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Coordinated Scheduling Strategy for Distributed Generation Considering Uncertainties in Smart Grids

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ABSTRACT Smart grid with great flexibility requirements will not accommodate high proportion of distributed generation with uncertainty in the future. Hence, it becomes indispensable to research scheduling strategy of distributed generation, aiming to reduce serious curtailment of renewable energy. This paper firstly proposes a virtual power supply, which consists of wind power (WP), photovoltaic (PV) power and pumped storage (PS) power. Based on that, a scheduling strategy structure considering stochastic characteristics caused by WP and PV is designed. After that, according to probability distribution of WP and PV, typical virtual power scenarios are obtained via scenario prediction and scenario reduction method. Furthermore, based on flexibility of virtual power and guidance of time-sharing electricity price mechanism, a coordinated scheduling model with optimization objective that maximizes profit is established. Finally, in simulation, validity of proposed model is verified via comparing with different scheduling models. Besides, profits of system under various peak-valley prices are analyzed, which can provide guidance for electricity pricing. The results illustrate that the proposed scheduling strategy can efficiently balance economy and flexibility in optimizing WP and PV consumption and profits of system are increased with 28% at most.

INDEX TERMS Coordinated scheduling, distributed generation, photovoltaic power, pumped storage power, wind power, uncertainty.

I. INTRODUCTION

There has been a significant increase in the development of distributed generation using resources such as wind power and photovoltaic power [1], [2], especially in China recently. However, with the gradual growth of renewable energy capacity, curtailment of wind and photovoltaic power occurs in smart grids. One of the leading causes is that the system lacks efficient regulation ability, and the distributed generation has characteristics of uncertainty. As a result of this uncertainty, the smart grid may not consume the renewable energy completely [3], [4]. Besides that, wind power and photovoltaic power in China are mainly installed in the "Three-North" area. Therefore, during the period of heat supply, cogeneration units are projected to produce heat. Meanwhile, the operational constraint of thermoelectric coupling decreases the wind power output, which further reduces the regulatory capacity [5]–[7].

References [8]–[12], which aimed at integrated electrothermal scheduling and considered heat storage and electric heating equipment, provided the additional consumption for distributed generation according to the demand for heat and the characteristics of thermal power plants. These researches proposed strategies which promote the consumption of wind power and diminish the negative effects brought by the aforementioned cogeneration units. However, the cogeneration units and other generators were considered as an additional assumption without any profit. As a result of an increase in installed distributed generation, a combined heat and power plant may fail to regulate the system efficiently, which influences the development of renewable energy.

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Energy storage technology has the ability to improve regulation of the system, which could also help the consumption of wind power [13]–[18]. Pumped storage power as a category of energy storage can efficiently achieve the flexible requirements of smart grid. Many researchers have discussed that pumped storage power participates in reducing peaks and filling valleys and in the consumption of wind power. Reference [19], based on the applied configuration theory, distributed the output of wind power and pumped storage power, achieving the goal of expanding the feasible range of wind power. Based on the rough set theory, a method was proposed in [20]. It included coordination of wind, photovoltaic and energy storage power stations, and achieved optimization of the financial and environmental benefits of the system. The proposed method was regarded as an efficient way to decrease the negative effects of fluctuations in renewable energy. Besides that, day-ahead scheduling and real-time scheduling models of pumped storage power stations have received increasingly more attention. For example, [21] considered the operation mechanism of power grid energy storage and proposed a strategy based on the aforementioned scheduling model. The strategy guaranteed the operational safety of renewable energy integration by complementing the power imbalance provided by pumped storage power. Considering that pumped storage power has a superior ability for peak-load shifting, [22] established a joint optimal scheduling model including pumped storage power and wind power, which enhanced the consumption of wind power. Some studies have also investigated the uncertainty of wind power. In [23], a joint optimal model with wind power, thermal power, and an energy storage system was built and its operation mechanism analyzed. This model with uncertainties has significant meaning for increasing the consumption of wind power. In brief, most research studies have provided insight into pumped storage as a peak regulation power source. This power source cooperates with wind power and photovoltaic power in power grid scheduling. Energy storage system such as pumped storage station plays an important role in enhancing consumption of renewable energy.

In the future smart grid, there will be a higher proportion of renewable energy. Uncertainty of the renewable energy could bring serious challenges for system operation. The aforementioned research only focused on the improvement of renewable energy consumption or profit of system without considering the coordination of wind, photovoltaic and pumped storage power or uncertainty of renewable energy. Both peak regulation service market and regulation ability of pumped storage still can be improved if scheduling strategy can be fully studied.

In this paper, a coordinated scheduling strategy is proposed. This strategy develops an energy management strategy for distributed generation including wind, photovoltaic, and pumped storage power. It guarantees that pumped storage station can store and utilize energy generated from renewable energy. The scenario prediction and reduction method are employed here to cope with uncertainty of renewable energy. When system operates based on this strategy, each unit will work to maximize system profit and consumption of renewable energy. Via simulation results, a guidance of electricity pricing is provided based on the proposed strategy. The main contributions of the paper are presented as: (1) By considering uncertainty of wind and photovoltaic power, model of coordinated scheduling strategy for wind, photovoltaic and pumped storage power are built with an aim to maximize profit of system and improve consumption of wind and photovoltaic power. (2) Based on the proposed scheduling strategy, different peak-valley prices and reserve price scaling factors, the system profits are analyzed, which provides a guidance for electricity pricing.

The rest of this paper is organized as follows. In Section II, the framework of coordinated scheduling strategy is presented. In Section III, scenarios of WP and PV are developed by scenario prediction and scenario reduction method. In Section IV, coordinated scheduling model is established. In Section V, simulation testing is provided to demonstrate the effectiveness of the proposed method. The conclusion is shown in Section VI.

II. COORDINATED SCHEDULING STRATEGY

The scheduling of wind and photovoltaic power can be affected by uncertainties [24], [25], so the large-scale integration of wind and photovoltaic power will have a serious impact on the smart grid. Considering the complementary and operational characteristics of wind, photovoltaic, and pumped storage power, this research applies a coordinated control method which participates in the electricity market. The wind, photovoltaic, and pumped storage power can be seen as a virtual power supply which provides the grid with several advantages. First, for peak power regulation with rapid response, a pumped storage power station has the ability to reduce the curtailment of wind and photovoltaic power caused by a system with insufficient regulation capacity. In addition, a pumped storage power station can support reserve capacity that allows wind and photovoltaic power stations to cope with the impact of power prediction errors on system scheduling and operation. It also enhances the system's regulation capacity and further improves the grid-connection characteristics of wind and photovoltaic power, which benefits the schedulability of the system. Specifically, the proposed virtual power supply can reduce the competitive pressure caused by the connection of high-penetration wind, photovoltaic power, and the power grid, so that coordination and management of renewable energy sources can be easily achieved. Figure 1 shows the structure of the proposed scheduling strategy.

During the coordinated scheduling of virtual power supply, renewable energy sources will participate in market competition. According to the virtual power generation plan conducted by the power grid, the outputs of wind, photovoltaic, and pumped storage power are determined by the objective of maximizing the income from the virtual power supply, so that

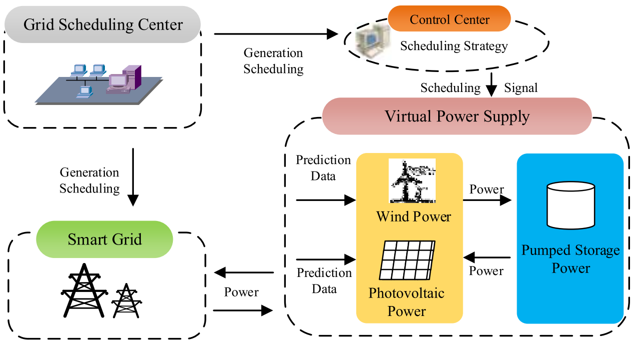

FIGURE 1. Coordinated scheduling strategy for wind, photovoltaic, and pumped storage power (virtual power).

power generation companies use their own power or buy reserve power from the grid to make up the output deviation.

In the proposed coordinated scheduling of virtual power supply, the pumped storage power station has three different operating states on the time scale: (1) Generation state: characteristic variable is set as X_t. (2) Energy storage state: characteristic variable can be described by Y_t. (3) Standby state: characteristic variable is set as Z_t.

When X_t, Y_t, and Z_t equal 0, it means that the pumped storage power station does not work at any operating state; when X_t, Y_t, and Z_t equal 1, pumped storage power stations are working at corresponding operating state. Since a pumped storage power station can only have one of the operating states at a certain moment, the characteristic variables have the following relationship:

$$X(t) + Y(t) + Z(t) = 1 \tag{1}$$

III. WIND AND PHOTOVOLTAIC POWER SCENARIOS

This research adopts the scenario prediction method to cope with the uncertainty and randomness of wind and photovoltaic power. First, based on the optimal discrete method of Wasserstein distance index, the optimal continuous probability distribution of wind power and photovoltaic power in each time period is discretized. Then, the discrete distribution of wind and photovoltaic power in each time period is combined to generate multiple scenario sets. Besides that, to simplify the quantity of scenarios and facilitate the calculation, synchronous back-generation technology is employed to reduce the typical scenarios.

A. SCENARIO PREDICTION BASED ON OPTIMAL DISCRETIZATION

The wind and photovoltaic power are random variables in the system due to natural factors. To obtain a typical power scenario, it is necessary to discretize the optimal continuous probability distribution of the random variable in each period firstly. After that, the discrete distribution of random variables in each time period is combined to obtain multiple scenarios. The basic principle of optimal discretization can be described as: firstly, set reasonable points and determine their probabilities; then, establish the discrete probability distribution, which minimizes the distance between them and a continuous probability distribution. To deal with a continuous probability distribution $h(x)$, the Wasserstein optimal discrete method [26]–[29] for distance index is employed here. The corresponding discrete probability distribution of the optimal points $z_q(q = 1, 2, \ldots, Q)$ has the following conditions:

$$\int_{-\infty}^{z_q} h^{1/2}(x)\mathrm{d}x = \frac{2q-1}{2Q}\int_{-\infty}^{\infty} h^{1/2}(x)\mathrm{d}x \tag{2}$$

The probability is further determined as:

$$p_q = \int_{\frac{z_{q-1}+z_q}{2}}^{\frac{z_q+z_{q+1}}{2}} h(x)\mathrm{d}x \tag{3}$$

where $z_0 = -\infty$ and $z_{Q+1} = +\infty$.

The forecast error of wind power is assumed in this paper to conform to normal distribution, namely $\Delta Pw \sim N(0, \sigma_{Pw}^2)$. So, the probability distribution of actual wind power can be expressed as [30]:

$$f(P_w) = \frac{1}{\sqrt{2\pi}\sigma_{P_w}} \exp[-(P_w - P_w^f)^2/2\sigma_{P_w}^2] \tag{4}$$

where p_w^f is the predicted wind power, and p_w is the actual WP power.

Besides that, photovoltaic power is commonly affected by climate and geography. Therefore, the PV power approximately conforms to a β distribution. Further, the probability distribution of actual PV power can be expressed as [31]:

$$f(P_{\text{pv}}) = \frac{1}{P_{\text{pv,max}}B(\alpha,\beta)}\left(\frac{P_{\text{pv}}}{P_{\text{pv,max}}}\right)^{\alpha-1}\left(1-\frac{P_{\text{pv}}}{P_{\text{pv,max}}}\right)^{\beta-1} \tag{5}$$

where α, β are beta distribution parameters, P_{pv} is the actual PV power, $P_{\text{pv,max}}$ is the maximum PV power, and $B(\alpha, \beta) = [\Gamma(\alpha)\Gamma(\beta)] / [\Gamma(\alpha+\beta)]$.

Accordingly, based on these probability distributions, the predicted scenarios of wind and photovoltaic power can be obtained by optimal discretization.

B. OPTIMIZATION OF SCENARIOS

After obtaining the continuous probability distribution for the optimal discrete wind and photovoltaic power output at each moment, a large number of output scenarios can be gained for the entire scheduling period, and the calculation scale will be seriously complex. Therefore, in order to solve the problem of dimension disaster and simplify the calculation, this paper adopts a scenario reduction method based on probability distance, to reduce the large number of output scenarios generated; typical scenarios are obtained on the premise of satisfying the accuracy.

For any two scenarios $\boldsymbol{P}_{\text{f}}^i$ and $\boldsymbol{P}_{\text{f}}^j$, set their possibilities as and π_i, π_j, respectively. Then the probability distance between $\boldsymbol{P}_{\text{f}}^i$ and $\boldsymbol{P}_{\text{f}}^j$ is defined as:

$$D(\boldsymbol{P}_{\text{f}}^i, \boldsymbol{P}_{\text{f}}^j) = \left\|\boldsymbol{P}_{\text{f}}^i - \boldsymbol{P}_{\text{f}}^j\right\|_2 \tag{6}$$

The reduced scenario set can be described as $\boldsymbol{P}_{\mathrm{f}}^{j}$, where J is the set of elimination scenarios, and $j \in \{1, \ldots, C\} \backslash J$. Scenario reduction is done to minimize the probability distance between all scenarios in the scheduling period and the typical reduced scenario set. According to (4), it can be specifically expressed as:

$$\min\{\sum_{i \in J} \pi^{i} \min_{j \notin J} D(\boldsymbol{P}_{\mathrm{f}}^{i}, \boldsymbol{P}_{\mathrm{f}}^{j})\} \tag{7}$$

In this paper, to achieve the goal expressed in (7), the synchronous back-generation technique [32] is employed. The specific process is shown as follows:

Step 1: Set the entire scenario set as C, and the number of iterations as $k = 1$. Set the scenario set of the iterative process as $C^{(k)} = C$; the scenario set of elimination is initialized as an empty set;

Step 2: Determine the probability distance of each pair of scenarios. $D_{i,j} = D(\boldsymbol{P}_{\mathrm{f}}^{i}, \boldsymbol{P}_{\mathrm{f}}^{j}), i, j \in C^{(k)}, i \neq j$;

Step 3: Find the scenario closest to scenario i. Determine the minimum distance between that scenario and the rest of the scenarios: $DJ_i = \min D(\boldsymbol{P}_{\mathrm{f}}^{i}, \boldsymbol{P}_{\mathrm{f}}^{j}), i, j \in C^{(k)}, i \neq j$. Then, find a scenario matching this minimum distance J.

Step 4: Multiply the minimum distance for each scenario by its corresponding probability to get a scenario that matches the minimum value determined in the previous step. Then, based on $Z_i = \pi^i \cdot DJ_i = \pi^i \cdot \min D(\boldsymbol{P}_{\mathrm{f}}^{i}, \boldsymbol{P}_{\mathrm{f}}^{j})$, determine the scenario $c_1, Z_{c_1} = \min Z_i, i \in C^{(k)}$;

Step 5: Eliminate scenario c_1, and at the same time transfer the probability of scenario c_1 to its closest one. The rest of the scenarios are set as: $C^{(k+1)} = C^{(k)} - \{c_1\}$. Eliminated scenarios are set as: $J^{(k+1)} = J^{(k)} + \{c_1\}$. If scenarios l and c_1 are closest, the possibility of l turns is $\pi^l = \pi^l + \pi^{c_1}$.

Step 6: Record the number of remaining scenarios. If the number of remaining scenarios meets the requirements, continue to Step 7; if not, return to Step 2. The number of iterations is set as $k = k + 1$.

Step 7: Retain the probability corresponding to each scenario in the remaining scenario set $C^{(k+1)}$ and $C^{(k)}$ after elimination.

IV. COORDINATED SCHEDULING MODEL OF VIRTUAL POWER BASED ON SCENARIO PREDICTION

In the electricity market, wind, photovoltaic, and pumped storage power are bundled to form virtual power supply and participate in grid scheduling based on peak-valley price. The regulation capacity and flexibility of the system are limited, so it is difficult to deal with the fluctuation and uncertainty of high-penetration wind power and photovoltaic power. Therefore, in order to ensure that high-penetration wind power and photovoltaic power systems operate safely and stably, virtual power generators need to purchase reserve capacity from the grid to cope with output deviation. In the coordinated scheduling strategy for virtual power supply, the total number of hours is set as T. The corresponding probability of each scenario is π_s, with I units in total, where $I = 3$, and $i = 1, 2, 3$ represent wind, photovoltaic, and pumped storage power, respectively.

A. OBJECTIVE FUNCTION AND RESTRICTIONS

The objective function is considered as the maximum expected profit from the virtual power supply under different output scenarios:

$$\max \sum_{s=1}^{S} \pi_s \sum_{t=1}^{T} \{\sum_{i=1}^{I} [\rho_t P_{\mathrm{G},i,t}^{s} - \rho_t^{\mathrm{up}} f(P_{\mathrm{grid},t}^{s}) - \rho_t^{\mathrm{down}} f(-P_{\mathrm{grid},t}^{s})] \Delta t - C_{\mathrm{PG},3,t}^{s}\} \tag{8}$$

where $P_{\mathrm{G},i,t}^{s}$ is the output of power i in period t; ρ_t is the grid-connection electricity price in period t; ρ_t^{up} and ρ_t^{down} are positive and negative reserve price, respectively; $P_{\mathrm{grid},t}^{s}$ is reserve capacity purchased from the grid by virtual power; $C_{\mathrm{PG},3,t}^{s}$ is the start-up cost for pumped storage during period t; and the piecewise function f is $f(A) = A, A > 0, f(A) = 0, A \leq 0$.

The start-up cost of a pumped storage station can be obtained by the following:

$$C_{\mathrm{PG},3,t}^{s} = C_{\mathrm{gen},t}^{s} + C_{\mathrm{pum},t}^{s} = C_{\mathrm{gen}} X_t^s (X_t^s - X_{t-1}^s) + C_{\mathrm{pum}} Y_t^s (Y_t^s - Y_{t-1}^s) \tag{9}$$

where C_{gen} is the start-up cost of pumped storage as power generation, and C_{pum} is the start-up cost of pumped storage under pumping conditions. When pumped storage works as power generation, $X_t^s = 1$. Otherwise, $X_t^s = 0$. When pumped storage works as energy storage, $Y_t^s = 1$. Otherwise, $Y_t^s = 0$.

For the piecewise function $f(\mathrm{A})$, set two non-negative relaxation variables $\boldsymbol{u}^s$ and $\boldsymbol{v}^s$; they represent the positive and negative reserve capacity, respectively, purchased from the grid by the virtual power supply in scenario s. Setting $\boldsymbol{P}_{\mathrm{grid}}^{s} = \boldsymbol{u}^s - \boldsymbol{v}^s$, the objective function can be described as:

$$\max \sum_{s=1}^{S} \pi_s \sum_{t=1}^{T} [\sum_{i=1}^{I} (\rho_t P_{\mathrm{G},i,t}^{s} - \rho_t^{\mathrm{up}} u_t^s - \rho_t^{\mathrm{down}} v_t^s) \Delta t - C_{\mathrm{PG},3,t}^{s}] \tag{10}$$

The constraint condition mainly includes four categories:

(1) Constraint of power balance:

$$\sum_{i=1}^{I} P_{\mathrm{G},i,t}^{s} + P_{\mathrm{grid},t}^{s} = P_{\mathrm{plan},t} \tag{11}$$

where $P_{\mathrm{plan},t}$ is the power generation plan of the virtual power source reported by the grid.

(2) Constraint of wind power output:

$$0 \leq P_{\mathrm{G},1,t}^{s} \leq P_{\mathrm{G},1,\max,t}^{s} \tag{12}$$

where $P_{\mathrm{G},1,t}^{s}$ is the output of wind power during period t, and $P_{\mathrm{G},1,\max,t}^{s}$ is the projected output of wind power during period t.

(3) Constraint of photovoltaic power output:

$$0 \leq P_{\mathrm{G},2,t}^{s} \leq P_{\mathrm{G},2,\max,t}^{s} \tag{13}$$

where $P^s_{G,2,t}$ is the generation of wind power during period t, and $P^s_{G,2,\max,t}$ is the predicted power generation of wind power during period t.

(4) Constraint of pumped storage power output:

The upper and lower limits of the pumped storage power station in each period are shown as follows:

$$E_{\text{up,min}} \leq E^s_{\text{up},t} \leq E_{\text{up,max}} \tag{14}$$

$$E_{\text{down,min}} \leq E^s_{\text{down},t} \leq E_{\text{down,max}} \tag{15}$$

According to the operating state of the pumped storage power station, the constraint is determined as:

If $X^s_t = 1$,

$$\begin{cases} E^s_{\text{up},t+1} = E^s_{\text{up},t} - \Delta t(\dfrac{P^s_{\text{gen},t}}{\eta_{\text{gen}}}) \\ E^s_{\text{down},t+1} = E^s_{\text{down},t} + \Delta t(\dfrac{P^s_{\text{gen},t}}{\eta_{\text{gen}}}) \end{cases} \tag{16}$$

If $Y^s_t = 1$,

$$\begin{cases} E^s_{\text{up},t+1} = E^s_{\text{up},t} + \Delta t P^{\text{s}}_{\text{pum,t}} \eta_{\text{pum}} \\ E^s_{\text{down},t+1} = E^s_{\text{down},t} - \Delta t P^s_{\text{pum},t} \eta_{\text{pum}} \end{cases} \tag{17}$$

If $Z^s_t = 1$,

$$\begin{cases} E^s_{\text{up},t+1} = E^s_{\text{up},t} \\ E^s_{\text{down},t+1} = E^s_{\text{down},t} \end{cases} \tag{18}$$

where $E^s_{\text{up},t}$ and $E^s_{\text{down},t}$ are the upper and lower water storage capacity in scenario s during period t; $E_{\text{up, min}}$ and $E_{\text{up, max}}$ are the upper and lower capacity limits of upper water storage; $E_{\text{down,min}}$ and $E_{\text{down,max}}$ are the upper and lower capacity limits of lower water storage; and $\eta_{\text{gen}}\eta_{\text{pum}}$ are the generation efficiency and storage efficiency of the pumped storage power station.

The operating power constraints of pumped storage power stations are given by:

$$\begin{cases} P_{\text{gen, min}} \leq P^s_{\text{gen},t} \leq \min[P_{\text{gen,max}}, \dfrac{E^s_{\text{up},t}}{\Delta t}\eta_{\text{gen}}], & X^s_t = 1 \\ P_{\text{pum, min}} \leq -P^s_{\text{pum},t} \leq \min[P_{\text{pum,max}}, \dfrac{E^s_{\text{down},t}}{\Delta t \eta_{\text{pum}}}], & Y^s_t = 1 \\ P^s_{\text{gen},t} = P^s_{\text{pum},t} = 0, & Z^s_t = 1 \end{cases} \tag{19}$$

where $P_{\text{gen,min}}$ and $P_{\text{gen, max}}$ are the upper and lower output limits of the pumped storage station, and $P_{\text{pum, min}}P_{\text{pum,max}}$ are the upper and lower capacity limits of the pumped storage station.

B. MODEL SOLVING METHOD

In the coordinated scheduling model of virtual power, scenario prediction method is employed to deal with uncertainties of wind and photovoltaic power, so this coordinated scheduling model can be turned from multi- scenario optimization problem to single-target scheduling optimization problem. When the system operates under the coordinated scheduling model, the power of wind $P^s_{G,1,t}$, photovoltaic cells $P^s_{G,2,t}$, pumped storage $P^s_{\text{gen},t}$, and storage $P^s_{\text{pum},t}$, and the capacity of water storage $E^s_{\text{up},t}$ and $E^s_{\text{down},t}$ are related to a random scenario of wind and photovoltaic power, which is a random decision variable, whereas the generation scheduling of virtual power is a deterministic decision variable. In addition, with an increasing number of wind and photovoltaic power scenarios, the coordinated scheduling model will face much more computation complexity and difficulties. Hence, the number of predicted power scenarios needs to be reduced. Based on that, the simulation is conducted considering the typical scenarios. Subsequently, CPLEX optimization software is employed to solve the coordinated scheduling model [33]–[35].

TABLE 1. Pumped storage plant parameters.

Parameter	Value	Parameter	Value
E^{u}_0 / MW·h	300	$P^{\text{gen}}_{\max}$ / MW	60
E^{d}_0 / MW·h	400	$P^{\text{pum}}_{\max}$ / MW	40
$E^{\text{u}}_{\min}$ / MW·h	100	C^{gen} / yuan	1500
$E^{\text{d}}_{\min}$ / MW·h	100	C^{pum} / yuan	2000
$E^{\text{u}}_{\max}$ / MW·h	600	η^{gen}	0.9
$E^{\text{d}}_{\max}$ / MW·h	600	η^{pum}	0.9

TABLE 2. Peak-valley price.

Time	Price (yuan/ (kW·h))	Time	Price (yuan/ (kW·h))	Time	Price (yuan/ (kW·h))
00:00	0.2	08:00	0.5	16:00	0.5
01:00	0.2	09:00	0.5	17:00	0.5
02:00	0.2	10:00	0.5	18:00	0.5
03:00	0.2	11:00	0.8	19:00	0.8
04:00	0.2	12:00	0.8	20:00	0.8
05:00	0.2	13:00	0.8	21:00	0.8
06:00	0.2	14:00	0.8	22:00	0.5
07:00	0.2	15:00	0.8	23:00	0.5

V. SIMULATION AND ANALYSIS

A. BASIC DATA OVERVIEW

This simulation scenario includes a wind power station, a photovoltaic power station, and a pumped storage power station, and their distributed generation forms a virtual power supply which operates as a coordinated scheduling model based on peak-valley price. The reserve electricity price is set as follows: $\rho^{\text{up}}_t = 0.75$ yuan/(kW·h), and $\rho^{\text{down}}_t = 0.18$ yuan/(kW·h). The parameters of the pumped storage power station are shown in Table 1. The electricity price at different times is shown in Table 2. The wind power capacity is 250 MW, whereas the photovoltaic power capacity is 50 MW. Here, the standard deviation of wind and photovoltaic power forecast error is set as 10% of the predicted value.

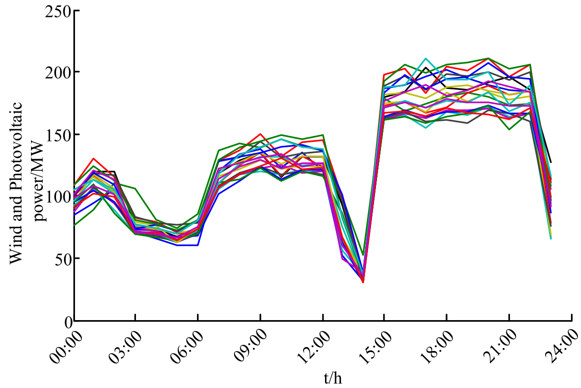

FIGURE 2. Typical prediction scenario for wind and photovoltaic power output.

TABLE 3. Probability values for each typical prediction scenario.

Typical Scenario	Probability	Typical Scenario	Probability
Scenario 1	0.052	Scenario 11	0.061
Scenario 2	0.046	Scenario 12	0.037
Scenario 3	0.037	Scenario 13	0.055
Scenario 4	0.041	Scenario 14	0.053
Scenario 5	0.073	Scenario 15	0.044
Scenario 6	0.051	Scenario 16	0.039
Scenario 7	0.035	Scenario 17	0.047
Scenario 8	0.042	Scenario 18	0.055
Scenario 9	0.036	Scenario 19	0.058
Scenario 10	0.085	Scenario 20	0.053

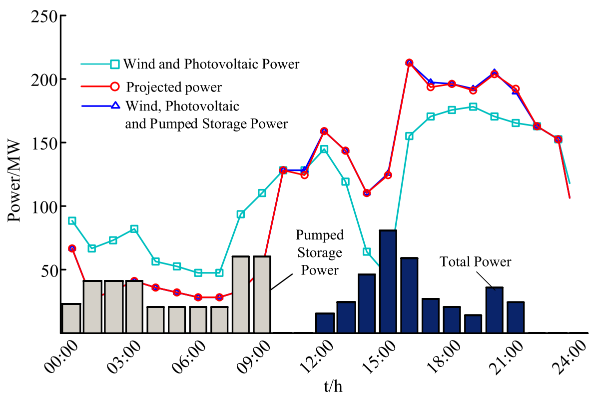

FIGURE 3. Coordinated scheduling results for wind, photovoltaic, and pumped storage virtual power.

B. DETERMINATION OF PREDICTION SCENARIOS

After reducing the number of scenarios for predicted wind and photovoltaic power, 20 typical scenarios are obtained and employed in the simulation. The wind and photovoltaic output power of the aforementioned typical scenarios is shown in Figure 2. The corresponding probability values for each typical prediction scenario are shown in Table 3.

C. ANALYSIS OF COORDINATED SCHEDULING

The results of coordinated scheduling in 20 typical scenarios can be seen in Figure 3.

The results suggest that there is a certain complementary relationship among wind, photovoltaic, and pumped storage power. Furthermore, the actual power of wind is remarkably less than the projected power when the system works during peak hours. With the stimulation of high electricity price, pumped storage power starts to complement the insufficient wind and photovoltaic power output. Besides that, the system cannot consume wind and photovoltaic power when the price is at its lowest. Therefore, to avoid curtailing the wind and photovoltaic power, pumped storage begins to store energy by pumping water at the valley electricity price. So, the wind and photovoltaic power stations can generate electricity according to the scheduling of the grid. However, there are still some deviations between actual power and scheduling power in virtual power, due to the uncertainties and randomness of wind and photovoltaic power. To cope with this issue, reserve capacity is bought to complement the deviation from the grid.

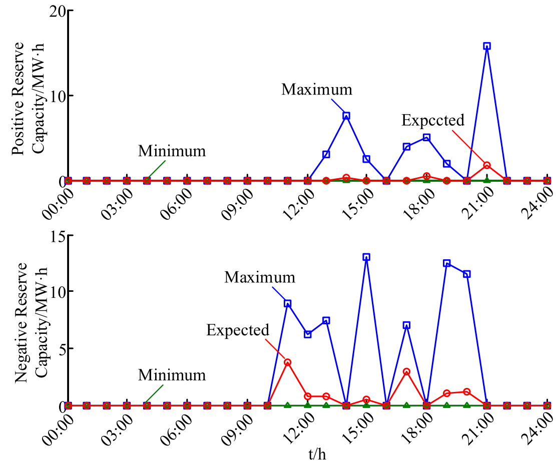

FIGURE 4. Reserve capacity under coordinated operation of wind, photovoltaic, and pumped storage power.

When virtual power operates according to the coordinated scheduling model, the curves of positive and negative reserve capacity bought from the grid are as presented in Figure 4.

A difference in reserve capacity bought from the grid can be seen in different output scenarios, because of the uncertainties and randomness of wind and photovoltaic power. The system needs to buy positive reserve capacity from the grid to complement the insufficient power generated by virtual power when the actual power is lower than the projected power. In contrast, the system gains a negative reserve capacity which offsets the extra power generated from virtual power when the actual power is more than the planned power. Generally speaking, the price of the negative reserve is lower than that of the positive one, which encourages the system to reduce the projected power and buy more negative reserve capacity.

D. ANALYSIS OF SYSTEM OPERATION WITH DIFFERENT SCHEDULING MODELS

To illustrate the superiority of the proposed coordinated scheduling strategy, the four categories of scheduling model shown in Table 4 are compared and analyzed. In Table 3, "Independent Operation" means that wind, photovoltaic, and pumped storage power operate independently, whereas

TABLE 4. Scheduling model situation.

Scheduling Model	Operation Situation
1	With Uncertainty, Independent Operation
2	With Uncertainty, Coordinated Operation
3	Without Uncertainty, Independent Operation
4	Without Uncertainty, Coordinated Operation

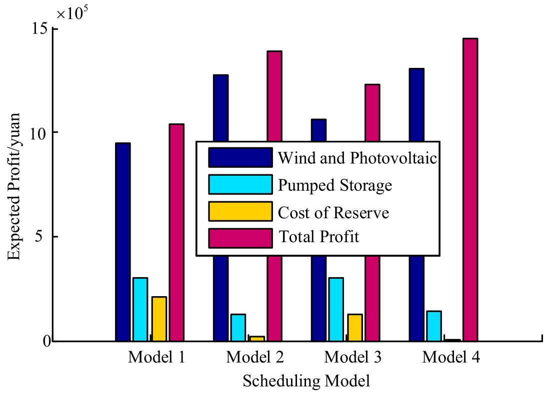

FIGURE 5. Operation in each scheduling model.

"Coordinated Operation" means that wind, photovoltaic, and pumped storage power operate in coordination.

The wind and photovoltaic power can be computed by maximizing the profit, when wind and photovoltaic power work as independent models. This profit is gained by the profit from connecting to the grid and the cost of reserve capacity. Importantly, in this model, pumped storage power will not buy reserve capacity in the independent model. Besides that, the maximum projected power is determined by the maximum wind, photovoltaic, and pumped storage power when the virtual power works as a coordinated scheduling model. Figure 5 depicts the profits for scheduling models in 20 typical scenarios.

Comparing model 1 with model 2, the system generates more profit when the virtual power works under coordinated operation, because pumped storage power can complement the uncertainties of wind and photovoltaic power. This can efficiently reduce the reserve capacity bought from the grid and increase the profit obtained from wind and photovoltaic power connecting with the grid. To be specific, profit is increased by 28%. So, the results of these two models suggest that coordinated scheduling can improve the consumption of wind and photovoltaic power. Besides that, although there is a decrease in the profit from pumped storage, the trend of total profit from virtual power rises. Moreover, in model 3 and model 4, uncertainty is not considered here. Profit of system with coordinated operation is also more than the system with independent operation. These show that coordinated operation can efficiently cope with fluctuations of wind and photovoltaic power, and the total profit is increased remarkably than independent operation model. In summary, the proposed strategy generally brings more profits than independent model.

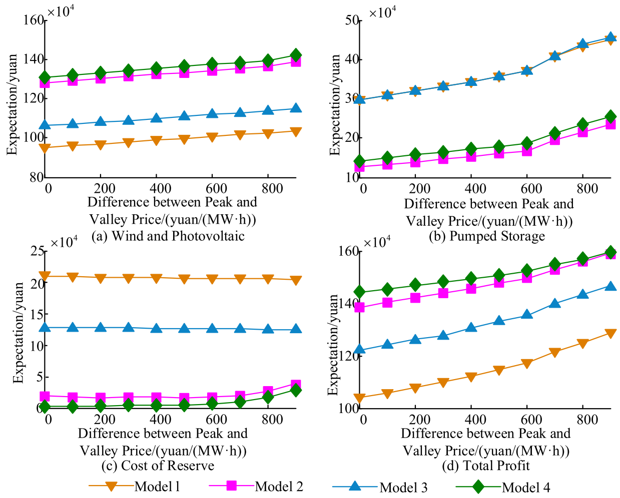

FIGURE 6. Impact of peak and valley spread on system revenue.

E. ANALYSIS OF THE IMPACT OF ELECTRICITY PRICE CHANGES ON SCHEDULING RESULTS

The electricity price of grid connection and reserve capacity will have a direct impact on the system scheduling results. The following analysis is based on the aforementioned price of reserve capacity. The profit of the system with different peak-valley prices and different scheduling models is shown in Figure 6.

The results shown in Figure 6 suggest that, for each scheduling model, the profit from wind and photovoltaic power shows a trend of increasing with growth of the difference in peak-valley price; the profit from pumped storage has the same trend. By comparing the expected profit from pumped storage power and the expected cost of reserve in model 3 and model 4, the result suggests that the profit difference between pumped storage power stations in model 3 and model 4 shows a rising tendency when the difference in peak-valley electricity price increases. In contrast, the difference in cost from that expected for reserve capacity gradually decreases because pumped storage has the ability to achieve peak-load shifting, which supplies more power for load and gains more profit when the peak-valley price difference increases. Meanwhile, regulation of wind and photovoltaic power fluctuation will be weakened, causing the price of reserve capacity to increase.

Defining the reserve price scaling factor as the ratio of reserve price to base value, and the aforementioned reserve price as the base value, the peak-valley price difference is set as 500 yuan/(MW·h). Based on this, the influence of reserve price on system scheduling results is discussed here. Figure 7 depicts the profits of the system under the four scheduling models at different reserve prices.

The reserve price reflects the requirement of the system for controllability of wind and photovoltaic power. To be specific, when the reserve price scaling factor is smaller than 1, wind and photovoltaic power has scheduling priority, which

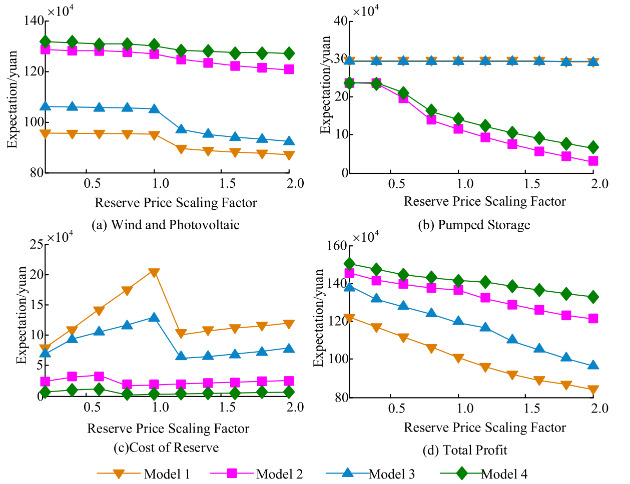

FIGURE 7. Impact of reserve price on system revenue.

means that the system will purchase more reserve capacity from the grid to increase the wind and photovoltaic power output. In contrast, when the reserve price scaling factor is larger than 1, the extra power which is connected to grid will increase the cost of reserve capacity. As depicted in Figure 7, when the reserve price scaling factor is smaller than 1, the reserve price will have little impact on the profit from wind and photovoltaic power for each scheduling model. Although the cost of reserve capacity will increase with an increase in price, the system puts no limits on wind and photovoltaic power to reduce the reserve capacity. Besides that, when the reserve price scaling factor is larger than 1, the system can decrease the cost of reserve capacity by reducing the wind and photovoltaic power output. With coordinated scheduling, pumped storage needs to start and stop frequently, which aims to cope with the fluctuation of wind and photovoltaic power and reduce the cost of reserve capacity. Hence, the profit will decrease with an increase in reserve capacity price.

VI. CONCLUSIONS

This research focuses on the contradiction between renewable energy and the flexibility required from smart grid. A coordinated scheduling model with virtual power supply formed by wind, photovoltaic, and pumped storage power is proposed. Initially, the uncertainty of wind and photovoltaic power is considered using a scenario prediction method. Thereafter, a coordinated scheduling model is established to maximize the profit from virtual power. Finally, the profit for different scheduling models is analyzed through simulation. In addition, the effect of changes in electricity price is also investigated. The following conclusions can be obtained:

1) The proposed virtual power system can efficiently utilize the flexibility of pumped storage power to cope with the uncertainty of wind and photovoltaic power under the coordinated scheduling model.
2) Based on a scenario prediction method, the proposed model of virtual power with coordinated scheduling can efficiently track the projected power curve to reduce the cost of reserve capacity and increase the profit of the system.
3) By considering impact of time-of-use electricity price, the proposed scheduling model can improve the characteristics of wind and photovoltaic power grid connection from the power supply side, which can reduce the cost of reserve capacity and increase the profit of system.

In summary, benefiting by the advanced communication device and monitoring equipment, the proposed strategy can be utilized to store and complement renewable energy in smart grid. Besides, the system can gain more profit, via the proposed strategy and adjustment of electricity pricing.

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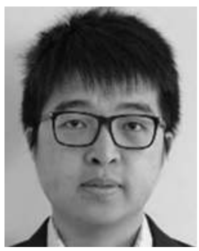

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