

# Day-ahead Coordinated Scheduling of Hydro and Wind Power Generation System Considering Uncertainties

Y. Z. Li, *Member, IEEE*, T. Y. Zhao, C. Liu, Y. Zhao, Z. Y. Yu, K. C. Li, and L. Wu, *Senior Member IEEE*,

**Abstract**—This paper presents a day-ahead coordinated scheduling method of hydro and wind power generation systems (HWPGSs) with consideration of uncertainties. In this method, we first formulate the coordinated scheduling model with two-part price and power flow constraints, which manifests the fixed and variable economic benefits as well as the secure operation of HWPGS, respectively. Then, the interval analysis is used to study the effect of uncertain wind power, water inflow, and electricity load on the coordinated scheduling model. Finally, we use a real test system in a western area of China to conduct simulation studies, which verify the effectiveness of the interval analysis and the effect of price mechanism on the day-ahead coordinated scheduling of HWPGS.

**Keywords**—Coordinated scheduling, hydropower, wind power, uncertainty, interval analysis.

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Y. Li is with the School of Automation, Ministry of Education Key Laboratory of Image Processing and Intelligence Control, Huazhong University of Science and Technology, Wuhan 430074, China. (Email: Yuanzheng\_Li@hust.edu.cn)

T. Zhao (Corresponding author) is with School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798. (Email: zhaoty@ntu.edu.sg)

C. Liu is with State Grid Changzhou Power Supply Company, No. 27 Juqian Street, Changzhou, was with School of Electrical and Electronics Engineering, Huazhong University of Science and Technology, Wuhan 430074, China. (Email: lcele@foxmail.com)

Z. Yu and K. Li are with School of Electrical and Electronics Engineering, Huazhong University of Science and Technology, Wuhan 430074, China. (Email: constk@hust.edu.cn likaicheng@hust.edu.cn)

Y. Zhao is with the School of Automation, Ministry of Education Key Laboratory of Image Processing and Intelligence Control, Huazhong University of Science and Technology, Wuhan 430074, China. (Email: zhiwei98530@hust.edu.cn)

L. Wu is with the Department of Electrical & Computer Engineering, Stevens Institute of Technology, Hoboken, NJ, USA New Jersey 07030, USA. (Email: lei.wu@stevens.edu)

## NOMENCLATURE

$T$	Total number of scheduling time slots
$N_W$	Total number of wind farms
$N_L$	Total number of load nodes
$N_H$	Total number of hydropower plants
$\Delta T$	Scheduling time interval
$c_{ex,p}^t$	Exchanged electricity price between HWPGS and the external power grid during the $t$ th time interval
$c_{ex,c}$	Capacity price of HWPGS
$c_w$	Penalty price of curtailed wind power
$c_l$	Penalty price of curtailed electricity load
$q_{H,i}^t$	Consumed water for the $i$ th hydropower generator
$Q_{H,i}^U$	Stored water that are needed for $i$ th hydropower generator to function as up reserves
$Q_{H,i}^D$	Stored water that are needed for $i$ th hydropower generator to function as down reserves
$P_{ex}^t$	Power that the HWPGS supplies to the external power grid in the $t$ th time interval
$P_{ex}^{U,t}$	Upper bound of the power that HWPGS supplies to the external power grid
$P_{ex}^{D,t}$	Lower bound of power that HWPGS supplies to the external power grid
$P_{H,i}^t$	Power output of the $i$ th hydropower plant
$R_{H,i}^{U,t}$	Up reserves of the $i$ th hydropower plant
$R_{H,i}^{D,t}$	Down reserves of the $i$ th hydropower plant
$I_{H,i}$	Unit commitments of the $i$ th hydropower plant
$P_{W,k}^t$	Power output of the $k$ th wind farm
$P_{W,k}^{U,t}$	Upper bound of curtailed wind power of the $k$ th wind farm
$P_{W,k}^{D,t}$	Lower bound of curtailed wind power of the $k$ th wind farm
$P_{W,cut,k}^t$	Curtailed wind power of the $k$ th wind farm
$P_{L,j}^t$	Electricity load of the $j$ th node
$P_{L,shed,j}^t$	Curtailed load of the $j$ th node
$P_{L,j}^{U,t}$	Upper bound of the $j$ th curtailed electricity load
$P_{L,j}^{D,t}$	Lower bound of the $j$ th curtailed electricity load
$F_{H,i}^{c,U}$	Upper bound of water inflow of the $i$ th hydropower plant
$F_{H,i}^{c,D}$	Lower bound of water inflow of the $i$ th hydropower plant
$RU_{H,i}$	Upper ramp of the $i$ th hydro generator

$RD_{H,i}$	Lower ramp of the $i$ th hydro generator
$C_h$	Incidence matrix between hydro generators and system nodes
$C_w$	Incidence matrix of wind farms and system nodes
$C_L$	Incidence matrix of transmission corridors and load nodes
$C_{ex}$	Incidence matrix of transmission corridors and the external power grid
$P'_H$	Power output vector of hydropower generators
$P'_W$	Power output vector of wind farms
$P'_L$	Power output vector of electricity load
$P'_{W,cut}$	Curtailed wind power vector of wind farm
$V'_H$	Volumes of water storage in a reservoir of hydropower plants at the end of time $t$
$F'_H$	Water inflow of the reservoir during the $t$ th time interval

## I. Introduction

With the rapid deployment of hydro and wind power in recent years [1-5], coordinated hydropower and wind power generation systems have drawn much attention [6]. It is known that wind power contributes to great economic benefits for power system operations. However, because of its high uncertainty, it is still difficult to well utilize this kind of energy. On the contrary, hydropower has various advantages for power system operations, such as its flexibility, controllability, and ability of storing energy. Therefore, the coordinated operation of a hydro and wind power generation systems (HWPGS) has been studied. It aims to use hydropower to accommodate the uncertain wind power, for maximizing its total economic benefit via supplying abundant electricity to an external power grid [7][8].

For instance, Ref. [9] evaluated three power systems, which are located in the areas of United States, Canada and Russia, respectively. Results showed that the coordinated operation of wind power plants and the existing hydropower station could bring about more economic benefits. Ref. [10] developed a method of the day-ahead operation of hydropower system combined with wind power, while uncertain power outputs of wind farms were also considered. The results indicated that their coordinated operation was beneficial for the minimization of curtailments of wind power. In addition, Ref. [11] verified that wind power could well be complemented by hydropower, i.e., a HWPGS delivered constant power rather than intermittent one which was inherent when using wind power merely. Moreover, Ref. [12] showed a systems-based modeling framework, in order to study operational impacts of integrated wind power on hydropower plants.

It is noted that wind power has been deployed rapidly in the western area of China. For instance, a large wind farm called "Gansu Jiuquan wind power base" has been established. In addition, this area has large hydropower stations. However, the electricity load is relatively low, as the local economy is expected to be developed. In this way, it is worthwhile for us to study coordinated operation of the HWPGS in this region, which can obtain economic benefit by supplying abundant

power for the external power grid, while ensuring its secure operation. This is the main motivation of our work.

However, it is difficult to obtain the optimal scheduling solution of the HWPGS, due to uncertainties of wind power, water inflow, and electricity load in a day-ahead time scale. At present, stochastic programming and robust optimization are two main methods used for power system scheduling. In detail, uncertainty factors are usually presented as stochastic variables in the former method, using probabilistic density functions. For instance, the Weibull distribution is adopted to describe uncertainties of the wind speed [13]. However, it should be mentioned that using such standard probability density functions in power system scheduling remains to be examined [14]. Moreover, we should obtain a large number of scenarios, which are generated by some sampling methods, such as Monte Carlo method [15][16]. This leads to an expensive computation for stochastic programming.

In recent years, the robust optimization is a popular method for solving power system scheduling problems with uncertainties [17], with the development of interval forecasting of uncertain renewable power [18]. However, this method is usually considered to be too conservative, as it tries to find the worst-case scenario solution which happens at a very low probability [19]. On the contrary, the interval analysis aims to optimize the upper and lower bounds of the uncertain optimization problem, and it does not need to transfer the original problem to the form of "minimum-maximum", compared with the robust optimization approach [20]. Consequently, we adopt the interval analysis to study day-ahead coordinated scheduling problem in a HWPGS, considering uncertainties of wind power, water inflow, and electricity load. This is the main contribution of our work.

In addition, the current electricity price mechanism in China is divided into one-part price, one-part peak and valley prices, two-part price, etc. [21]. Compared with other types of price mechanisms, the two-part price consists of capacity and exchanged electricity prices, which well manifest economic benefits of capacity and power exchange for the HWPGS, respectively. In this way, we use the two-part tariff to formulate the day-ahead coordinated scheduling model of the HWPGS in this paper, while considering power flow constraints. Finally, a real test system in a western area of China is used to conduct simulation studies, in order to verify the effectiveness of interval analysis and investigate the effect of price mechanism on the day-ahead coordinated scheduling of HWPGS.

The rest of this paper is organized as follows. Section II presents formulations of day-ahead coordinated scheduling model of a HWPGS considering the two-part price and power flow. Section III introduces the interval analysis for the coordinated scheduling model considering uncertain wind power, electricity load and water inflow. In Section V, simulation studies are conducted based on a real test system, in order to verify the effectiveness of interval analysis. Finally, conclusions are drawn in Section VI.

## II. DAY-AHEAD COORDINATED SCHEDULING MODEL OF HWPGS CONSIDERING TWO-PART TARIFF AND POWER FLOW

### A. Objective Function

The HWPGS generates hydropower and wind power, and its characteristic of power outputs is different from that of traditional generation units. In this paper, the objective function of day-ahead coordinated scheduling of HWPGS is formulated as follows.

$$f = \max_{P_{H,i}^t, R_{H,i}^{U,t}, R_{H,i}^{D,t}, I_{H,i}^t} \left\{ \sum_{t=1}^T c_{ex,p}^t P_{ex}^t + c_{ex,c} \min_{t \in [1,T]} (P_{ex}^t) - c_w \sum_{t=1}^T \sum_{k=1}^{N_W} P_{W,cut,k}^t \Delta T - c_L \sum_{t=1}^T \sum_{j=1}^{N_L} P_{L,shed,j}^t \Delta T \right\} \quad (1)$$

where  $P_{ex}^t$  is the power that the HWPGS supplies to the external power grid in the  $t$ th ( $t=1,2,\dots,T$ ) time interval, where  $T$  is the total number of scheduling time slots.  $P_{W,cut,k}^t$  is the curtailed wind power of the  $k$ th ( $k=1,2,\dots,N_W$ ) wind farm, where  $N_W$  is the number of farms.  $P_{L,shed,j}^t$  stands for the curtailed load of  $j$ th ( $j=1,2,\dots,N_L$ ) node in the HWPGS, where  $N_L$  stands for the total number of load nodes.  $\Delta T$  is the scheduling time interval.  $c_{ex,p}^t$  stands for the exchanged electricity price between HWPGS and the external power grid, during the  $t$ th time interval.  $c_{ex,c}$  is the capacity price of HWPGS. Besides,  $c_w$  and  $c_l$  are penalty prices of curtailed wind power and electricity load. The decision variables of (1) consist of power outputs, up reserves, down reserves, and unit commitments of hydropower plants. They are denoted as  $P_{H,i}^t$ ,  $R_{H,i}^{U,t}$ ,  $R_{H,i}^{D,t}$ , and  $I_{H,i}^t$  for the  $i$ th ( $i=1,2,\dots,N_H$ ) hydropower plant, where  $N_H$  is the total number of these plants.

The economic benefit of capacity is expressed as the capacity price multiplying the minimum capacity of HWPGS. It should be mentioned that the minimum capacity is set as the minimum  $P_{ex}^t$  for all time intervals in this paper. Therefore, the economic benefit of capacity of HWPGS is shown as the second term in the objective function (1), i.e.,  $c_{ex,c} \min_{t \in [1,T]} (P_{ex}^t)$ .

The symbol of "min" does not stand for a minimization function. Instead, it aims to sort the power exchange, and find the minimum one. What is more, the first term of (1),

$\sum_{t=1}^T c_{ex,p}^t P_{ex}^t$  means the economic benefit of power exchange.

Meanwhile, curtailments of wind power and hydropower are attempted to be minimized, therefore, the signs of the last two terms are negative.

### B. Constraints

#### 1) Power flow constraint

The power flow constraints in the HWPGS are formulated as follows:

$$P_{Lmin} \leq A(C_h P_H + C_w P_W - C_L P_L - C_{ex} P_{ex}) \leq P_{Lmax}, \forall t \in [1, T] \quad (2)$$

where  $A$  is the matrix of distribution factors between the injected power at each node and the power flow in each

branch, and  $C_h$  is the incidence matrix between hydro generators and system nodes.  $C_w$  denote the incidence matrix of wind farms and system nodes. In addition,  $C_L$  stands for the incidence matrix of transmission corridors and load nodes in the HWPGS.  $C_{ex}$  is the incidence matrix of transmission corridors and the external power grid.  $P_H$ ,  $P_W$ , and  $P_L$  are power output vectors of hydropower generators, wind farms, and electricity load in the HWPGS, respectively.  $P_{Lmin}$  and  $P_{Lmax}$  are the upper and lower bounds of power flow. Therefore, (2) means that the power flow in each branch of the HWPGS is within the range of  $[P_{Lmin}, P_{Lmax}]$ . It is noted that the power flow is usually formulated as the susceptance multiplied by the phase angle difference between two adjacent buses in DC power systems. However, it can be also expressed by using distribution factors. That is, the power flow is a linear sum function, presented as power outputs of generators multiplied by their distribution factors. In this way, the computation complexity for power flow is lessened [22][23].

#### 2) Power balance constraint

The HWPGS supplies electricity for the external power grid, and curtailments of wind power  $P_{W,cut}$  and electricity load  $P_{L,shed}$  may exist. In this way, the constraint of power balance can be shown as follows.

$$P_{ex}^t = P_H^t + (P_W^t - P_{W,cut}^t) - (P_L^t - P_{L,shed}^t), \forall t \in [1, T] \quad (3)$$

#### 3) Reserve constraint

In order to guarantee the secure operations of HWPGS, the reserve constraint of hydropower generators should be satisfied, and formulations are presented as follows.

$$\sum_{i=1}^{N_H} R_{H,i}^{U,t} = \sum_{i=1}^{N_H} P_{H,i}^t + \sum_{k=1}^{N_W} (P_{W,k}^t - P_{W,cut,k}^t) - \sum_{j=1}^{N_L} P_{L,j}^t - P_{ex}^{U,t}, \forall t \in [1, T] \quad (4)$$

$$\sum_{i=1}^{N_H} R_{H,i}^{D,t} = \sum_{i=1}^{N_H} P_{H,i}^t + \sum_{k=1}^{N_W} P_{W,k}^t - \sum_{j=1}^{N_L} (P_{L,j}^t - P_{L,shed,j}^t) - P_{ex}^{D,t}, \forall t \in [1, T] \quad (5)$$

where  $R_{H,i}^{U,t}$  and  $R_{H,i}^{D,t}$  are up and down reserves provided by the  $i$ th hydropower generator, respectively. In terms of the first equation (4), when wind power curtailment is considered while load curtailment is not allowed, the power outputs of hydro and wind are lower. By subtracting the upper bound power that the HWPGS supplies to the external power grid, we get the lower bound of the reserve. Similarly, when excluding the wind power curtailment while considering load curtailment, we get the upper bound of the reserve by subtracting the lower bound  $P_{ex}^{D,t}$ .

#### 4) Operational constraints of hydropower

As we know, the power output of a hydropower generator is related to its capacity, water inflow and water storage. Therefore, operational constraints of hydropower are formulated as follows.

$$P_{H,i}^t + R_{H,i}^{U,t} \leq I_{H,i}^t P_{Hmax,i}^t, \forall i \in [1, N_H], t \in [1, T] \quad (6)$$

$$I_{H,i}^t P_{H \min,i}^t \leq P_{H,i}^t - R_{H,i}^{U,t}, \forall i \in [1, N_H], t \in [1, T] \quad (7)$$

$$R_{H,i}^{U,t} \geq 0, \forall i \in [1, N_H], t \in [1, T] \quad (8)$$

$$R_{H,i}^{D,t} \geq 0, \forall i \in [1, N_H], t \in [1, T] \quad (9)$$

$$P_{H \max,i}^t = \min(f_{q2P,i}(q_{H,i}^t + q_{H,i}^{U,t}), P_{H \max,i}), \forall i \in [1, N_H], t \in [1, T] \quad (10)$$

$$P_{H \min,i}^t = \max(f_{q2P,i}(q_{H,i}^t + q_{H,i}^{D,t}), P_{H \max,i}), \forall i \in [1, N_H], t \in [1, T] \quad (11)$$

where  $I_{H,i}^t$  is the start-stop status/unit commitments of the  $i$ th hydropower generator in the  $t$ th time interval, where 1 and 0 indicates status of "ON" and "OFF", respectively.  $P_{H \max,i}^t$  and  $P_{H \min,i}^t$  are the maximum and minimum power outputs of the  $i$ th hydropower generator.  $f_{q2P,i}$  represents the water-electricity transform characteristic.  $q_{H,i}^t$  is the consumed water for the  $i$ th hydropower generator.  $q_{H,i}^{U,t}$  and  $q_{H,i}^{D,t}$  stand for the stored water that are needed for  $i$ th hydropower generator to function as up and down reserves, respectively.

As for hydropower generators with variable water head, the relationship between power output and water discharge is formulated as follows.

$$f_{q2P,i}(q_{H,i}^t) = a_{H,i}(q_{H,i}^t)^2 + b_{H,i}q_{H,i}^t + c_{H,i}, \forall i \in [1, N_H], t \in [1, T] \quad (12)$$

where  $a_{H,i}$ ,  $b_{H,i}$ ,  $c_{H,i}$  are the transform coefficients between water discharge and power output.

In terms of the ramp constraints, they are formulated as follows.

$$P_{H,i}^t - P_{H,i}^{t-1} \leq RU_{H,i} I_{H,i}^{t-1}, \forall i \in [1, N_H], t \in [1, T] \quad (13)$$

$$P_{H,i}^{t-1} - P_{H,i}^t \leq RD_{H,i} I_{H,i}^t, \forall i \in [1, N_H], t \in [1, T] \quad (14)$$

where  $RU_{H,i}$  and  $RD_{H,i}$  are the upper and lower ramps of the  $i$ th hydro generator, respectively.

In addition, the minimum on and off constraints of the hydro generator are presented as follows.

$$\sum_{i'=\max(0,t-DT_i+1)}^t z_{H,i}^{i'} \leq I_{H,i}^t, \forall i \in [1, N_H], t \in [1, T] \quad (15)$$

$$\sum_{i'=\max(0,t-UT_i+1)}^t y_{H,i}^{i'} \leq 1 - I_{H,i}^t, \forall i \in [1, N_H], t \in [1, T] \quad (16)$$

where  $DT_i$  and  $UT_i$  are the minimum off and on time for the  $i$ th hydropower generator.  $z_{H,i}^t$  and  $y_{H,i}^t$  are indicators of start-up and shut-down during the  $t$ th time interval.  $t'$  and  $t''$  stand for the time of start-up and shut-down of the hydro generator.

### 5) Water storage constraint

The water level of a reservoir is usually formulated as follows.

$$V_H^{t+1} = V_H^t - q_H^t + F_H^t, \forall t \in [1, T] \quad (17)$$

where  $V_H^t$  stands for the volume of water storage in a reservoir of hydropower plants at the end of time  $t$ , and  $q_H^t$  is the

consumed water for electricity generation. Moreover,  $F_H^t$  denotes the water inflow of the reservoir during the  $t$ th time interval.

In addition, the volume of water storage should be within a certain range, which is formulated as follows.

$$V_{\min} \leq V_H^t \leq V_{\max}, \forall t \in [1, T] \quad (18)$$

where  $V_{\min}$  and  $V_{\max}$  are the minimum and maximum volume of water storage in the reservoir, respectively.

Considering that the normal operation of hydropower stations should not be interrupted during the following scheduling time, the water level of the reservoir is required to be equal to the former place. In this way, the corresponding formulation is shown as follows.

$$V_H^0 = V_H^T \quad (19)$$

where  $V_H^0$  and  $V_H^T$  represent the initial and final volumes of water storage in a reservoir of hydropower plants, for the scheduling time cycle. The superscripts of "T" and "0" stand for the initial and final time with respect to the time cycle, respectively.

## III. INTERVAL ANALYSIS FOR THE COORDINATED SCHEDULING MODEL WITH UNCERTAIN WIND POWER, ELECTRICITY LOAD AND WATER INFLOW

### A. Description of uncertainties and analysis of lower and upper bounds

In terms of the day-ahead scheduling of the HWPGS, it is important to consider the following factors, such as the uncertain values of wind power, electricity load and water inflow. With the development of interval forecasting method [18], these uncertainties can be presented as interval numbers [18][24][25]. In this way, the uncertain wind power, electricity load and water inflow are formulated as interval variables for the day-ahead coordinated scheduling model for the HWPGS, shown as follows.

$$\overline{[P_{W,k}^t]} = [P_{W,k}^{t,D}, P_{W,k}^{t,U}], \forall k \in [1, N_W], t \in [1, T] \quad (20)$$

$$\overline{[P_{L,j}^t]} = [P_{L,j}^{t,D}, P_{L,j}^{t,U}], \forall j \in [1, N_L], t \in [1, T] \quad (21)$$

$$\overline{[F_i^t]} = [F_i^{t,D}, F_i^{t,U}], \forall i \in [1, N_H], t \in [1, T] \quad (22)$$

where  $\overline{[P_{W,k}^t]}$ ,  $\overline{[P_{L,j}^t]}$  and  $\overline{[F_i^t]}$  denote intervals for the wind power, electricity load and water inflow, respectively.

$P_{W,k}^{t,D}$ ,  $P_{W,k}^{t,U}$ ,  $P_{L,j}^{t,D}$ ,  $P_{L,j}^{t,U}$ ,  $F_i^{t,D}$  and  $F_i^{t,U}$  stand for their corresponding lower and upper values.

For investigating the effect of interval disturbances of wind power, load and water inflow on the scheduling objective of the HWPGS, we need to analyze an equation in the form of  $Ax = b$  where  $A \in \mathbf{R}_{n \times m}$ , and  $x$  is interval number. Then we aims to find the interval of  $b$ .

It is noted that Ref. [20] adopts a convex optimization method, and transforms equations of calculating upper and lower bounds of  $\mathbf{b}$  into the quadratic forms to solve this problem. However, the computation complexity is significant. Consequently, we introduce auxiliary duality logic variables to find uncertain upper and lower bounds of  $\mathbf{b}$ , taking the first element of  $\mathbf{b}$  for example:

$$[b_1^D, b_1^U] = \sum_{i=1}^m a_{1,i} [x_i^D, x_i^U] \quad (23)$$

where  $b_1^D$  and  $b_1^U$  stand for lower and upper bounds of  $b_1$ . What is more,  $x_i^D$  and  $x_i^U$  are the lower and upper bounds of  $x_i$ .

When auxiliary duality logic variables are introduced into (23), the following formulations are obtained:

$$b_1^D = \sum_{i=1}^m (a_{1,i} > 0) a_{1,i} x_i^D - \sum_{i=1}^m (a_{1,i} \leq 0) a_{1,i} x_i^U \quad (24)$$

$$b_1^U = \sum_{i=1}^m (a_{1,i} > 0) a_{1,i} x_i^U - \sum_{i=1}^m (a_{1,i} \leq 0) a_{1,i} x_i^D \quad (25)$$

Therefore, Eqs. (23)-(24) transforms the problem into a linear programming one, which has the advantage of less computation complexity.

#### B. Influence of uncertain wind power and load on power flow

As the wind power and electricity load are formulated as interval variables, the power exchange between the HWPGS and the external power grid is also an interval variable, shown as follows.

$$\mathbf{P}_{ex}^t \in [\overline{\mathbf{P}_{ex}^t}] = [\mathbf{P}_{ex}^{D,t}, \mathbf{P}_{ex}^{U,t}], \forall t \in [1, T] \quad (26)$$

Therefore, the expectation of  $\mathbf{P}_{ex}^t$  is formulated in the following equation.

$$\overline{\mathbf{P}_{ex}^t} = \frac{\mathbf{P}_{ex}^{D,t} + \mathbf{P}_{ex}^{U,t}}{2}, \forall t \in [1, T] \quad (27)$$

Combined with (4) and (5), the reserve of each hydropower unit can be obtained. In this way, power outs of hydropower generators are presented as follows.

$$[\overline{\mathbf{P}_H^t}] = [\mathbf{P}_H^t - \mathbf{R}_H^{D,t}, \mathbf{P}_H^t + \mathbf{R}_H^{U,t}], \forall t \in [1, T] \quad (28)$$

According to (2), the constraint of power flow concerning interval uncertainty of injections is shown as follows.

$$\begin{aligned} \mathbf{A}(\mathbf{C}_h[\overline{\mathbf{P}_H^t}] + \mathbf{C}_w[\overline{\mathbf{P}_W^t}] - [\overline{\mathbf{P}_L^t}] - \mathbf{C}_{ex}[\overline{\mathbf{P}_{ex}^t}]) \\ \subset [\mathbf{P}_{L,\min}, \mathbf{P}_{L,\max}], \forall t \in [1, T] \end{aligned} \quad (29)$$

In addition, (29) can be transformed to be the following formulations:

$$\begin{aligned} \sup(\mathbf{A}([\overline{\mathbf{P}_L^t}] - \mathbf{C}_w[\overline{\mathbf{P}_W^t}] + \mathbf{C}_{ex}[\overline{\mathbf{P}_{ex}^t}]) \\ + \mathbf{P}_{L,\min}) \leq \inf(\mathbf{A}(\mathbf{C}_h[\overline{\mathbf{P}_H^t}])), \forall t \in [1, T] \end{aligned} \quad (30)$$

$$\begin{aligned} \inf(\mathbf{A}([\overline{\mathbf{P}_L^t}] - \mathbf{C}_w[\overline{\mathbf{P}_W^t}] + \mathbf{C}_{ex}[\overline{\mathbf{P}_{ex}^t}]) \\ + \mathbf{P}_{L,\max}) \geq \sup(\mathbf{A}(\mathbf{C}_h[\overline{\mathbf{P}_H^t}])), \forall t \in [1, T] \end{aligned} \quad (31)$$

where "inf" and "sup" indicate upper and lower bounds of an interval variable, respectively. Besides, since coefficient matrixes  $\mathbf{A}$ ,  $\mathbf{C}_h$ ,  $\mathbf{C}_w$ ,  $\mathbf{C}_{ex}$  are all real-values, upper and lower bounds can be obtained by solving linear programming problem which is introduced in the previous subsection. Taking the first item of (30) for instance:

$$\begin{aligned} \sup(\mathbf{A}([\overline{\mathbf{P}_L^t}] - \mathbf{C}_w[\overline{\mathbf{P}_W^t}] + \mathbf{C}_{ex}[\overline{\mathbf{P}_{ex}^t}]) = \sup(\mathbf{A}[\overline{\mathbf{P}_L^t}]) \\ + \inf(\mathbf{A}\mathbf{C}_w[\overline{\mathbf{P}_W^t}]) + \sup(\mathbf{A}\mathbf{C}_{ex}[\overline{\mathbf{P}_{ex}^t}]), \forall t \in [1, T] \end{aligned} \quad (32)$$

Note that constraints (30) and (31) may not be satisfied, and the curtailments of wind power and electricity load should be conducted. Therefore, power outputs of wind farms and the load are expressed as follows.

$$[\overline{\mathbf{P}_{W,k}^t}] = [\mathbf{P}_{W,k}^{t,D}, \mathbf{P}_{W,k}^{t,U}] - [\mathbf{P}_{W,cut,k}^{t,D}, \mathbf{P}_{W,cut,k}^{t,U}], \forall k \in [1, N_W], t \in [1, T] \quad (33)$$

$$[\overline{\mathbf{P}_{L,j}^t}] = [\mathbf{P}_{L,j}^{t,D}, \mathbf{P}_{L,j}^{t,U}] - [\mathbf{P}_{L,shed,j}^{t,D}, \mathbf{P}_{L,shed,j}^{t,U}], \forall j \in [1, N_L], t \in [1, T] \quad (34)$$

where  $\mathbf{P}_{W,cut,k}^{t,D}$  and  $\mathbf{P}_{W,cut,k}^{t,U}$  stand for lower and upper bounds of curtailed wind power of the  $k$ th wind farm, during the  $t$ th time interval.  $\mathbf{P}_{L,shed,j}^{t,D}$  and  $\mathbf{P}_{L,shed,j}^{t,U}$  represent lower and upper bounds for the  $j$ th curtailed electricity load, respectively.

#### C. Influence of uncertain wind power and load on reserve of hydropower

Based on (3), the power provided by the HWPGS for the external power grid can be formulated in (35), while taking interval disturbances of wind power and load into account.

$$[\overline{\mathbf{P}_{ex}^t}] \subset [\overline{\mathbf{P}_H^t}] + [\overline{\mathbf{P}_W^t}] - [\overline{\mathbf{P}_{W,cut}^t}] - [\overline{\mathbf{P}_L^t}] + [\overline{\mathbf{P}_{L,shed}^t}], \forall t \in [1, T] \quad (35)$$

In addition, the maximum and minimum vales of  $\mathbf{P}_{ex}^t$  can be obtained based on (28) and (35), which are shown as follows.

$$\mathbf{P}_{ex}^{t,U} = \sum_{i=1}^{N_H} (\mathbf{R}_{Hi}^{t,U} + \mathbf{P}_{Hi}^t) + \sum_{k=1}^{N_W} (\mathbf{P}_{W,k}^{t,U} - \mathbf{P}_{W,cut,k}^{t,D}) - \sum_{j=1}^{N_L} (\mathbf{P}_{L,j}^{t,D} - \mathbf{P}_{L,shed,j}^{t,U}), \forall t \in [1, T] \quad (36)$$

$$\mathbf{P}_{ex}^{t,D} = \sum_{i=1}^{N_H} (\mathbf{P}_{Hi}^t - \mathbf{R}_{Hi}^{t,D}) + \sum_{k=1}^{N_W} (\mathbf{P}_{W,k}^{t,D} - \mathbf{P}_{W,cut,k}^{t,U}) - \sum_{j=1}^{N_L} (\mathbf{P}_{L,j}^{t,U} - \mathbf{P}_{L,shed,j}^{t,D}), \forall t \in [1, T] \quad (37)$$

#### D. Influence of uncertainty of water inflow on hydropower

From (17), we can obtain the following formulations in terms of hydropower considering interval disturbances of water inflow:

$$\overline{[V_{H,i}^{t+1} - V_{H,i}^t]} \subset \overline{[F_{H,i}^t]} - \overline{[q_{H,i}^t]}, \forall t \in [1, T] \quad (38)$$

$$\overline{[V_{H,i}^t]} \subset [V_{H,i}^{\min}, V_{H,i}^{\max}], \forall t \in [1, T] \quad (39)$$

$$\overline{[q_{H,i}^t]} = [q_{H,i}^t - q_{H,i}^{t,D}, q_{H,i}^t + q_{H,i}^{t,U}], \forall t \in [1, T] \quad (40)$$

where  $V_{H,i}^{\min}$  and  $V_{H,i}^{\max}$  represent the minimum and maximum amounts of reserved water in the reservoirs.  $\overline{[q_{H,i}^t]}$  is the interval of consumed water, which are needed for hydropower units to generate electricity in the  $t$ th time interval.  $q_{H,i}^{t,D}$  and  $q_{H,i}^{t,U}$  stand for the reserved water required for providing down and up reserves for hydropower units, respectively.

In this way, (38)-(40) can be transformed into deterministic constraints as follows.

$$V_{H,i}^t - (q_{H,i}^t - q_{H,i}^{t,D}) + F_{H,i}^{t,U} \leq V_{H,i}^{\max}, \forall t \in [1, T] \quad (41)$$

$$V_{H,i}^t - (q_{H,i}^t + q_{H,i}^{t,U}) + F_{H,i}^{t,D} \geq V_{H,i}^{\min}, \forall t \in [1, T] \quad (42)$$

According to the analysis shown above, it is observed that the objective function of the proposed day-ahead coordinated scheduling model of HWPGS is (1). Decision variables consist of power outputs, reserves, and unit commitments of hydropower plants, and the operational constraints are (6)-(19) and (26)-(42). The above descriptions of the scheduling model are also shown in Table I.

Table I Objective function, decision variables and constraints of the proposed model

Objective function	(1)
Decision variables	$P_{H,i}^t, R_{H,i}^{U,t}, R_{H,i}^{D,t}, I_{H,i}^t$
Constraints	(6)-(19), (26)-(42)

#### IV. CASE STUDY

##### A. Description of the test system

In this part, we use a real test system in the region of Western China. The configuration of the HWPGS is shown in Fig. 1, which comprises 5 wind farms and 4 hydropower stations. The total generation capacity of 5 wind farms is up to 829.5 MW, and they are connected to 220 kV and 110 kV buses. What is more, the total capacity of the 4 hydropower plants is 394 MW. Fig. 2 presents the interval forecasting information of wind power in the HWPGS. In addition, we assume that the actual values of inflow water and electricity load fluctuates within 5% and 3% around predictive values, in which the inflow water for the 4 hydropower stations are 120, 20, 40 and 30 m<sup>3</sup>/h, and electricity load data are listed in Table II.

In order to study the effect of different prices on the day-ahead coordinated scheduling of the HWPGS, two tariff mechanisms are designed and used for simulation studies. In

the first one,  $c_{ex,c}$  and  $c_{ex,p}$  are set to be 1 \$/MWh and 10 \$/MWh, respectively.  $c_l$ ,  $c_w$  and  $c_h$  are 10000 \$/MWh, 100 \$/MWh and 100 \$/Hm<sup>3</sup>, respectively. In the second mechanism,  $c_{ex,c}$  is set as 0.5 \$/MWh during 0:00 a.m.~8:00 a.m. and 17:00 p.m.~23:00 p.m., and 1.5 \$/MWh during other time intervals. Based on the interval analysis, the proposed scheduling model is established as a deterministic mixed-integer linear programming problem, which can be solved by the classic mixed-integer linear programming method [26-29]. Consequently, the day-ahead coordinated scheduling model of HWPGS is solved via the toolbox of YALMIP in our work [30].

Table II Date of electricity load for the studied HWPGS in the 24 hours

T (h)	1	2	3	4	5	6
$P_L$ (MW)	92.4	87.4	84.8	83.8	85.3	92.1
T (h)	7	8	9	10	11	12
$P_L$ (MW)	103.4	116.4	128.1	135.3	138.3	134.6
T (h)	13	14	15	16	17	18
$P_L$ (MW)	129.2	128.1	128.5	130.2	132.7	135.3
T (h)	19	20	21	22	23	24
$P_L$ (MW)	141.4	145.9	142.9	133.4	117.7	102.2

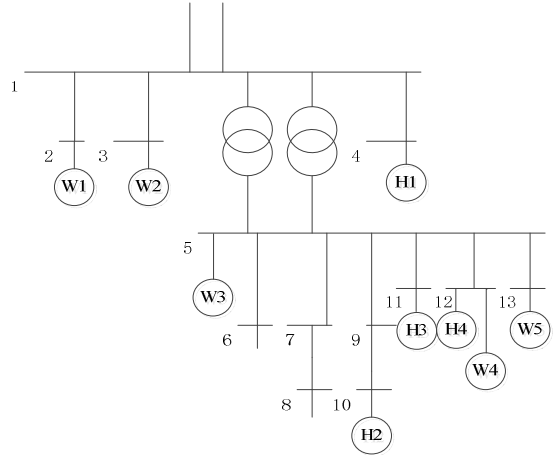


Fig. 1 The configure of the studied HWPGS

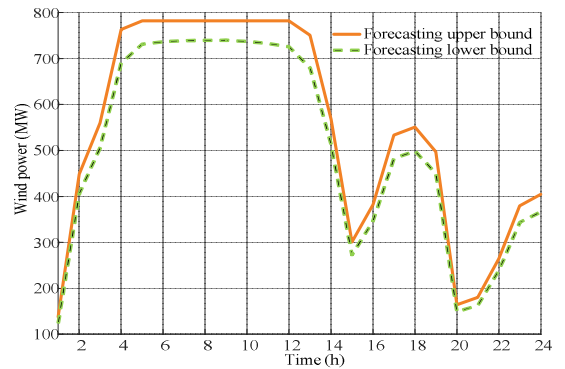


Fig. 2 Day-ahead wind power forecasting interval

## B. Results analysis

### 1) Effectiveness of interval analysis

In terms of the first tariff mechanism, we can obtain the interval power exchange between HWPGS and the external power grid, and the corresponding economic benefit of HWPGS is \$19557.86. What is more, Fig. 3 shows the upper bound, the expectation, and the lower bound of power exchange in each time interval, respectively. We also use the stochastic optimization approach to conduct a comparison to verify the effectiveness of the interval analysis. Specifically, the Monte Carlo (MC) simulation is used to obtain 10000 samples of wind power, electricity load, and water inflow using the forecasting values and corresponding errors, which are then used to compute samples of the power exchange. These samples are obtained as shown in Fig. 3.

It is easily seen that the expected value of these samples is almost the same with that obtained by the interval analysis approach. Moreover, the power exchange samples obtained by MC simulation are well bounded by the lower and upper values of those derived by interval analysis. It means that the interval analysis can well consider the uncertainties for the day-ahead coordinated scheduling of HWPGS. Furthermore, we can easily observe that the computation complexity of interval analysis is much smaller than that of MC simulation, as the lower and upper bounds can be easily obtained by solving the mixed-integer linear programming problem in this paper, which greatly helps lessen the computation complexity.

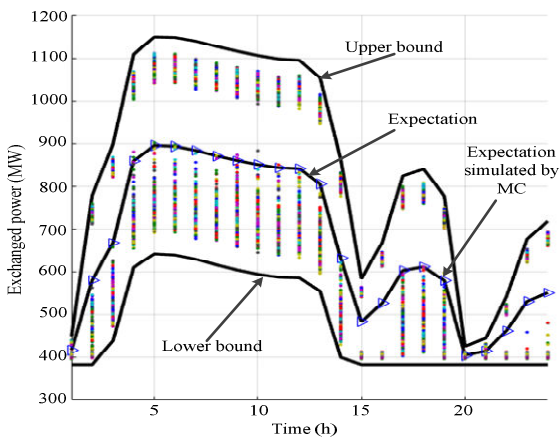


Fig. 3 The results obtained by interval analysis and MC simulation

To further verify the outperformance of interval analysis over the robust optimization approach, we obtain the economic benefit of HWPGS corresponding to the robust optimization approach, i.e., \$18692.40. Due to the limited space of this paper, and the popularity of the robust optimization, the detailed procedure is not included and can be referred to Ref. [19]. We can see that the economic benefit of HWPGS obtained by the interval analysis is \$19557.86, larger than \$18692.40 derived via robust optimization. The main reason is that robust optimization is usually considered to be

too conservative as it always tries to find the worst-case scenario solution which happens with a very low probability [19]. On the contrary, the interval analysis aims to minimize the interval of scheduling objective function rather than using the worst case scenario. Consequently, the interval analysis is less conservative than robust optimization, and it obtains more economic benefit for the HWPGS.

In this way, we conclude that the scheduling performance of interval analysis is comparable to the stochastic optimization for the day-ahead coordinated operations of HWPGS, considering uncertain wind power, electricity load and water inflow. The main advantages of the interval analysis is that its lower computational complexity and less solution conservativeness, compared with the stochastic optimization and robust optimization, respectively.

### 2) Influence of electricity price

Fig. 4 shows the upper bound, the lower bounds, and the expectation of power exchange between HWPGS and the external power grid under the two different tariff, respectively. It is observed that upper bounds in the two cases are the same, while the lower bounds and expectations are different. In addition, it is noted that summations of the expectation of power exchange for the two tariffs are the same, i.e., 12420.50 MWh.

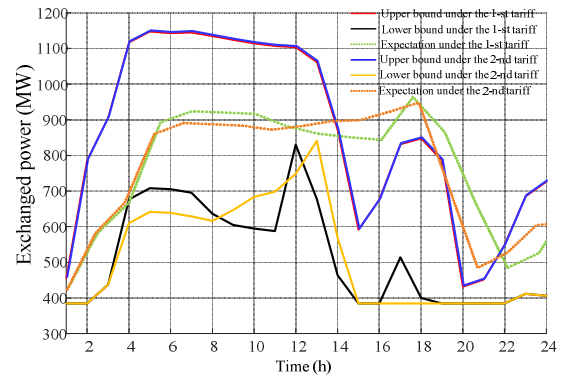


Fig. 4 Power exchange between HWPGS and the external power grid under different tariffs

Therefore, the expected values of power exchange regarding the second tariff are more than those of the first tariff in some time intervals, while less for other time intervals. In addition, the economic benefit of HWPGS is \$18313.42 for the second tariff, which is smaller than \$19557.86 that corresponds to the first tariff. In this way, it has been verified that the scheduling of HWPGS is affected by the tariff mechanism.

### 3) The influence of wind power forecasting error

As for the second pricing mechanism, we set the forecasting error of wind power within the range of [5%, 15%], with the step size of 0.5%. In this way, we can investigate values of the power exchange between the HWPGS and external power grid, regarding different wind power forecasting errors. Fig. 5 shows the upper and lower bounds of the power exchange,

respectively. We observe that the upper bound of power exchange increases while lower bounds become smaller, with the rise in the forecasting error of wind power. This means the whole range of the power exchange expands if the forecasting error of wind power rises up.

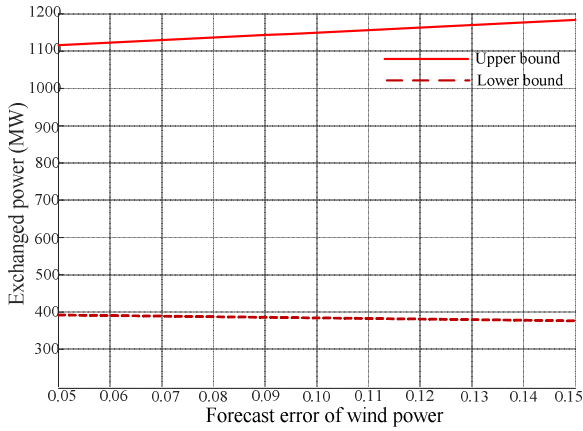


Fig. 5 Impacts of forecast error of wind power on the power exchange

Furthermore, it can be easily observed from Fig. 6 that the economic benefit of HWPGS decreases linearly with the increase in the wind power forecast error, which changes from \$ 18507.24 to \$ 18100.11, and the reduction rate is about 2.20%. This verifies that the HWPGS can benefit more if the forecasting error of wind power is smaller. In this way, we can obtain more economic benefits of HWPGS if the forecasting accuracy of wind power is improved. In addition, decision variables of 4 hydropower stations under different forecasting errors, from 5% to 15% with a 1% step change, are presented in Fig. 7.

From the simulation results in the Part B of Section IV, it is found that the interval analysis is effective for dealing with uncertainties of wind power, electricity load and water inflow for the day-ahead coordinated scheduling of HWPGS. What is more, the power exchange between HWPGS and external grid is affected by the pricing mechanism and the wind power forecasting errors.

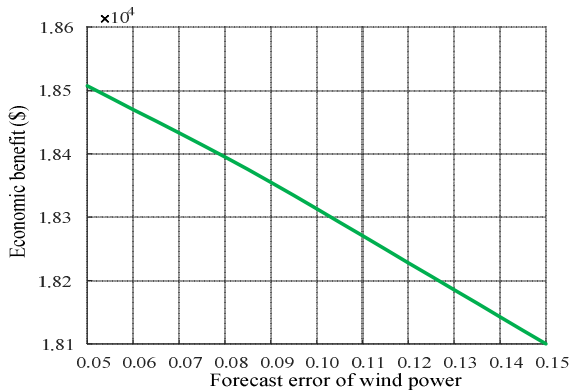


Fig. 6 Impacts of forecast error of wind power on the economic benefit

Furthermore, it is worth explaining the effectiveness of coordinated scheduling of the HWPGS. As we use a real test system in the region of Western China in the case study, which consists of 5 wind farms and 4 hydropower stations. The wind farms and hydropower stations are coupled in the test system, as shown in Fig. 1. Therefore, if the hydro and wind power are not operated coordinately, the wind farms or hydropower stations will be cut off. In this way, the power supplied for the external power grid by the HWPGS will be decreased, which leads to the reduction of economic benefits. On the other hand, it is seen from our study that hydro power can provide reserves to deal with uncertainties of wind power. In other words, we should buy reserves from the third entity if hydro and wind power are not operated coordinately. In this case, the economic benefit of the HWPGS will be also decreased. Consequently, we conclude that the coordinated scheduling of the HWPGS contributes to more economic benefit, compared with their separated operations.

## V. CONCLUSION

In this paper, we have proposed a day-ahead coordinated scheduling model for hydropower and wind power generation system (HWPGS), with consideration of uncertain wind power, electricity load and water inflow. First, we have established formulations of the scheduling model with the two-part price and power flow constraints. Afterwards, we use the interval analysis to investigate the effect of uncertainties on the model. Finally, a real test system in a western area of China is adopted to verify effectiveness of the proposed scheduling model. According to the study, we have found that the interval analysis can well consider uncertainties of wind power, electricity load and water inflow for the day-ahead coordinated scheduling of HWPGS. In addition, we also observe that different pricing mechanisms affect power exchange between HWPGS and the external grid. Therefore, an appropriate pricing mechanism should be made for the HWPGS. In the future work, the interval analysis could be used to study control of energy storage [31-32], state estimation of networked systems [33], optimal power flow [34], frequency control [35], hydropower reservoirs scheduling [36-37], multiple energy systems [38], etc.

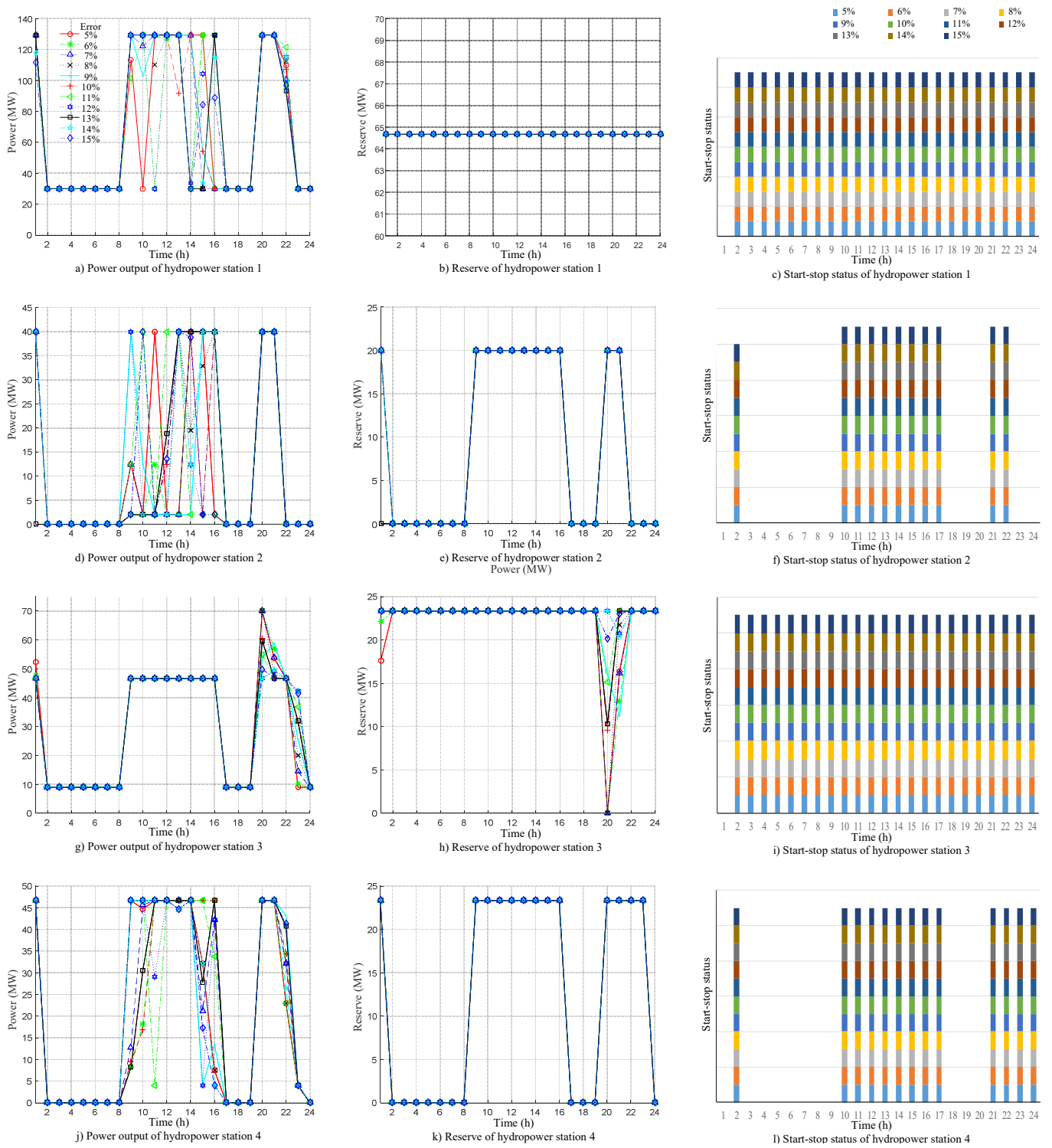


Fig. 7 Decision variables of 4 hydropower stations under different forecasting errors of wind power

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**Yuanzheng Li** (M'18) received the M.S. degree from Huazhong University of Science and Technology, Wuhan, China, in 2011, and the Ph.D. degree in electrical engineering from South China University of Technology, Guangzhou, China, in 2015. His current research interests include optimal power system dispatch and decision making.

**Tianyang Zhao** received the B.Sc. and M.Sc. degree in automation of electric power systems from North China Electric Power University, Beijing China in 2011 and 2013. Currently, he is a Reserch Fellow in Nanyang Technological Univeristy, Singapore.

**Chang Liu** received the B.Sc. degree from Huazhong University of Science and Technology in electrical engineering, Wuhan, China, in 2016. He is currently with State Grid Changzhou Power Supply Company, Changzhou.

**Yong Zhao** received the Ph.D. degree from Huazhong University of Science and Technology in automation and system engineering in 1996. He is currently a Professor in the same university.

**Zhiyuan Yu** is currently an undergraduate student at School of Electrical and Electronics Engineering of Huazhong University of Science and Technology.

**Kaicheng Li** received the Ph.D. degree in electrical engineering from the Huazhong University of Science and Technology, Wuhan, China, in 1998. He is currently a Professor in the same university.

**Lei Wu** (SM'13) received the B.S. degree in electrical engineering and the M.S. degree in systems engineering from Xian Jiaotong University, Xian, China, in 2001 and 2004, respectively, and the Ph.D. degree in electrical engineering from the Illinois Institute of Technology, Chicago, IL, USA, in 2008. He was a Professor with the Electrical and Computer Engineering Department, Clarkson University, Potsdam, NY, USA till 2018. Currently, he is an Associate Professor with the Electrical and Computer Engineering Department, Stevens Institute of Technology, Hoboken, NJ, USA. His research interests include power systems operation and planning, energy economics, and community resilience microgrid.