of bilateral transactions, the influence of confidence interval on unit commitment, wind power consumption and power generation cost is studied, using 200 random wind power scenes generated by MATLAB, the wind power accommodation ability of unit commitment is tested, results are shown in **Table 3**.

5.3. Analysis of Running Results

(1) Validity of the Priority Coordination of Different Power Components and Execution Fairness of Power Plants.

As can be seen from **Table 2**, the bilateral transaction reduction of Case 1 is reduced by 83.66% compared to that of Case 2, Sangong contract reduction of

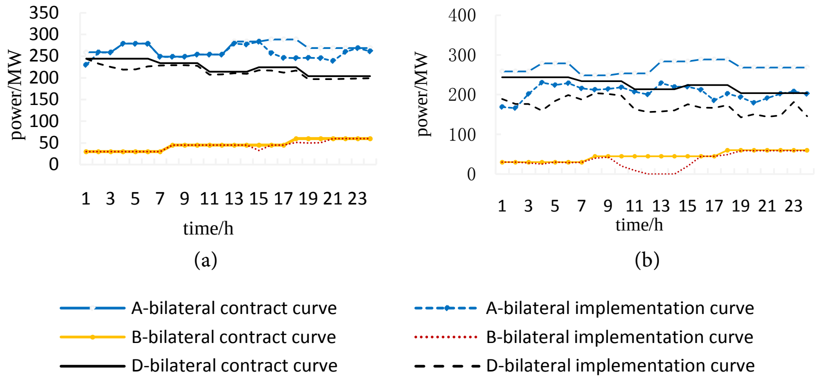
(a)
(b)

Figure 3. (a) Bilateral implementation when bilateral transactions execution is given priority; (b) Bilateral implementation when Sangong contracts execution is given priority.

Table 2. Contract reductions and generation costs under different execution priority.

Cases	Bilateral reductions/MWh				Sangong reductions/MWh				Generation costs/¥
	A	B	D	Total	A	B	D	Total	
Case 1	248.57	41.26	207.31	497.14	1283.01	212.98	1070.03	2566.02	2128408.1
Case 2	1521.36	252.55	1268.8	3042.71	0	0	0	0	2113071.1

Table 3. Results under different wind power confidence intervals.

Units	Confidence intervals			
	60%	80%	90%	98%
G1	all day	all day	all day	all day
G2	1 - 5	1 - 5	1 - 5	1 - 5
G3	all day	all day	all day	all day
G4	all day	all day	all day	all day
G5	all day	all day	all day	all day
G6	1 - 2, 14 - 21	1 - 2,13 - 21	1 - 2, 12 - 22	1 - 3, 10 - 22
G7	all day	all day	all day	all day
Generation costs/¥	2,105,317.9	2,108,770.6	2,115,675.9	2,128,408.1
Wind power consumption rate/%	64	79	93	99.5

Case 2 is reduced by 100% compared to that of Case 1. Case1 is given the priority for bilateral transactions, Case 2 is given the priority for Sangong contract, and the results show that the model can flexibly achieve the coordination of different power components. In addition, the bilateral transaction is given priority, the system's generation cost and the system total contract reductions are higher, this is because the electric power contract not only requires to finish the power quantities determined by the contract, but also requires the output curve in accordance with the contract power curve as much as possible, the implementation of electric power contracts will cure more regulatory resources, making the implementation more difficult.

Figure 3 shows the bilateral power implementation curves in both cases. It can be seen that the bilateral implementation curves under Case1 are better, with the deviation of the bilateral power contract curve is smaller, however, the deviation of bilateral execution curve with the contract curve under Case2 is larger, contract execution is poor. **Table 2** and **Figure 3** both verify the effectiveness of the model in coordinating the execution priorities of different charge components.

According bilateral transaction reductions and Sangong reductions in **Table 2**, it can be seen that the power plant bilateral reduction is proportional to total bilateral reduction, the proportion is equal to bilateral cutting factor of this plant, such conclusion can be get about Sangong contract reduction, which shows that the model can ensure the fairness implementation among power plants.

(2) The Impact of Confidence Intervals on Wind Power Consumption Ability and Power Generation Costs.

According to **Table 3**, the unit operation hours, generation costs and wind power consumption rate all increase as the confidence interval increases. This is because the more possible wind power output is considered when the confidence interval is larger, the unit operation hours increase to ensure that the system has stronger ability to adjust and resulting the increase of generation costs. In this study, when the confidence interval reaches 98%, the wind power consumption rate reaches 99.5%, unit commitment reliability reaches more than 99%.

(3) The Impact of the Flow Constraint on Contract Implementation.

The power transfer factors of line A-E on the node B, C, D, E are −0.112, −0.2629, −0.321 and −0.4805. Considering the volatility of wind power and the priority execution of bilateral transactions, the confidence interval is 98%, and the contract reductions ignoring the power flow constraints are obtained as shown in **Table 4**. The bilateral transaction execution curves are shown in **Figure 4**, and there is a comparison of contract reductions between the two cases of considering power flow limit and ignoring power flow limit in **Figure 5**.

Compare **Table 4** with Case1 in **Table 2**, it can be seen that there is significant decrease in the amount of contract reductions and power generation cost when there is no power flow limits. Compare **Figure 4** with **Figure 3(a)**, the bilateral

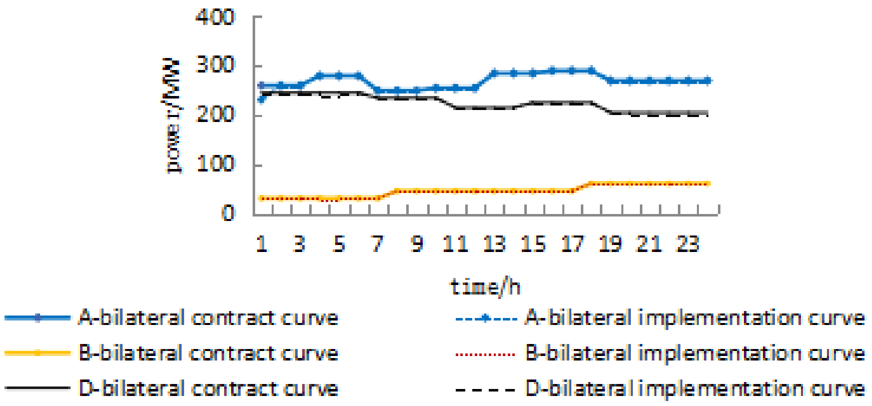

Figure 4. Bilateral implementation curves under conditions ignoring flow limits.

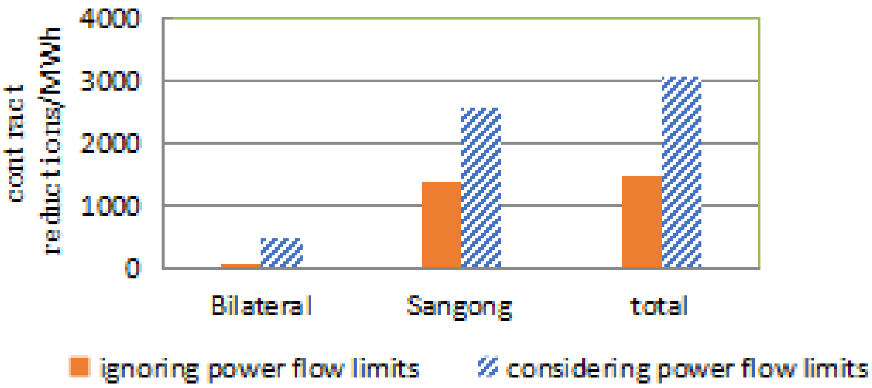

Figure 5. The impact of power flow limits on contract reductions.

Table 4. Contract implementation in the case of ignoring power flow constraints.

Case	Contract reductions/MWh			Generation cost/¥
	Total	Bilateral	Sangong	
Ignoring power flow limits	1471.23	A: 28.63 B: 4.75 D: 23.87	A: 706.99 B: 117.36 D: 589.63	1969647.8

transaction execution curve is much closer to the contract curve when there is no power flow limits. Compare contract reductions in **Figure 5**, it is clear that the line blockage will not be conducive to the implementation of the contract.

(4) The Impact of Wind Farm Location on Contract Implementation.

Wind power location affects power trend, which will have different effects on the implementation of the contract. Three cases has been studied. Case0: no wind; Case-E: Wind farm at point E; Case-A: Wind farm at point A. Contract implementations of Case0, Case-E and Case-A are shown in **Table 5**. Comparison of contract reductions in three cases is shown in **Figure 6**.

According to **Table 5**, it can be seen that in three cases of Case0, Case-E and Case-A: wind farm at E point is conducive to the implementation of the contract, the contract reduction is minimal; wind farm at point A is not conducive to the implementation of the contract, the contract reduction is largest. Because wind power causes reverse trend in the blocking line in Case-E, which can promote the implementation of contract power, bilateral contract reduction decreases by 57.71% and Sangong contract reduction decreases by 20.21% compared to Case0; the other hand, wind power causes positive current In the blocking line in Case-A, squeezes the thermal power transmission channel, affecting the implementation of the contract, bilateral contract reduction increases by 221.33% and Sangong contract reduction increases slightly. It is pointed out that the influence of wind power consumption on contract execution should be determined together with the trend. If the conclusion can be used rationally, it can promote the consumption of wind power and the implementation of bilateral transaction at the same time through reasonable planning and market design.

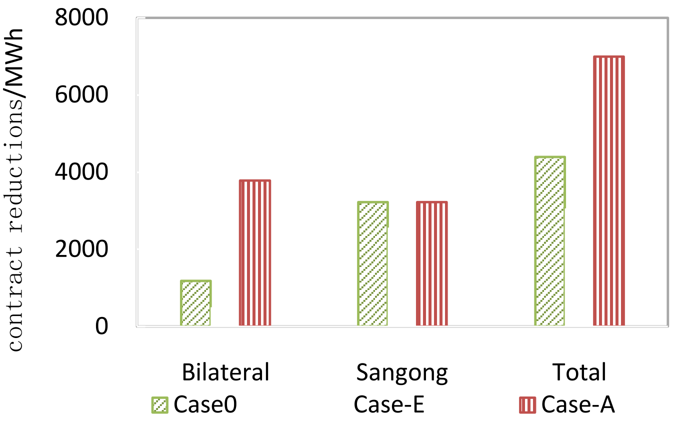

Figure 6. Comparison of contract reductions under different cases.

Table 5. The impact of wind farm location on contract implementation.

Cases	Contract reductions/MWh		
	Total	Bilateral	Sangong
Case0	4391.45	A: 587.74 B: 97.57 D: 490.18	A: 1607.98 B: 266.93 D: 1341.06
Case-A	6998.14	A: 1888.60 B: 313.51 D: 1575.10	A: 1610.47 B: 267.34 D: 1343.13
Case-E	3063.16	A: 248.57 B: 41.26 D: 207.31	A: 1283.01 B: 212.98 D: 1070.03

6. Conclusion

This paper validates the effectiveness of the proposed unit commitment model, which can effectively ensure new energy consumption, transaction execution and the fairness among power plants, power grid security and power generation economy, this paper analyzed the influence of different power components execution priorities on the results of transaction execution, and analyzed the influence of different confidence interval selection on unit combination reliability and wind power consumption ability, and analyzed the influence of wind power location on transaction execution, and proposed that when the wind power causes reverse trend in the block line, it will promote the implementation of the contract, and when wind power causes positive trends, it will hinder the implementation of the contract, the conclusion can provide reference for wind power planning and bilateral trading market.

Acknowledgements

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Appendix

Table A. Parameters of thermal units.

Plants	Units	Upper Output/MW	Lower Output/MW	Ramping Capacity/(MW/h)	Lower Startup Time/h	Lower Stop Time/h	Coal Consumption Rate			Startup Cost/¥	Coal Price/(¥/GJ)
							a/GJ	b/(GJ/MWh)	c/(GJ/MW2 h)		
A	1	100	10	50	4	4	176.9	13.5	0.0004	100	7.7467
	2	200	50	60	2	3	129.9	32.6	0.0004	300	7.7418
	3	300	60	30	1	1	137.4	17.6	0.0004	100	7.7424
B	4	100	20	30	2	2	125.8	20	0.0003	200	7.7436
D	5	120	20	40	1	1	140.6	30	0.0006	200	7.7421
	6	180	30	50	2	1	145.7	40	0.0006	300	7.7436
	7	200	40	40	1	2	156.9	10	0.0006	100	7.7410

Table B. Forecast load and forecast wind power.

Hour	Load (Lc/Ld/Le)/MW	Forcast wind power/MW	Hour	Load (Lc/Ld/Le)/MW	Forcast wind power/MW	Hour	Load (Lc/Ld/Le)/MW	Forcast wind power/MW	Hour	Load (Lc/Ld/Le)/MW	Forcast wind power/MW
1	206.40	44	7	224.46	100	13	242.06	84	19	218.66	10
2	211.78	70.2	8	230.13	100	14	241.20	80	20	212.45	5
3	211.56	76	9	227.85	78	15	242.29	78	21	214.44	6
4	212.24	82	10	227.07	64	16	229.26	32	22	227.71	56
5	213.02	84	11	242.87	100	17	220.00	4	23	227.68	82
6	214.83	84	12	242.70	92	18	215.58	8	24	216.25	52

Table C. Bilateral electric power contract information of power plant A, B, D.

Time	A/MW	B/MW	D/MW	Time	A/MW	B/MW	D/MW	Time	A/MW	B/MW	D/MW
1	258.625	29.771	243.854	9	248.625	44.771	233.854	17	288.625	44.771	223.854
2	258.625	29.771	243.854	10	253.625	44.771	233.854	18	288.625	59.771	223.854
3	258.625	29.771	243.854	11	253.625	44.771	213.854	19	268.625	59.771	203.854
4	278.625	29.771	243.854	12	253.625	44.771	213.854	20	268.625	59.771	203.854
5	278.625	29.771	243.854	13	283.625	44.771	213.854	21	268.625	59.771	203.854
6	278.625	29.771	243.854	14	283.625	44.771	213.854	22	268.625	59.771	203.854
7	248.625	29.771	233.854	15	283.625	44.771	223.854	23	268.625	59.771	203.854
8	248.625	44.771	233.854	16	288.625	44.771	223.854	24	268.625	59.771	203.854