Robust optimal dispatch of integrated energy system considering with coupled wind and hydrogen system

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Abstract—Hydrogen production from renewable energy will become one of the important features of the integrated energy system in the future. By considering the coupled wind and hydrogen system, it can not only take the advantages of fast power regulation of hydrogen energy, but improve the economy of wind and hydrogen system. In view of the high volatility of the wind power, this paper proposes a robust optimal scheduling model for integrated energy system considering with coupled wind and hydrogen system. Firstly, it establishes a comprehensive energy system model with wind and hydrogen system, forming an efficient electric-gas-electric energy closed-loop flow model with fuel cells. Then, based on improved multi-interval uncertainty sets, the model of wind turbines, electrical load and hydrogen load are described respectively, which can reduce the conservatism compared with the traditional robust optimization. And the two-stage robust optimal scheduling model is established and it can be solved by adopting Column and Constraint Generation method (C&CG). Finally, an example is given to verify the advantages of the proposed method.

1. INTRODUCTION

Low-carbon energy system has drawn considerable attention to address the challenges caused by climate change. And developing renewable energy generation and reducing traditional fossil energy are identified as vital measures to achieve the goal [1][2]. Wind power, one of the absolute main energy of the renewable energy installation, has formed a completely industrial chain and supply chain in China [3]. By the end of 2020, the wind power capacity in China has reached 280 million kilowatts. However, the large-scale wind power integration will pose a great challenge to the grid, caused by its high volatility and seasonal variation of power generation [4]. Hydrogen energy is generally acknowledged as clean energy with high energy density, which is considered to be one of the most promising energy in the 21st century [5]. The coupled wind and hydrogen system can regulate the power rapidly and make full use of the abandoned wind power to improve the economic efficiency of wind power [6].

Research institutes at home and abroad have carried out extensive research for the combination of wind power and hydrogen energy. In [7], it makes water-electrolytic hydrogen making equipment as a flexible and controllable load to use the wasted wind power during the peak of the energy system efficiently. A coordinated optimization model of the thermal-electric-hydrogen system is presented in [8], which contains the fuel cell power generation system to improves the efficiency of the wind power. The wind power hydrogen-energy coupling system is proved that it can shorten the investment...
payback period from the perspective of life-cycle cost evaluation [9]. It further combined the wind-hydrogen energy storage system with ultracapacitors and make the simulation of the model in [10]. However, the above studies mainly focus on the economy of the wind power and hydrogen system. The above studies consider the impact of the uncertainty of wind power and load, which will lead to the infeasibility of system optimization results and damage the whole system severely.

Several studies are conducted in research work on the methods with the uncertainty of wind power, which mainly includes random optimization [11] and robust optimization [12]. Compared to the random optimization, the robust optimization can meet all the constraints and achieve the optimal solution with the greatest toughness. Besides it does not require accurate probability distribution function for the uncertain set. In [13], the study presents a typical structure of two-stage robust optimization model, and provides the solution of the system operation strategy under the worst scenarios. However, the probability of extreme scenarios is extremely small, which make the solution the solution relatively conservative when pursue to operate stably under the extreme scenarios. A flexible optimization model is proposed to improve the economy and robustness of the energy system by considering the uncertainty of wind power [14]. The actual output of wind power is the sum of the predicted power and prediction error. However, robust optimization often too conservative to ignore the actual probability distribution function. In [15], it adopts an uncertain set about moment uncertainty that it can obtain statistical information from the samples of random data, match the actual output of renewable energy and establish a data-driven optimization model to reduce the conservativeness of traditional robust optimization and random data and obtain more accurate scheduling results. In [16], it combines kernel density estimation and autoregressive moving average model to establish the probability distribution model of wind power, which is used to solve the cooperative optimization problem of long-term operation and short-term dispatching of units.

Based on the aforementioned discussions, this paper proposes a new robust optimization model of integrated energy system with coupled wind power and hydrogen. It takes electric energy and hydrogen energy as the main input energy and models the hydrogen electric energy conversion equipment. Then, it constructs the robust optimization model of the integrated energy system based on multi-interval uncertain sets of the wind power. Finally, the model is solved by the column-and-constraints Generation (C&CG) algorithm [17].

2. THE OPTIMIZATION MODEL WITH WIND-COUPLED AND HYDROGRN SYSTEM

Coupled wind and hydrogen system can be divided into three parts, which include electrolytic-hydrogen unit, fuel cell unit and hydrogen storage unit. Electrolytic-hydrogen unit is an electrolytic water process that produces hydrogen and oxygen without any contamination of other production. When the power is charged too much, the electrical energy can flow into the hydrogen-making equipment to produce hydrogen and store it in hydrogen storage equipment such as hydrogen storage tanks or directly supply hydrogen loads such as fuel cells. When the system is short of charge, the fuel cell is activated for discharge and the chemical energy stored by hydrogen is converted into electrical energy to into the power grid.

The integrated energy system is mainly composed of wind power, Coupled wind and hydrogen system, fuel cell, hydrogen storage tank and battery. The scheduling of the system is globally optimized, and all the equipment in the system is controllable, and the minimum operating cost of the system is realized by adjusting the contribution of each equipment in the system and the load response from the outside world.

2.1. Objective Function

The optimization model is formulated as a linear model that identifies the least cost of the system to meet the power balance and the restriction on system operation.

\[
C = C_e + C_{spe} + C_{su} + C_{car}
\]

\[
0 \leq q_{sell}^t \leq Q_{sell}^{max}, \quad 0 \leq q_{buy}^t \leq Q_{buy}^{max} \quad \forall t \in N_t
\]
Where $C$ reflects the whole operation cost of the system. $C_e$ is the interaction cost between the main grid and the system and $C_{sur}$ is the start-stop cost of the electrolytic-hydrogen unit. $C_{ope}$ is the operating cost and $C_{cur}$ is the punishment penalty of wind abandonment.

1) The interacting cost between the main grid and the system contains the expense of buying and selling electricity from the main grid.

$$ C_e = \sum_{i \in N} \left( p_{buy}^i q_{buy}^i - p_{sell}^i q_{sell}^i \right) $$

In (3), $p_{buy}^i$, $p_{sell}^i$ represent the price of electricity purchased and sold by the main grid respectively. And $q_{buy}^i$, $q_{sell}^i$ represents the power bought and sold by the main grid. $Q_{buy}^{max}$, $Q_{sell}^{max}$ are the maximum power for buying and selling electricity.

2) It needs extra expense when the equipment is operating and starting up.

$$ C_{ope} = C_{ope}(t) $$

$$ C_{SU} = C_{SU}(\delta(t) - \delta(t - 1)) $$

$C_{ope}$, $C_{SU}$ are the operating cost and start-up cost of hydrogen-making equipment, respectively. $C_{ope}$, $C_{SU}$ represent the actual operating cost and start-stop cost of the equipment at the time $t$. $\delta(t)$ is the binary variable and reflects the operation status of equipment at the time $t$.

3) It needs extra cost when the wind power is abandoned for the power balance.

$$ C_{cur} = \sum_{i \in N} C_{cur}^i P_{cur,i} $$

In (6), $P_{cur,i}$ is the abandoned power at the time $t$ and $C_{cur}$ is the punishment factor.

### 2.2. Operational Constraints of the Integrated Energy System

1) The model of electrolytic-hydrogen equipment is established as a linearized model to reduce the calculation time without significant loss of model accuracy within the normal operating range [18].

$$ F_{t}^{pH} = \Gamma_{t}^{pH} \cdot \eta_{t}^{pH} \cdot P_{t}^{pH} $$

$$ F_{t}^{min} \leq F_{t}^{pH} \leq F_{t}^{max} \quad t \in N_t $$

In (7) and (8), $F_{t}^{pH}$, $F_{t}^{min}$ are the flow of the hydrogen produced and the electricity power consumed by the equipment at the time $t$. $\eta_{t}^{pH}$, $\Gamma_{t}^{pH}$ are the efficiency of the equipment and the conversion efficiency of the process making-hydrogen, respectively. $F_{t}^{max}$, $F_{t}^{min}$ are the max and min hydrogen flow. $N_t$ is the number of hydrogen-making equipment.

2) Considering the safety of the tank, the capacity of the tank must be limited to a certain extent.

$$ \text{SOC}_{h,t} = \text{SOC}_{h,(t-1)} + \left( F_{h,t}^{hr,dis} - F_{h,t}^{hr,ch} - \gamma_{h,t}^{dp} \cdot \text{SOC}_{h,t} \right) \times \Delta t $$

$$ 0 \leq F_{h,t}^{hr,dis} \leq F_{h,t}^{max,dis}, \quad 0 \leq F_{h,t}^{hr,ch} \leq F_{h,t}^{max,ch} $$

$$ \text{SOC}_{h,t}^{min} \leq \text{SOC}_{h,t} \leq \text{SOC}_{h,t}^{max}, \quad t \in N_t, \quad h \in N_h $$

The equation (9) reflects the variation of the hydrogen storage capacity between the time $t-1$ and the time $t$. $\text{SOC}_{h,t}$, $\text{SOC}_{h,(t-1)}$ represent the storage capacity of hydrogen in the tank at the time $t$ and at the time $t-1$. $F_{h,t}^{hr,dis}$, $F_{h,t}^{hr,ch}$ represent the rate of hydrogen charge and hydrogen discharge; $\gamma_{h,t}^{dp}$ is the rate of hydrogen dissipation; $F_{h,t}^{max,ch}$, $F_{h,t}^{max,dis}$ represents the maximum and minimum charge rate of hydrogen, $\text{SOC}_{h,t}^{max}$, $\text{SOC}_{h,t}^{min}$ represents the maximum and minimum storage of hydrogen and $N_h$ is the number of tanks.

3) The fuel cell can produce electricity by consuming hydrogen, which is the critical equipment of the system [19].

$$ F_{t}^{pH} = \Gamma_{t}^{pH} \cdot \eta_{t}^{pH} \cdot P_{t}^{pH} $$

$$ F_{t}^{min} \leq F_{t}^{pH} \leq F_{t}^{max} \quad t \in N_t $$
The equation (12) presents the conversion function and physical restrictions of the fuel cell. $F_{ptH}$, $P_{ptH}$ are the consumed hydrogen and the generated electricity. $P^{fuel,\text{max}}$, $P^{fuel,\text{min}}$ are the max and min flow of hydrogen and $\eta^{fuel}$ is the efficiency of the hydrogen production.

4) In order to extend the life of the battery, over-charging and over-discharging is not allowed.

$$SOC_{i,t} = SOC_{i,t-1} + \eta_{i}^{ES,ch} P_{i,t}^{ES,ch} - \eta_{i}^{ES,dis} P_{i,t}^{ES,dis}$$

(14)

$$0 \leq P_{i,t}^{ES,dis} \leq P_{i,max}^{ES,dis}, 0 \leq P_{i,t}^{ES,ch} \leq P_{i,max}^{ES,ch}$$

(15)

$$SOC_{i,min} \leq SOC_{i,t} \leq SOC_{i,max}$$

(16)

In (14), $SOC_{i,t}$, $SOC_{i,t-1}$ represents the battery's storage during the t-period; $P_{i,t}^{ES,ch}$, $P_{i,t}^{ES,dis}$ represents the charge and discharge rate of the battery; $P_{i,max}^{ES,ch}$, $P_{i,max}^{ES,dis}$ represents the maximum charge and discharge rate of the battery; $\eta_{i}^{ES,ch}$, $\eta_{i}^{ES,dis}$ represents the charge and discharge efficiency of the battery.

and $SOC_{i,max}$, $SOC_{i,min}$ represents the maximum and minimum storage of the battery, respectively.

5) Power balance and hydrogen flow balance

$$P_{buy}^{t} = P_{sell}^{t} + \sum_{i=1}^{n_{x}} g_{i}^{t} - \sum_{i=1}^{n_{y}} P_{i,t}^{ES,\text{ch}} + \sum_{i=1}^{n_{y}} P_{i,t}^{ES,\text{dis}}$$

(17)

$$- \sum_{i=1}^{n_{x}} P_{i,t}^{PH} + \sum_{i=1}^{n_{x}} P_{i,t}^{fuel} - \sum_{i=1}^{n_{x}} x_{i}^{t} = 0$$

$$\sum_{i=1}^{n_{x}} P_{i,t}^{H,\text{ch}} + \sum_{i=1}^{n_{x}} P_{i,t}^{H,\text{dis}} - \sum_{i=1}^{n_{x}} F_{i,t}^{PH} - \sum_{i=1}^{n_{x}} F_{i,t}^{fuel} = 0$$

(18)

Where (17) represents the system's dynamic power balance and (18) presents the system's hydrogen flow balance.

3. ROBUST OPTIMIZE THE SCHEDULING MODEL AND SOLVITATION

3.1. Classic Robust Optimization Scheduling

The basic requirement of a classic robust optimization model is the toughness that the system is able to combat interruptions under the most extreme scenarios [19]. The model can be described as (19).

$$\min_{x} \left[ c^{t} x + \max_{w \in \Delta} \min_{x \in \mathcal{X}(x, w)} b^{t} \Delta x \right]$$

(19)

$$\begin{cases}
  Dx = d \\
  Gx = 0 \\
  D(x + \Delta x).d \\
  G(x + \Delta x) = 0
\end{cases}$$

In (11), $c^{t}$, $b^{t}$ are cost factor vectors associated with $x$, $\Delta x$, respectively; $d$ is the constant column vector; $x$ is the decision variable, which is the system power under the deterministic constraint, $D$, $G$ is the coefficient matrix to meet the constraint of the variable.

The uncertain set of the robust model is normally described as a predictive deviation model of the power generation.

$$w^{x} = w^{x}_{s} + w^{x}_{s} e^{x}_{s} - w^{x}_{s} e^{x}_{s}, 0 \leq e^{x}_{s}, e^{x}_{s} \leq 1$$

(20)

$w^{x}_{s}, w^{x}_{s}$ for the actual power generation load, forecast force, $w^{x}_{s}, w^{x}_{s}$ is the maximum up-and-down deviation of the actual power generation load, $e^{x}_{s}$, $e^{x}_{s}$. The control factor for predicting the deviation for the power generation load makes $w^{x}_{s}$ in the intervals $[w^{x}_{s}, w^{x}_{s}, w^{x}_{s}, w^{x}_{s}]$. 


3.2. The improved robust optimization scheduling model

The classical robust optimization model has a extremely robustness, but it often ignores the probability information of the data itself, which makes the results too conservative. As shown in the Fig.1, the classic robust optimization often produces a strategy that makes the strategic result on the boundary. However, the probability that the result occurs is tiny in practice, which often results in a greater loss on the economics of the power system.

Therefore, this paper proposes an improved robust optimization model with the multi-interval uncertainty set based on the actual probability of power generation to analyze the characteristics of the data. As shown in the Fig.2, the basics of the model is that the system power generation output basically falls in the place where the prediction deviation is small and only a small part falls at the larger deviation according to the probability of the actual power, so as to improve the practicality of the scheduling strategy.

Based on the above analysis, we divide the original prediction deviation intervals of $\left[ w_{\partial,t}, w_{\partial,t} + w_{\partial,t}^{+}, w_{\partial,t}^{-} \right]$ into the Intervals $K$ and the $k$'th interval can be describe as $\left[ w_{\partial,t}^{k,+}, w_{\partial,t}^{k,-} \right]$. Then we can obtain the probability of the deviation with the historical power data by Monte Carlo Simulation in each interval. In order to maintain the uncertainty about the power generation, the uncertainty is divided into intervals according to the scale and deviation size.

In (21), $M_{\partial}^{k}$, $M_{\partial}^{k+1}$ are the uncertainty allocated by the $k$'th interval and the $k+1$'th interval. $\rho_{k}$, $\rho_{k+1}$ the probability of deviation in the $k$'th interval and the $k+1$'th interval.

As a result, an improved uncertainty set can be obtained:

$$ w_{\partial,t} = w_{\partial,t}^{*} + \sum_{k=1}^{K} \left( w_{\partial,t}^{k,+} e_{\partial,t}^{k,+} - w_{\partial,t}^{k,-} e_{\partial,t}^{k,-} \right) $$
\[ 0 \leq \varepsilon_{t,k}^{k,\pm} \leq 1 \]  
\[ 0 \leq \sum_{k=1}^{K} (\varepsilon_{t,k}^{k,\pm} + \varepsilon_{t,k}^{k,\mp}) \leq 1 \]  
\[ \sum_{t=1}^{N_t} (\varepsilon_{t,k}^{k,\pm} + \varepsilon_{t,k}^{k,\mp}) \leq M_{k,w} \]  
\[ \sum_{t=1}^{N_t} \sum_{k=1}^{K} \varepsilon_{t,k}^{k,\pm} = \sum_{t=1}^{N_t} \sum_{k=1}^{K} \varepsilon_{t,k}^{k,\mp} \]  

Where (22) to (26) describe the entire uncertainty set. \( w_{k,w}^+, w_{k,w}^- \) represent the maximum upper and lower limits of power generation in the interval \( k \). \( \varepsilon_{k}^{k,\pm} \) and \( \varepsilon_{k}^{k,\mp} \) represent the control factors for the deviation of power generation in the interval \( k \) respectively. Equation (22) and (23) reflect the relationship between the predicted power and the actual power. Equation (24) and (25) ensure that the deviation size will be in any interval and in any period and (26) indicates that the upper deviation is basically equal to the lower deviation.

### 3.3. Solve the algorithm

In view of the robust optimization model proposed above, this paper solves it by column and constraint generation algorithm (C&CG). The algorithm decomposes the original problem as the main problem and sub-problem, the main problem solves the optimal solution to meet the constraint conditions under the known probability to realize the system's daily scheduling, where \( x^m \) is the optimal solution of the \( m \)th iteration, as shown in [20].

\[ \min C^T x + \eta \]  
\[ \eta > b^T x^m \]  

The sub-problem is to look for the worst scenario under given the variable \( x \) given by the main problem and then return to the main problem for the next iteration

\[ \eta(*) = \max_{w,w} \min_{\Delta x(\xi,w)} b^T \Delta x \]  

According to the theory of pairing, the inner minimum function is transformed to the maximum and its upper bound can be calculated. In (28), \( \lambda, \gamma \) are the pair variables of each constraint; \( x \) is the solution of the main problem, \( \Delta x \) is the variation of power.

\[ \max_{w \in U, \lambda, \gamma} d^T \lambda \]  
\[ \text{s.t. } D^T \lambda + G^T \gamma \leq b \]  
\[ \lambda \geq 0, \gamma \geq 0 \]  

The equation (17) and (29) can be iterated until the difference between the upper and lower bound values reaches the desired precision \( \varepsilon \), then stop the iteration and return the optimal solution.

### 4. Case Study

To verify the validity of the proposed model and method, this paper analyzes the study in the integrated energy system.

The historical predication data and the actual power data of a wind farm in northwest China are selected. The proportion of each error interval is obtained by calculating the prediction error of wind power transmission. The wind power forecast curve is shown in Fig.3. The forecast curve for electrical and hydrogen load is shown in Fig.4. The time of use electricity price is shown in Fig.5.
4.1. Study Optimization Results
As Fig.6 and Fig.7 show, wind power is higher than the electrical load, the system has residual power and starts to charge and the hydrogen-making equipment also begin to work from 1h to 6h and from 23h to 24h. Besides, the system also starts to buy electricity on account of the relatively low electricity
price. From 7h to 9h, the time-of-use electricity price is lower than fuel cell power generation cost, so it will take priority over purchasing electricity from the main grid to meet the power gap. From 9h to 13h, the power price gets higher and the cost of generating electricity is lower than buying price from outside, it is still necessary to continue to purchase electricity from outside the network to meet the power shortage due to the ramping-rate constraint and the high demand for hydrogen load at this time. From 13h to 17h and 20h to 23h, time-of-use electricity price is higher than the cost of power generation, so the system will give priority to generate electricity by itself and at this time hydrogen production is surplus, the fuel cell will start to work to consume hydrogen and generate electricity to make up the power gap.

4.2. Model Economic Analysis
In order to verify the validity of the model proposed by this paper, a comparative analysis is made with the classical robust optimization model. Fig.8 shows the abandoned wind power in the classical robust algorithm and the improved algorithm, it can be concluded that the improved robust optimization reduces the amount of abandoned wind power in the system and promotes wind power consumption.

![Fig.6 The power optimization results of the model](image1)

![Fig.7 The optimization results of the charge and discharge power of energy storage](image2)
Fig. 8 The optimization results of wind abandoned power

As Tab. 1, the improved robust optimization model not only reduces the abandoned wind power, but also reduces the scheduling costs. The classic robust optimization aims to find the operation strategy under the worst scenario, so the regulation scheme should set aside enough spare capacity for the equipment to meet the maximum possible fluctuation of the system. But the improved robust optimization can control the spare more accurately to obtain a better economy. In the real-time operation, the classic two-stage robust optimization may make the conservative scheduling plan, which can lead to the increase of wind power disposal with selling excess power at a lower price and buying the missing power at a higher price.

| Scheme                        | Classic robust optimization | Improve robust optimization |
|-------------------------------|----------------------------|----------------------------|
| Total cost                    | 1970.16 yuan               | 1748.14 yuan               |
| The amount of abandoned power | 2.176 MW*h                 | 1.817 MW*h                 |

5. CONCLUSION

Based on the improved robust optimization model, this paper constructs a recent scheduling model of the integrated energy system that takes into account wind power production and the uncertainty of the user's electrical load, optimizes the energy scheduling of the system, and discusses the economics and environmental protection of hydrogen in the integrated energy system, and its broad application scenario. Finally, the feasibility of the proposed model is verified by the study, and it can be found that compared with the classical robust optimization, the scheduling scheme proposed to improve the two-stage robust optimization, without affecting robustness, reduces the conservativeness of the scheme, is more in line with the practical engineering application, and is more economical.

ACKNOWLEDGMENT

This work was supported by Technology Project of Stategrid Zhejiang Co. Ltd. (Grant ID: SGTYHT/19-JS-217).

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