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Bilateral Coordinated Dispatch of Multiple Stakeholders in Deep Peak Regulation

FEIXIANG PENG¹, ZHENGNAN GAO¹, SHUBO HU¹, WEI ZHOU¹, HUI SUN¹,
AND ZHONGHUI WANG²

¹Faculty of Electronic Information and Electrical Engineering, Dalian University of Technology, Dalian 116024, China

²State Grid Liaoning Electric Power Co., Ltd., Shenyang 110006, China

Corresponding author: Hui Sun (sunhui_ee@163.com)

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ABSTRACT Driven by high penetration renewable energy roadmaps, making full use of wind power is still an important work for wind industry and the goal of China. Considering the multiple stakeholders in power supply side and the unbalanced development of them, coordinated dispatch can maximize the wind power utilization. Deep peak regulation (DPR) market in China now has facilitated the coordination. However, wind farms in the market are involved passively for the cost sharing which is not conducive to wind farms to make full play of its advantages. Besides, the electricity of wind farm benefiting from deep peak regulation market cannot be clearly calculated. To solve this problem, a bilateral coordinated dispatch of wind power and other power generation companies (GENCOs) can be introduced in deep peak regulation. In this paper, the bilateral coordination of wind power and other GENCOs in DPR is studied. The potential economic feasible regions in bilateral coordination are analyzed and the compensation pricing ranges are given according to the individual rationality (IR) constraints. The contributions of different participants are clearly calculated using Shapley value, according to which the fair profit allocation is ensured. An affine decision rule is utilized for the simplification and fast computation. A real system in northeast China is utilized for case study to verify the potential economic feasible region. The results can provide reference for the implementation and profit allocation of bilateral coordination.

INDEX TERMS Bilateral coordination, deep peak regulation (DPR), Shapley value, wind power.

I. INTRODUCTION

High penetration renewable energy roadmaps for the year 2050 have been put forward by different countries and regions [1]–[3]. The goal of China in 2050 is to generate 85% of electricity from renewable sources [3]. Wind power, as a type of renewable energy, has been developing rapidly in the world [4], [5]. Total installed wind power capacity all over the world has reached 591549 MW in the year 2018 with new installation of 51300 MW [6]. In mainland China, the total installed capacity of wind power has reached 211392 MW, which is more than 35% of the capacity in the world [6]. Thus how to make full use of wind power in the dispatch makes great sense for both the wind industry and the goal of high penetration of China.

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The coordinated dispatch of wind power and other flexible power sources can help promote wind power accommodation. Hydropower [7], [8], battery energy storage (BES) [9], [10], combined heat and power [11] and demand side response [12] are chosen due to their good technical characteristics for wind power accommodation. The most common way of the coordinated dispatch is the coordination of wind power and hydropower. Reference [7] presents a day-ahead coordinated dispatch method for hydro and wind power generation systems, which shows that coordinated dispatch can contribute to more economic benefit compared with the separated operation of hydro and wind power. The coordination scheme of wind power and hydropower employing stochastic optimization to maximize total profit is proposed in [8] with the transmission capacity considered under electricity market. As one of the demand side sources, BES is suitable for the coordination with wind power. A two-stage method determining the optimal power and capacity of BES in systems is

proposed in [9] to decrease wind power curtailment, of which the results indicate that the coordinated operation can reduce the cost of wind farms. Second life batteries (SLBs) are utilized for coordination with wind power in [10] to reduce the operation cost. Heat storage tanks are utilized in [11] to improve the flexibility of combined heat and power (CHP) units in deep peak regulation, which is beneficial to wind power accommodation.

The power system in China is a coal-dominated energy system with a penetration rate of fossil fuels more than 71% in current period [13]. Thus the flexibility of thermal power units is relatively important and the demand of deep peak regulation (DPR) in China is huge [14]. To improve the flexibility of power system, National Energy Administration of China has set a target to complete the flexibility transformation of 220 MW thermal power units during the period of the 13-th Five-year Plan and to improve the unit capability of peak regulation by 46 MW [15]. Until now, 22 demonstration projects of thermal power flexibility transformation have been completed [16] and the flexibility of units at low load has been improved, which has brought vast space for the coordinated dispatch of wind power and thermal power units from a technical viewpoint.

It is also possible to provide more space for wind power accommodation through ancillary services market transactions with the deepening of power market reform in China, especially in the deep peak regulation market [17]–[19]. The essence of shortage of peak regulation resources is actually the competition of all kinds of power sources for the power generation space, which is profit allocation problem [20]. This makes the coordinated dispatch a characteristic of interest conflict from an economic viewpoint. Therefore, the appropriate compensation scheme makes great sense for the coordination among multiple stakeholders of power generation companies (GENCOs), which decides whether or not the coordinated dispatch can be implemented. If any one of the participants suffers utility loss, coordinated dispatch is difficult to be carried out.

In China, there are five main power generation group companies and some other small ones. Each of them is an individual stakeholder. Most of them have a develop trend that the thermal power are the main units and many kinds of clean energy power generation are developed [11]. In a certain area, different power units may be invested by different power generation group companies and one power generation group company may have limited type of power units. The unbalanced resources of different stakeholders make the deep peak regulation market in China have obvious coordination characteristics. Actually, the main idea of deep peak regulation market in China is that units providing DPR gain the compensation while other units share the total compensation expenses. Thus the mechanism for deep peak regulation compensation is studied in many works. Reference [18] points out that the deep peak regulation market has significant benefits in social harmony, environmental protection and economic efficiency, which can improve peak regulation capacity and

reduce wind power curtailment. A compensation model is proposed in [19] with cost caused by flexibility transformation of thermal power units and participating in deep peak load regulation of power system considered. In [21], the Kaldor improvement based DPR mechanism is proposed, where the initiative of thermal power units to carry out DPR operation is discussed according to the Kaldor compensation and the marginal cost. Reference [11] takes the welfare utilities of different stakeholders into consideration in coordinated dispatch, and the compensation is introduced according to the peak regulation auxiliary service rules.

The works above pay more attention to the thermal power units but less to the wind farms. Actually, in deep peak regulation market in China, only the power sources providing DPR service can actively participate in the market through pricing. Wind power in the market is involved in passive cost sharing and the electricity of wind farm benefiting from deep peak regulation market cannot be clearly calculated [22]. It is not conducive to the realization of high penetration renewable energy roadmap. To overcome this problem faced by wind power enterprises and to improve the profitability of wind farms in coordinated dispatch, the bilateral coordination of wind power and thermal power units can be carried out through bilateral agreements. Also, the clearing price of electricity from wind farms in China is higher than that of electricity from thermal power units because of the subsidy for renewable energy, which brings the economic feasibility for the bilateral coordination and the overall utility can be obtained.

In this paper, the bilateral cooperation of multiple GENCOs for coordinated dispatch is studied. The DPR of thermal power units are utilized to facilitate the coordinated dispatch of wind power and thermal power units. So that more wind power can be consumed and wider economic feasible region can be obtained. The potential economic feasible regions in bilateral cooperation with different participants are analyzed and the compensation pricing ranges are given according to the individual rationality (IR) constraints. Considering that the maximization of overall utility can not necessarily satisfy every participant stakeholder [23], a reasonable profit allocation scheme is given according to contributions of different GENCOs, which can be calculated by Shapley value [8]. Uncertainty of wind power is considered to further illustrate the influence on the economic feasible region. Case study in this paper is based on a real system in northeast China.

The major contributions of this paper are in three aspects:

- 1) A bilateral coordinated dispatch scheme for multiple GENCOs is proposed to pursue the maximization of the overall profit, which can provide more initiatives and choice for wind farms in deep peak regulation operation.

- 2) A Shapley value based compensation settlement is proposed. The profit for each participant is determined according to the contribution, which can guarantee the fairness of allocation and improve the initiative of participants in bilateral coordination.

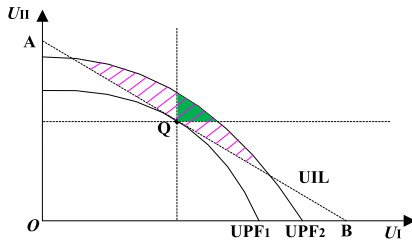


FIGURE 1. Economic feasible region marked in UPF curve.

3) The economic feasible regions under different uncertainty levels of wind power are studied and the corresponding feasible ranges of compensation price are analyzed to give the participants further reference for the implementation of bilateral coordination under uncertain scenarios.

The rest of this paper is organized as follows. The economic feasible constraints as well as the feasible compensation pricing range of the bilateral coordinated dispatch are given in Section II. The Shapley value based profit allocation method is introduced in Section III. Section IV presents the dispatch process and modeling. Case study of the real system in northeast China is carried out in Section V and the further discussion is given in Section VI. Conclusions are drawn in Section VII.

II. FEASIBILITY ANALYSIS FOR BILATERAL COORDINATED DISPATCH

A. UTILITY POSSIBILITY FRONTIER AND ECONOMIC FEASIBLE REGION

For a individual stakeholder, the economic feasibility constraints can be described using individual rationality constraints, which are as (1) and (2) show.

$$U_C \geq 0 \tag{1}$$

$$U_C \geq U_A \tag{2}$$

where U_C is the welfare utility of a individual in the chosen scheme; U_A is the utility in the abandoned scheme. Constraint given in (1) reflects the behavior motivation of an individual to choose a scheme. A individual will participate in a scheme only when it is profitable. While the constraint of (2) determines that the individual will not give up the scheme and choose another. Therefore, if the two constraints are satisfied for all the participants, the scheme can be accepted and implemented.

For a coordinated dispatch in power system, the DPR operation mode of thermal power units can be chosen if (3) is satisfied. It can be visualized in utility possibility frontier (UPF) curve [24] as Figure 1 shows. The region marked green is the potential economic feasible region under the constraint of (3).

$$U_{DPR,x} \geq U_{RPR,x} \geq 0 \quad (x = 1, 2, \dots, N_{GENCO}) \tag{3}$$

where N_{GENCO} is the number of the GENCOs in the given system; $U_{RPR,x}$ and $U_{DPR,x}$ are respectively the utilities of the x -th GENCO under regular peak regulation (RPR) mode and DPR operation modes.

The constraint of economic feasibility constraint given in (3) can be written as (4) before compensation settlement. It means that if the overall utility can be increased, the scheme is feasible under the group rationality (GR) constraints. The economic feasibility region defined by (4) is the region with pink shadow marked.

$$\sum_{x=1}^{N_{GENCO}} U_{DPR,x} \geq \sum_{x=1}^{N_{GENCO}} U_{RPR,x} \geq 0 \tag{4}$$

In Figure 1, U_I and U_{II} are respectively the utilities of individual I and II. Q is the utility point before coordination and the dotted line AB is the utility indifference line (UIL) passing through point Q. UPF1 and UPF2 are the UPF curves when coordination carried out under different conditions. Under the condition of UPF1, coordinated dispatch cannot be formed as there is no economic feasibility region where the overall utility can be improved compared with point Q, while the area economic feasible region can be found under the condition of UPF2.

The UPF curve can be obtained by an optimization model as (5) shows.

$$\begin{cases} \max U_{GENCO-II} \\ \text{s.t. } P \subset S \\ U_{GENCO-I} = U_{GENCO-I}^* \\ U_{GENCO-I,min} \leq U_{GENCO-I}^* \leq U_{GENCO-I,max} \end{cases} \tag{5}$$

where P is the set of decision variables and S is the feasible region of the optimization model constrained by security constraints. $U_{GENCO-I}$ and $U_{GENCO-II}$ are respectively the utilities of GENCO-I and GENCO-II; $U_{GENCO-I}^*$ is the given amount of GENCO-I's utility; $U_{GENCO-I,max}$ and $U_{GENCO-I,min}$ are the corresponding maximum and minimum amounts of GENCO-I's utilities, which can be determined by (6) and (7).

$$U_{GENCO-I,max} = \max_{\{P \subset S\}} U_{GENCO-I} \tag{6}$$

$$U_{GENCO-I,min} = \min_{\{P \subset S\}} U_{GENCO-I} \tag{7}$$

In this paper, the UPF curve is utilized for the economic feasible region analysis. The prime-dual interior point method can be used to solve the optimization process given by (5), (6) and (7).

B. FEASIBLE RANGE OF COMPENSATION PRICING

Appropriate compensation pricing is necessary for the formation of coordinated dispatch. For a wind farm benefiting from the coordinated dispatch under DPR mode, IR constraint with compensation paid is as (8) shows and the IR constraint of GENCO providing ancillary services under DPR mode is shown in (9). Here, we call it an alliance if the bilateral coordinated dispatch is built.

$$U_{C-D,W} - U_{COM} \geq U_{S-D,W} \tag{8}$$

$$U_{C-D,GENCO} + U_{COM} \geq U_{S-D,GENCO} \tag{9}$$

where $U_{C-D,W}$ and $U_{C-D,GENCO}$ are the utilities of the corresponding participants in coordinated dispatch before compensation paid; $U_{S-D,W}$ and $U_{S-D,GENCO}$ are those under separated operation; U_{COM} is the compensation, which is as (10) shows.

$$U_{COM} = \lambda_{COM} \sum_{t \in T_C} (P_{G,S-D,GENCO,t} - P_{G,C-D,GENCO,t}) \quad (10)$$

where T_C is the set of the time periods during which wind curtailment occurs under separated operation; $P_{G,S-D,GENCO,t}$ and $P_{G,C-D,GENCO,t}$ are the overall outputs before and after the coordination during wind curtailment periods of GENCO suffering loss; λ_{COM} is the compensation price. According to (8) and (9), compensation price needs to be within the range of (11).

$$\begin{aligned} \frac{U_{S-D,GENCO} - U_{C-D,GENCO}}{\sum_{t \in T_C} (P_{G,S-D,GENCO,t} - P_{G,C-D,GENCO,t})} &\leq \lambda_{COM} \\ &\leq \frac{U_{C-D,W} - U_{S-D,W}}{\sum_{t \in T_C} (P_{G,S-D,GENCO,t} - P_{G,C-D,GENCO,t})} \end{aligned} \quad (11)$$

where the lower boundary of the price means the cost recovery price of GENCO providing deep regulation service in coordinated dispatch, while the upper boundary is the maximum potential utility value of curtailed wind power for wind farms. If the price of compensation is less than the lower boundary of the price, GENCO providing deep regulation service will refuse to carry out a coordinated dispatch, while wind farm would rather accept the wind curtailment than coordination when the compensation price is higher than the upper boundary.

III. PROFIT ALLOCATION BASED ON SHAPLEY VALUE

In addition to settlement through price mechanism, an allocation according to the contributions of the participants can guarantee fairness. Shapley value is applied in this paper to realize this purpose. Shapley value is an important theory of cooperative game theory that ensures the fairness according to marginal contribution. Thus it is a reasonable method for profit allocation and is utilized in many works. Also, it can avoid equalitarianism in allocation and reflect the real contribution of individual in the alliance.

For an individual in a cooperative alliance, the contribution can be described as follows.

$$\phi_i(N, V) = \frac{1}{|N|!} \sum_{S \subseteq N \setminus \{x_i\}} [|S|! (|N| - 1 - |S|)! (\Delta V_S(x_i))] \quad (12)$$

$$\Delta V_S(x_i) = V(S \cup \{x_i\}) - V(S) \quad (13)$$

where N is the cooperative alliance with all the participants contained; $\phi_i(N, v)$ is the contribution of participant x_i in the alliance N ; $|N|$ is the number of participants in N ; $N \setminus \{x_i\}$ means a set without individual x_i ; $V(\cdot)$ is the overall utility function of an alliance; $\Delta V_S(x_i)$ is the marginal contribution of x_i when joining in the sub-alliance S , which

is as (13) shows; $(|N|!)$ reflects the number of all the permutations in which all individuals enter the alliance while $(|S|! (|N| - 1 - |S|)!)$ is the number of permutations that x_i enters the alliance follows sub-alliance S . When all possible sub-alliance S have been taken into consideration, the contribution of x_i can be obtained. That is also the profit allocated to x_i as (14) shows.

$$\sum_{\{x_i\} \subseteq N} \phi_i(N, V) = V(N) \quad (14)$$

When the number of participants is relatively large, it is difficult to compute the Shapley value directly. But it can be used in this paper because the wind curtailment in certain periods is limited and the bilateral coordinated dispatch is carried out among a few stakeholders.

IV. CALCULATION MODELING AND IMPLEMENTATION

A. CALCULATION MODELING

In this paper, the linear utility function is utilized for the overall utility pursuing, which means the utility of a GENCO stakeholder is the amount of profit the GENCO can obtained. For wind farm, the operation cost is ignored, thus the utility function is as (15) shows. The utility function of GENCO with only thermal power units is shown in (16).

$$U_W = \lambda_W \sum_{t=1}^T P_{W,t} \quad (15)$$

$$U_x = \sum_{t=1}^T \left(\lambda_G \sum_{i=1}^{N_{G,x}} P_{G,i,t} - \sum_{i=1}^{N_{G,x}} f_{C,i,t}(P_{G,i,t}) \right) \quad (16)$$

where U_W is the utility of the wind farm in the power dispatch; U_x is utility of the x -th GENCO; T is the number of time periods; $N_{G,x}$ is the number of thermal power units belong to GENCO- x ; $P_{W,t}$ is the consumed wind power of wind farm in time t ; $P_{G,i,t}$ is output of thermal power unit i in time t ; λ_W is the clearing price of wind power and λ_G is the clearing price of thermal power units; $f_{C,i,t}$ is the fuel cost function of thermal power unit i in time t , which is as (17) shows under RPR operation mode and (18) shows under DPR operation mode.

$$\begin{aligned} f_{C,i,t}(P_{G,i,t}) &= \lambda_{coal} (a_i P_{G,i,t}^2 + b_i P_{G,i,t} + c_i), \\ &(P_{G,i,t} \geq P_{G,\min,RPR,i}) \end{aligned} \quad (17)$$

$$\begin{aligned} f_{C,i,t}(P_{G,i,t}) &= \lambda_{coal} (a_i P_{G,i,t}^2 + b_i P_{G,i,t} + c_i) \\ &+ \lambda_{oil} \mu_i (P_{G,\min,RPR,i} - P_{G,i,t}), \\ &(P_{G,\min,DPR,i} \leq P_{G,i,t} < P_{G,\min,RPR,i}) \end{aligned} \quad (18)$$

where $P_{G,\min,RPR,i}$ and $P_{G,\min,DPR,i}$ are the minimum outputs of unit i under RPR operation mode and DPR operation mode, respectively. a_i , b_i and c_i are the coal consumption coefficients of thermal power unit i ; μ_i is the oil consumption coefficient of thermal power unit i under DPR mode; λ_{coal} and λ_{oil} are the prices of coal and oil.

The coordinated dispatch in this paper is implemented to solve the problem of wind curtailment, thus only the time

periods with wind curtailment are considered in the utility calculation. The overall utility of the alliance is as (19) shows. And the objective function is to find the maximum utility of the alliance in coordinated dispatch.

$$\max U_{C-D} = \lambda_W \sum_{t \in T_C} P_{W,t} + \sum_{x=1}^{N_{GENCO}} \sum_{t \in T_C} \left(\lambda_G \sum_{i=1}^{N_{G,x}} P_{G,i,t} - \sum_{i=1}^{N_{G,x}} f_{C,i,t}(P_{G,i,t}) \right) \quad (19)$$

where U_{C-D} is the overall utility of the potential alliance.

Generally, the wind power output cannot be accurately predicted. The probability distribution function of wind output can be obtained according to the long-term statistical data, which can be utilized for the uncertainty analysis. The coefficient of variations (COVs) can describe the dispersion degree of wind power. If we use the expectation of wind power output as the predicted wind power output, the COV can be written as:

$$COV_t = \frac{\sigma_{W,t}}{\mu_{W,t}} = \frac{\sigma_{W,t}}{P_{W,pre,t}} \quad (20)$$

where COV_t is the COV of power output in time t ; $\sigma_{W,t}$ is the standard deviation of wind power output; $\mu_{W,t}$ is the mean value of wind power output; $P_{W,pre,t}$ is the predicted wind power output in time t .

Different distribution functions are used in uncertainty description of wind power in many works, among which Beta distribution is a basic bounded distribution. It can approximate many different probability distribution forms according to different parameters [25]. Thus in this paper, Beta distribution is used to describe the uncertainty of wind power output, which is as (21) shows.

$$f_W(P_{W,N,t}) = \frac{P_{W,N,t}^{\alpha-1} (1 - P_{W,N,t})^{\beta-1}}{B(\alpha, \beta)} \quad (21)$$

where $P_{W,N,t}$ is the normalized real wind power output in time t , which is a stochastic variable as (22) shows; $B(\alpha, \beta)$ is the Beta function shown in (23); α and β are the shape parameters of Beta distribution.

$$P_{W,N,t} = \frac{P_{W,real,t} - P_{W,min}}{P_{W,max} - P_{W,min}} \quad (22)$$

$$B(\alpha, \beta) = \int_0^1 P_{W,N,t}^{\alpha-1} (1 - P_{W,N,t})^{\beta-1} dP_{W,N,t} \quad (23)$$

where $P_{W,real,t}$ is the real wind power output in time t ; $P_{W,max}$ and $P_{W,min}$ are the maximum and minimum outputs of wind farm. In practice, the maximum output is the installed capacity of wind farm and the minimum output is zero, thus (22) can be simplified as:

$$P_{W,N,t} = \frac{P_{W,real,t}}{P_{W,max}} \quad (24)$$

For a given level of COV_t , parameters α and β can be calculated by (25) and (26):

$$\alpha_t = \frac{(1 - \mu_t) \mu_t^2}{\sigma_t^2} - \mu_t \quad (25)$$

$$\beta_t = \frac{1 - \mu_t}{\mu_t} \alpha_t \quad (26)$$

where μ_t and σ_t are the mean and variance of $P_{W,N,t}$, which can be defined by (27) and (28).

$$\mu_t = \frac{P_{W,pre,t}}{P_{W,max}} \quad (27)$$

$$\sigma_t = \frac{\sigma_{W,t}}{P_{W,max}} = \frac{P_{W,pre,t} COV_t}{P_{W,max}} \quad (28)$$

Then, analysis considering uncertainty can be carried out on this basis.

During the periods with wind curtailment occurring, the upper limit of wind power consumed is limited by the security constraints. The expected utility can be used to describe the utility of wind power with uncertainty considered. Thus the utility function of wind power in a separated dispatch can be written as:

$$U_{W,S-D,t} = \int_0^{P_{W,S-D,N,t}} \lambda_W P_{W,real,t} f_W(P_{W,N,t}) dP_{W,N,t} + \int_{P_{W,S-D,N,t}}^1 \lambda_W P_{W,S-D,t} f_W(P_{W,N,t}) dP_{W,N,t} \quad (29)$$

where $U_{W,S-D,t}$ is the utility of wind farm under a separated dispatch in time t ; $P_{W,S-D,t}$ is the maximum wind power can be consumed under separated dispatch limited by security constraints and $P_{W,S-D,N,t}$ is normalized $P_{W,S-D,t}$, which is as (30) shows.

$$P_{W,S-D,N,t} = \frac{P_{W,S-D,t}}{P_{W,max}} \quad (30)$$

When a coordination is formed, the utility of the alliance with wind power can be written as (31).

$$\begin{aligned} EU_{C-D,t} &= \int_0^{P_{W,S-D,N,t}} \left(\lambda_W P_{W,real,t} + \lambda_G \sum_{i=1}^{N_{G,C-D}} P_{G,min,RPR,i} - \sum_{i=1}^{N_{G,C-D}} f_{C,i,t}(P_{G,min,RPR,i}) \right) f_W(P_{W,N,t}) dP_{W,N,t} \\ &+ \int_{P_{W,S-D,N,t}}^{P_{W,DPR,N,t}} \left(\max \left(\lambda_W P_{W,real,t} + \lambda_G \sum_{i=1}^{N_{G,C-D}} P_{G,i,t} - \sum_{i=1}^{N_{G,C-D}} f_{C,i,t}(P_{G,i,t}) \right) \right) f_W(P_{W,N,t}) dP_{W,N,t} \\ &+ \int_{P_{W,DPR,N,t}}^1 (\lambda_W (P_{W,S-D,t} + \Delta P_{W,DPR,t})) \end{aligned}$$

$$\begin{aligned}
 & +\lambda_G \sum_{i=1}^{N_{G,C-D}} (P_{G,\min,DPR,i}) \\
 & - \sum_{i=1}^{N_{G,C-D}} f_{C,i,t} (P_{G,\min,DPR,i}) \Big) f_W (P_{W,N,t}) dP_{W,N,t} \quad (31)
 \end{aligned}$$

where $EU_{C-D,t}$ is the utility of the alliance under a coordinated dispatch in time t ; $N_{G,C-D}$ is the number of thermal power units participating in the coordinated dispatch; $\Delta P_{W,DPR,t}$ is the available peak regulation depth of GENCOs coordinated with wind power in time t , which can be calculated by (32); $P_{W,DPR,N,t}$ is the maximum normalized wind power can be consumed under coordinated dispatch limited by security constraints, which is shown in (33).

$$\Delta P_{W,DPR,t} = \sum_{i=1}^{N_{G,C-D}} (P_{G,\min,RPR,i} - P_{G,\min,DPR,i}) \quad (32)$$

$$P_{W,DPR,N,t} = \frac{P_{W,S-D,t} + \Delta P_{W,DPR,t}}{P_{W,\max}} \quad (33)$$

Therefore, the objective function in this paper is the maximization of the expectation of overall utility.

Constraints of the dispatch model in this paper include the balance constraint of electric power in each time period for the coordinated GENCOs, operation limits of thermal power units and the utility constraints.

1) Electric power balance constraints

$$\sum_{i=1}^{N_{G,C-D}} P_{G,i,t} + P_{W,t} = P_{Load,t} \quad (34)$$

where $P_{Load,t}$ is the overall load in time t to be undertaken by the wind farm and GENCOs in the alliance according to the power generation plan from the superior dispatching organization.

2) Operation limit constraints of power units

When the coordination is not formed, thermal power units are operated under RPR mode, thus the electric power output limits is as (35) shows. And it is as (36) shows when the alliance formed.

$$\begin{aligned}
 \max \{P_{G,\min,RPR,i}, P_{G,i,t,0} - DR_i\} & \leq P_{G,i,t} \\
 & \leq \min \{P_{G,\max,i}, P_{G,i,t,0} - UR_i\} \quad (35)
 \end{aligned}$$

$$\begin{aligned}
 \max \{P_{G,\min,DPR,i}, P_{G,i,t,0} - DR_i\} & \leq P_{G,i,t} \\
 & \leq \min \{P_{G,\max,i}, P_{G,i,t,0} - UR_i\} \quad (36)
 \end{aligned}$$

where $P_{G,\max,i}$ is the maximum power output of thermal power unit i ; UR_i and DR_i are the upward and downward ramping ability of thermal power unit i ; $P_{G,i,t,0}$ is the power generation plan of thermal power unit i from the superior dispatching organization.

The utility constraints are given by (3) for the separated dispatch and (4) for the coordinated dispatch.

Uncertainty of wind power brings difficulty to the accurate prediction. For the security of the system, the spinning reserve

for wind power needs to be considered. According to the ‘‘Operation rules of northeast electric power auxiliary service market (Provisional)’’ [26], the spinning reserve transaction only occurs in the peak load period when there is no deep peak regulation transaction. Thus it is supposed that the spinning reserve for wind power is provided by spinning reserve units with sufficient capacity in the time periods with wind curtailment. And the reserve settlement is not considered as we focus on the deep peak power regulation.

B. SIMPLIFICATION OF THE CALCULATION MODEL

When the COV of wind power output is zero, the objective function is as (19) shows. The prime-dual interior point method can be used to solve the optimization model. However, when the COV of wind power is not zero, the objective function given by (31) can be written as (37):

$$EU_{C-D,t} = EU_{W,C-D,t} + EU_{GENCO,C-D,t} \quad (37)$$

where $EU_{W,C-D,t}$ is the expected utility of wind farm in coordinated dispatch; $EU_{GENCO,C-D,t}$ is the expected utility of GENCOs. They can be written as (38) and (39).

$$\begin{aligned}
 & EU_{W,C-D,t} \\
 & = \int_0^{P_{W,DPR,N,t}} (\lambda_W P_{W,\text{real},t}) f_W (P_{W,N,t}) dP_{W,N,t} \\
 & + \int_{P_{W,DPR,N,t}}^1 (\lambda_W (P_{W,S-D,t} \\
 & + \Delta P_{W,DPR,t})) f_W (P_{W,N,t}) dP_{W,N,t} \quad (38)
 \end{aligned}$$

$$\begin{aligned}
 & EU_{GENCO,C-D,t} \\
 & = \int_0^{P_{W,S-D,N,t}} \left(\lambda_G \sum_{i=1}^{N_{G,C-D}} P_{G,\min,RPR,i} \right. \\
 & - \left. \sum_{i=1}^{N_{G,C-D}} f_{C,i,t} (P_{G,\min,RPR,i}) \right) f_W (P_{W,N,t}) dP_{W,N,t} \\
 & + \int_{P_{W,S-D,N,t}}^{P_{W,DPR,N,t}} \left(\max \left(\lambda_G \sum_{i=1}^{N_{G,C-D}} P_{G,i,t} \right. \right. \\
 & - \left. \left. \sum_{i=1}^{N_{G,C-D}} f_{C,i,t} (P_{G,i,t}) \right) \right) f_W (P_{W,N,t}) dP_{W,N,t} \\
 & + \int_{P_{W,DPR,N,t}}^1 \left(\lambda_G \sum_{i=1}^{N_{G,C-D}} (P_{G,\min,DPR,i}) \right. \\
 & - \left. \sum_{i=1}^{N_{G,C-D}} f_{C,i,t} (P_{G,\min,DPR,i}) \right) f_W (P_{W,N,t}) dP_{W,N,t} \quad (39)
 \end{aligned}$$

There is an optimization process in the integral formula in (39), which can be solved by Monte Carlo method. However, the pseudo random number will increase the calculation. In this paper, an affine decision rule [27] is utilized for the simplification to realize a fast computation. The real power output of wind farm beyond $P_{W,S-D,t}$ is uniformly distributed

to the thermal power units according to the available DPR capacity of each thermal power unit. The power output of thermal power in this can be written as (40):

$$P_{G,i,t} = P_{G,\min,RPR,i} - \xi_i (P_{W,\text{real},t} - P_{W,S-D,t}) \quad (40)$$

$$\xi_i = \frac{\min \{P_{G,\min,RPR,j} - P_{G,\min,DPR,j}, DR_i\}}{\sum_{j=1}^{N_{G,C-D}} (\min \{P_{G,\min,RPR,j} - P_{G,\min,DPR,j}, DR_j\})} \quad (41)$$

where ξ_i is the ratio of available DPR capacity of each thermal power unit.

Therefore, (39) can be simplified as (42).

$$\begin{aligned} EU_{GENCO,C-D,t} &= \int_0^{P_{W,S-D,N,t}} \left(\lambda_G \sum_{i=1}^{N_{G,C-D}} P_{G,\min,RPR,i} \right. \\ &\quad - \sum_{i=1}^{N_{G,C-D}} f_{C,i,t} (P_{G,\min,RPR,i}) \left. \right) f_W (P_{W,N,t}) dP_{W,N,t} \\ &\quad + \int_{P_{W,S-D,N,t}}^{P_{W,DPR,N,t}} (\lambda_G (P_{Load,t} - P_{W,\text{real},t})) \\ &\quad - \sum_{i=1}^{N_{G,C-D}} f_{C,i,t} (P_{G,\min,RPR,i} - \xi_i (P_{W,\text{real},t} - P_{W,S-D,t})) \left. \right) \\ &\quad \times f_W (P_{W,N,t}) dP_{W,N,t} \\ &\quad + \int_{P_{W,DPR,N,t}}^1 \left(\lambda_G \sum_{i=1}^{N_{G,C-D}} (P_{G,\min,DPR,i}) \right. \\ &\quad - \sum_{i=1}^{N_{G,C-D}} f_{C,i,t} (P_{G,\min,DPR,i}) \left. \right) f_W (P_{W,N,t}) dP_{W,N,t} \quad (42) \end{aligned}$$

C. SIMULATION IMPLEMENTATION

The simulation is implemented as follows. First of all, a separated dispatch is carried out to find the time periods with potential wind curtailment. And then, the economic feasibility of coordinated dispatch under DPR operation mode is illustrated by UPF curves and the reference price ranges are given in compensation settlement process. The optimal model is simplified utilizing the affine decision rule and the security check is carried out for the results from the simplified calculation model. At last, an allocation based on Shapley value is proposed to ensure the fairness. The whole process can be seen in Figure 2.

V. CASES STUDY

A. A REAL SYSTEM IN NORTHEAST CHINA

A real provincial power system in Northeast China is utilized in this paper to verify the economic utility potential of the bilateral coordination and the feasible compensation price range is given. The allocation scheme based on Shapley value is utilized in the real system. The influence of uncertainty is also analyzed. The problem of wind curtailment in Northeast

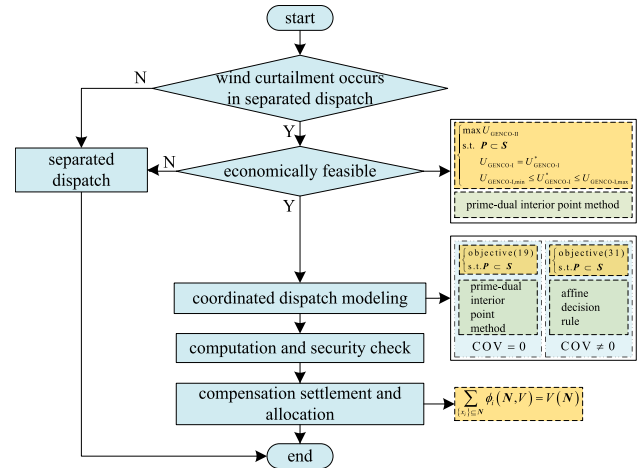


FIGURE 2. Simulation implementation process proposed in this paper.

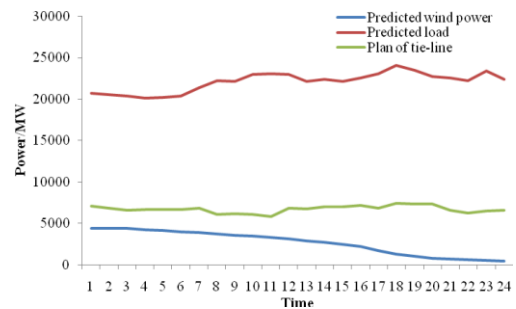


FIGURE 3. The predicted load demands, predicted wind power and the plan of tie-line in the province.

China often occurs in winter, especially in the middle period of heating. Thus a day in December 2016 is selected as a typical operation day. On that day, there are 35 thermal power plants in 13 regions being in operation. These thermal power plants belong to 16 different GENCOs. The installed capacity of wind power in this province is 6219.61 MW in 2016. The predicted load demands, predicted wind power and the plan of tie-line in the given day are as Figure 3 shows.

Clearing prices of electricity in 2019 are utilized for the utility calculation, which are 520 yuan/MWh for electricity from wind farms and 368.5 yuan/MWh for electricity from thermal power units in the chosen province. In 2016, the minimum stable combustion output of most thermal power units in this province is higher than 50% that is the benchmark for peak regulation in the Northeast. With the promotion of thermal power flexibility transformation, thermal power units can be operated at a load rate of 40%-50% [28]. Units operated at a load rate higher than the benchmark need to pay for the peak regulation compensation [18]. Thus we suppose that all the thermal power units can meet the benchmark of peak regulation.

Under the benchmark operation mode, which is a RPR mode in this paper, the wind curtailment in the whole province is calculated under a separated dispatch. Based on this, the coordinated dispatch is carried out. To illustrate the

TABLE 1. Parameters of thermal power units.

Unit	GENCO	$P_{G,max}/MW$	$P_{G,min,RPR}/MW$	$P_{G,min,DPR}/MW$	$a/t*MW^{-2}*h^{-1}$	$b/t*MW^{-1}*h^{-1}$	$c/t*h^{-1}$	$\mu/t*MW^{-1}*h^{-1}$	$UR,DR/MW$
G1	I	220	110	88	0.000254	0.242	10.339	0.05	200
G2	I	220	110	88	0.000254	0.242	10.339	0.05	200
G3	II	200	100	80	0.000254	0.242	10.339	0.05	200
G4	II	200	100	80	0.000254	0.242	10.339	0.05	200
G5	II	200	100	80	0.000254	0.242	10.339	0.05	200
G6	III	600	300	240	0.000033	0.233	32.363	0.02	360
G7	III	300	150	120	0.000068	0.243	16.867	0.03	300
G8	III	300	150	120	0.000068	0.243	16.867	0.03	300
G9	III	25	12.5	12.5	0.001	0.278	1.8	0	25
G10	III	25	12.5	12.5	0.001	0.278	1.8	0	25
G11	III	60	30	30	0.000508	0.278	3.35	0	25

TABLE 2. Shape parameters of Beta distribution.

Time	1		2		3		4		5		6		7	
parameters	α	β	α	β	α	β	α	β	α	β	α	β	α	β
COV=0.1	29.10	12.36	28.64	11.90	28.67	11.93	30.81	14.17	33.33	17.16	35.60	20.24	37.39	22.92
COV=0.2	6.75	2.87	6.63	2.75	6.64	2.76	7.19	3.31	7.84	4.03	8.42	4.79	8.88	5.45
COV=0.3	2.61	1.11	2.55	1.06	2.56	1.06	2.81	1.29	3.12	1.60	3.39	1.93	3.60	2.21
COV=0.4	1.16	0.49	1.13	0.47	1.13	0.47	1.28	0.59	1.46	0.75	1.63	0.93	1.76	1.08

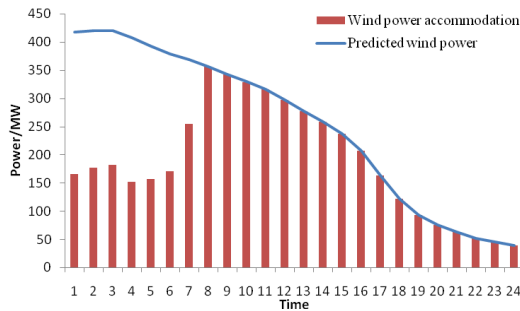


FIGURE 4. Wind power accommodation under the separated dispatch.

case study, one region with a wind farm and three GENCOs is chosen from the 13 ones in the province. For the wind farm in this region, the predicted wind power and wind power accommodation under the benchmark operation mode are as Figure 4 shows. In time periods 1-7, there are wind curtailment occurring. Thus in following coordinated dispatch, only time periods 1-7 are considered. Parameters of thermal power units in the region are as Table 1 shows. In the time periods with wind curtailment, all these thermal power units are operated at the benchmark of peak regulation. The shape parameters of Beta distribution in different time periods with different COVs are shown in Table 2.

The data of wind power installation, thermal power installation, wind power prediction, power load, tie line, unit startup are the historical data in the actual operation of the real provincial power system. And Beta distribution parameters are calculated according to (25) and (26) under different coefficient of variations (COVs) of wind power output.

B. ECONOMIC FEASIBLE REGIONS CALCULATION

Economic feasible region of wind power coordinated with GENCO-I is illustrated in Figure 5, where the COV of wind

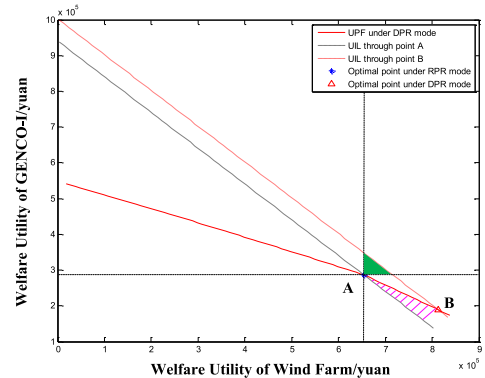


FIGURE 5. UPF curve of wind farm and GENCO-I and economic feasible region under the coordinated dispatch.

power is zero. We can find from Figure 5 that utility of GENCO-I has a decrease while wind power farm has an increase. The area marked with pink shadows is the economic feasible region of the coordinated bilateral coordination of wind power and GENCO-I and the green region is the feasible region for compensation settlement. The overall utility is increased after coordination as is shown in Figure 6.

The overall utility increment is used to quantify the economic feasibility of bilateral coordination. The economic feasible regions of different coordination schemes under different COVs are as Figure 7 shows. In the figure, W-I means a coordination of wind farm and GENCO-I. W-I-II means a coordination of wind farm, GENCO-I and GENCO-II. Other abbreviations are similar to this.

When wind farm is coordinated with only one GENCO, a wider economic feasible region can be obtained if GENCO-III is chosen. The utility of scheme W-III is even larger than that of W-I-II. The most efficiency scheme for

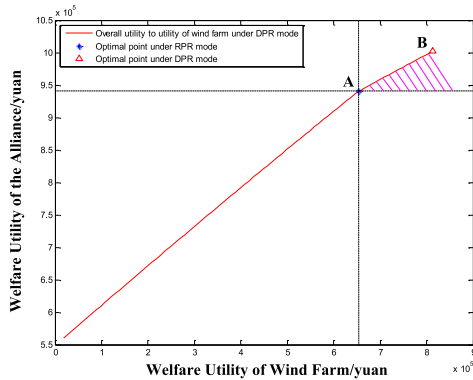


FIGURE 6. Relationship between overall utility and utility of wind farm under the coordinated dispatch.

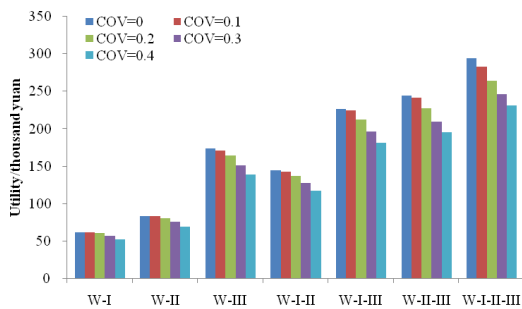


FIGURE 7. Economic feasible regions of different coordination schemes under different COVs.

wind farm is the coordination with all the three GENCOS. That is because the potential wind curtailment in the chosen day of the system is large and demand of peak regulation capacity is large, too. Also, the oil injection of thermal power units increases with the increase in peak regulation depth. Thus participation of more units in the DPR operation can reduce the cost of oil and leads to the utility increase. It may be different if the potential wind curtailment is less. When the potential wind curtailment has been reduced to one third of the current, the economic feasible regions of different coordination schemes can be seen in Figure 8. The COV of wind power output in Figure 8 is zero. It can be seen that utilities of coordination scheme W-III, W-I-III, W-II-III and W-II-III are the same. It means when GENCO-III participates in the coordination, other two GENCOS have no contributions for the alliance. Thus it is better for wind power to seek a bilateral coordination with only GENCO-III.

It can be also seen from Figure 7 that when the COV of wind power output increases, the economic feasible region of a certain coordination scheme becomes smaller. This means that the more obvious the dispersion of wind power output is, the less the expectation of overall utility is for the alliance.

C. COMPENSATION RANGES AND ALLOCATION BASED ON SHAPLEY VALUE

The feasible compensation pricing ranges of the three GENCOS in the scheme W-I, W-II and W-III are shown

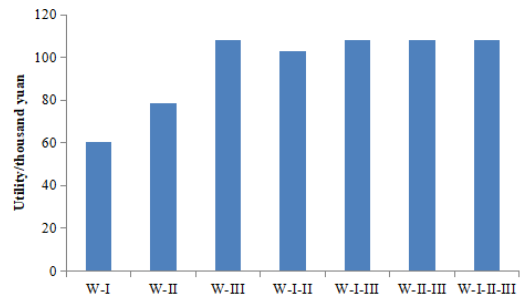


FIGURE 8. Economic feasible regions of different coordination schemes under when less wind curtailment occurs.

TABLE 3. Compensation pricing ranges of three GENCOS.

GENCO	I	II	III
Pricing range/(yuan/MWh)	[319.85,520]	[322.14,520]	[311.92,520]

TABLE 4. Profit allocation result for COV = 0.

GENCO	Utility under separated scheme/yuan	Utility under coordinated scheme/yuan	Increase of profit/ %
Wind farm	653470.45	804887.72	23.17
I	287263.27	314383.62	9.44
II	384520.60	421345.11	9.58
III	856794.27	935838.35	9.23

in Table 3. It can be seen that the cost recovery price of GENCO-III is lowest among the three GENCOS. It indicates that there will be a greater potential economic utility for wind farm to form a coordinated dispatch with GENCO-III. Thus when the wind curtailment is not serious, the best scheme for wind power to carry out a coordinated dispatch is the coordination with GENCO-III. And it is followed by GENCO-I and GENCO-II with the increase in the wind curtailment. Also GENCO-III will have more superiority when participating in the peak regulation market among the three GENCOS because of the lower cost for electricity generation.

Profit allocation in this paper is based on the contributions of different GENCOS in the coordinated dispatch, which is calculated by Shapley value. The allocation result of coordinated dispatch scheme W-I-II-III is listed in Table 4, which is a result when the COV is zero. We can see that all the participants benefit from the coordinated dispatch thus the initiative of participants can be ensured when carrying out the bilateral coordination. The profit allocations under different COVs are shown in Table 5. It can be seen that the profit allocated to each participant has a downward trend with the increase in the uncertainty of wind power output. It is because the economic feasible region is much smaller when the COV is relatively large. But there is still a large potential profit for the coordinated dispatch.

TABLE 5. Profit allocation with different COVs.

GENCO	Wind farm	I	II	III
COV=0	804887.72	314383.62	421345.11	935838.35
COV=0.1	801330.33	312260.81	418763.04	933051.29
COV=0.2	791540.61	310267.86	415905.55	927132.35
COV=0.3	771435.55	308996.20	414048.51	921879.19
COV=0.4	736212.17	308174.12	412849.64	918309.81

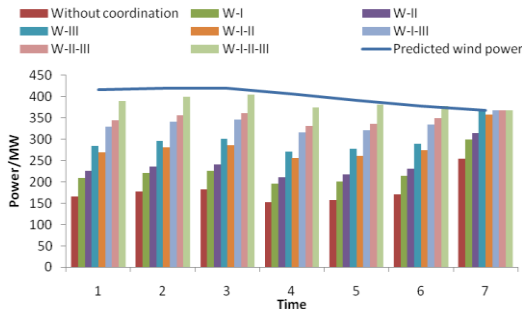


FIGURE 9. Wind power accommodation of different coordinated dispatch schemes with COV = 0.

TABLE 6. Increment of wind power accommodation of different coordination schemes under different COVs.

COV	0	0.1	0.2	0.3	0.4
W-I	308.00	307.52	300.61	282.39	259.31
W-II	420.00	418.67	407.50	381.13	349.73
W-III	833.38	821.43	787.07	727.00	668.60
W-I-II	728.00	717.31	690.04	638.97	586.84
W-I-III	1097.38	1090.69	1031.71	950.63	880.24
W-II-III	1193.38	1180.90	1110.87	1024.56	952.12
W-I-II-III	1441.74	1389.76	1295.91	1205.28	1134.74

D. WIND POWER ACCOMMODATION

Wind power accommodation of different coordinated dispatch schemes when COV is zero are given in Figure 9. It can be seen that all the coordinated dispatch schemes can obtain a higher wind power accommodation of the given system. With the number of GENCOs chosen by wind farm for coordinated dispatch increases, wind power accommodation increases.

The overall wind power accommodation of different coordinated dispatch schemes under different COVs are shown in Table 6. The trend of wind power accommodation is consistent with that of economic feasible regions. It can be easily understood that more wind power accommodation means more profits as the clearing price of wind power is much higher than thermal power units in the given province. Thus the change of economic feasible region is actually the change of wind power accommodation space obtained through bilateral coordination.

VI. DISCUSSION

It can be seen in Figure 5 and 6 that there is economic feasible region in bilateral coordinated dispatch in the given case. It means that the potential utility can be obtained. That is because coordination of wind power and thermal power units can reduce the wind curtailment so that wind power

accommodation can be improved. At present, the clearing price of electricity from wind farms is higher than that from thermal power units due to the renewable energy subsidies. Thus the overall profit can be improved by the bilateral coordination. And also, there is profit margin for wind power and thermal power units in bilateral cooperation because of the price difference so as to ensure the feasibility of bilateral coordination. The relationship between wind power accommodation and utility can also be seen from Figure 7 and Table 6.

Figure 7 indicates that scheme W-III has higher utility than that of W-I and W-II when the potential wind curtailment is relatively large. That is because GENCO-III has more peak regulation units and capacity, which can provide more space for wind power accommodation. And that leads to more contribution of GENCO-III for the potential utility of the alliance. The peak regulation capacities of the three GENCOs are respectively 44 MW, 60 MW and 120MW. It means that the scheme W-III can provide more space for wind power accommodation than W-I-II and can lead to a larger utility, which can be seen in Figure 7.

The decrease in economic feasible region with the increase in COV of wind power output is shown in Figure 7. That is because the alliance cannot obtain the same profit when wind power output is less than that in the plan. At the same time, due to the limitation of peak load regulation capacity and output plan, wind power output beyond that in the plan cannot be fully converted into profit of alliance.

It becomes clear in Figure 8 and Table 3 that cost recovery price of GENCO-III is lowest among the three GENCOs, thus wind farm should give priority to GENCO-III in coordination, especially when the potential wind curtailment is small.

VII. CONCLUSION

In this paper, the bilateral coordination of wind and other GENCOs is studied. Deep power regulation of thermal power units are utilized to provide space for wind power accommodation. The potential economic feasible regions in bilateral cooperation with different participants are analyzed under different levels of wind power uncertainty. The compensation pricing ranges are analyzed according to the individual rationality constraints and a reasonable profit allocation scheme is given according to the contributions of wind farm and GENCOs based on Shapley value. An affine decision rule is utilized to realize a fast computation. According to the case study of a wind farm and three GENCOs in a region system northeast China, conclusions can be drawn as follows.

1) A bilateral coordinated dispatch scheme can make full use of the flexible of thermal power units under deep power regulation to provide more space for wind power accommodation compared with that under RPR mode in coordinated dispatch. And the economic feasible region can be extended through the clearing price difference between electricity from wind farm and thermal power units.

2) Among the three GENCOs, GENCO-III has the lowest cost recovery price carrying out DPR operation. Therefore, it has more superiority when participating in the peak

regulation market. And it is better for wind power to form coordination with GENCO-III when wind curtailment is not serious.

3) The allocation based on Shapley value can clearly calculate the contributions of different participants in the bilateral coordinated dispatch, which provides the exact basis for deep peak regulation compensation. The initiative of participants can be ensured by the fair allocation when carrying out the bilateral coordination.

4) With the uncertainty of wind power increases, the potential economic feasible region will decrease due to the decrease in wind power expectation. But it is still profitable compared with that in separated dispatch.

This paper mainly focuses on the feasibility of the coordinated dispatch. The optimal coordination mode based on cooperative game theory and more flexible coordination scheme can be further studied in the future.

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FEIXIANG PENG received the B.S. degree in electrical engineering from the Dalian University of Technology, Dalian, China, in 2015, where he is currently pursuing the Ph.D. degree with the Faculty of Electronic Information and Electrical Engineering.

His research interests include power system optimal dispatch and renewable energy accommodation.



ZHENGAN GAO received the B.S. and M.S. degrees in electrical engineering from the Dalian University of Technology, Dalian, China, in 2016 and 2019, respectively, where he is currently pursuing the Ph.D. degree with the Faculty of Electronic Information and Electrical Engineering.

His research interests include power big data application and smart grid technology.



SHUBO HU received the B.S. and Ph.D. degrees in electrical engineering from the Dalian University of Technology, Dalian, China, in 2012 and 2019, respectively.

She holds a postdoctoral position at the Faculty of Electronic Information and Electrical Engineering, Dalian University of Technology. Her research interests include new and renewable power system dispatch optimization and battery energy storage.



HUI SUN received the B.S. and M.S. degrees from the Electrical Engineering Department, Northeast Institute of Electrical Power, and the Ph.D. degree from the School of Electrical Engineering, Dalian University of Technology, Dalian, China, in 2003.

She is currently a Professor with the Dalian University of Technology. Her research interest includes modern power system analysis and control.



WEI ZHOU received the B.S. and Ph.D. degrees in electrical engineering from the Dalian University of Technology, China, in 2004 and 2010, respectively.

She is currently an Associate Professor with the Faculty of Electronic Information and Electrical Engineering, Dalian University of Technology. Her areas of interest include power system optimal operation and wind power integration.



ZHONGHUI WANG is currently an Engineer with the Electric Power Dispatch and Communication Center, State Grid Liaoning Electric Power Co., Ltd., Shenyang, China.

His research interest is mainly in power system planning and operation.

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