A Multi-Objective Risk Scheduling Model of an Electrical Power System-Containing Wind Power Station with Wind and Energy Storage Integration

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Abstract: The integrated operation of wind storage is a developmental trend for future wind power stations. Compared with energy storage and wind power system scheduling, the utilization ratio of wind power is improved. This paper analyzes the power system scheduling risks that are brought about by wind power stations with wind and energy storage integration and puts forward the corresponding risks indexes, which are based on the physical structure and the long-operation features of the battery energy storage system. This paper also proposes the multi-objective optimization scheduling model, considering the economy of optimization, risk of load-shedding, and wind power curtailment that is caused by the full failure and partial failure of energy storage and wind turbines, and the uncertainty of the wind power output. Example results have shown that the optimization scheduling model can apply to various control strategies and different risk levels of the system, and reduce the risk of an electric power system containing a wind power station with wind and energy storage integration. In the meantime, it can also improve the economical efficiency and utilization rate of the wind power system.

Keywords: wind power; risk; optimal operation; battery energy storage

1. Introduction

In recent years, with the development of energy storage technology, the integrated operation of energy storage and wind power has been rapidly developed as an effective method to mitigate the uncontrollability of wind power [1]. The connection of power stations with integrated wind power and energy storage to the power grid can help to reduce wind power fluctuations, and enhance the utilization ratio of wind power stations. This is conducive to the improvement of the wind farm reliability index. On the other hand, from the perspective of risk, the system needs to bear the uncertainty of wind power and energy storage at the same time. Influenced by operation strategies in the wind farm, the uncertainties of the overall output of the wind storage-integrated power plant need to be considered in the process of formulating the dispatching plan. However, the wind storage integration of a power station is different from the traditional wind farm in the operation mode of the joint storage system; traditional risk analyses and modeling cannot be applied to solve the above problem. Therefore, a study on the risk scheduling issues for electrical power systems containing wind power stations with wind and energy storage integrated will have very important theoretical and practical significances.
The integrated operation of wind power and energy storage includes two patterns, which are traditional dispatchable energy storage, and integrated wind power and energy storage. The energy storage system of the former is independently regulated by the grid dispatching center, which does not have direct connection with the wind power output [2]. In the case of wind power connected to the grid, the power grid economy with a large-scale energy storage system is boosted [3]. A wind-storage combined system (WSCS) can mitigate the output fluctuations and improve wind power utilization [4]. With the added support of energy storage, a group of techniques can be applied to increase the economic value of bidding in a number of sequential electricity markets, under uncertain power production and prices [5].

However, the fluctuation and intermittent nature of wind not only results in substantial reliability and stability defects, but it also weakens the competitiveness of wind generation in the electric power market. Further enhancing system reliability, and effectively improving the market profits of wind farms is one of the most important aspects of wind-energy storage joint operational design. Some studies propose generation-scheduling optimization of a wind battery storage unit [6–12]. However, they do not consider the impact of the integration of wind and storage on the operation of a power system. At present, there are few studies regarding the optimal scheduling of a power system with integrated wind power and energy storage. In reference [13], a market-oriented-optimized dispatching strategy for a wind farm with a multiple-stage hybrid energy storage system (ESS) is proposed. Increasing the participation of wind energy in the power market is of paramount importance, in order to increase the penetration of wind energy in power systems. Reference [14] proposes a system that consists of a wind farm and a generic energy storage system, and it develop a deterministic model of such a plant that participating in day-ahead and reserve markets, which are used to decide the operation strategy of the system, and to evaluate the cost of the uncertainty that is linked to several parameters of the model.

However, the risk in the power grid is not considered in the above references. The failure of wind power and energy storage, and the variable management strategies of the energy storage system can affect the power output properties of the integrated power stations, which will bring about non-negligible risks to the system. Scheduling methods under traditional patterns can hardly be directly applied to scheduling under integrated wind power and energy storage patterns. Therefore, it is essential to carry out an optimal scheduling study on a power system with integrated wind power and energy storage, considering the system risk.

Based on the analysis of the operation mode and the power output characteristics of power stations with integrated wind power and energy storage, the load shedding wind power curtailment risks of system operation that result from failures of energy storage and wind turbines are taken into consideration in this paper, with the establishment of a multi-objective optimal scheduling model of a power system with integrated wind power and energy storage [15] and the verification of the rationality and superiority of the model proposed herein, through various examples.

2. Results of the Operation Mode of Power Stations with Integrated Wind Power and Energy Storage

For power stations with integrated wind power and energy storage, the battery system only assists with the access of the wind power stations to the power grid. At present, the main task of scheduling is to use the scheduling plan requirements within the wind power stations as the internal dispatchable resources, thereby realizing the peak load shifting. The output power $P_{wBess}$ of the power stations with integrated wind power and energy storage is as shown in Equation (1), which is jointly determined by the battery system and wind power:

$$P_{wBess} = P_w - P_{Bess}$$ (1)

The positive and negative signs represent the charging and discharging status, respectively. Specifically, the positive sign represents the charging status, while the negative sign represents the discharging status.
The wind power output shall satisfy the following inequality constraints of Equation (2):

\[ 0 \leq P_w \leq \min(P_w0, P_{w\text{max}}) \]  

(2)

For control centers, the dispatchable range of the power station with integrated wind power and energy storage shall be smaller than the rated power of the wind power station, as in Equation (3):

\[ 0 \leq P_{w\text{Bess}} \leq P_{w\text{max}} \]  

(3)

During actual operation, for operation patterns where the access power of the wind power is restricted, wind power curtailment risk exists. In this case, the utilization ratio of wind power varies. As shown in Figure 1, a comparison result is given between operation modes of power stations with integrated wind power and energy storage, when the integrated power of the wind power is restricted.

![Figure 1. The operation mode of the integration of the wind energy storage power station.](image)

Due to the wind power priority in accessing to power grid, the output of wind power stations under the dispatchable energy storage pattern is \( \min(P_w, P_{w\text{limit}}) \). In Figure 1, the scenarios A and B are taken as follows: For scenario A, \( P_w > P_{w\text{limit}} \), as per the scheduling requirements, \( P_{w\text{Bess}} = P_{w\text{limit}} \). Through the coordination of wind power and energy storage, the power station with wind power and energy storage can absorb surplus wind power to store the energy, making the actual outputs of the wind turbines exceed the \( P_{w\text{limit}} \). Compared with the dispatchable energy storage patterns, it can enhance the utilization ratio of wind power. For scenario B, \( P_w < P_{w\text{limit}} \), the output of the joint operation mode of a power station with integrated wind power and energy storage is equal to that of the “power determined by wind”. Therefore, the utilization ratio of the wind power is the same.

### 3. Operation Risk Analysis in a Power Grid

The risk for power stations with integrated wind power and energy storage involves the failure of the wind turbine and that of the battery energy storage system, which causes the overall output power of power stations with integrated wind power and energy storage to become absent or excessive, and brings about the risk of load shedding and wind power curtailment to the power system operation.

#### 3.1. Failure Model of the Wind Power Generator System

Except for the failure rate of the wind turbine itself, the extra failure rate resulting from different wind speeds is shown as below in Equation (4) [16]:

\[ \lambda_{\text{wind}} = \lambda_0 + \Delta \lambda_{\text{wind}}(v) \]  

(4)

The increase in failure rate \( \Delta \lambda_{\text{wind}}(v) \) presents quadratic relations with the wind speed \( v \), as in Equation (5):

\[ \Delta \lambda_{\text{wind}}(v) = k_{\text{wind}} + (\lambda_{\text{max}} v^2 - \lambda_{\text{min}} v^2)/(v_{ci}^2 - v_{ci}^2) \]  

(5)
The correspondence between the wind speed and the wind power is shown as below in Equation (6) [17]:

\[
P_w = \begin{cases} 
0, & 0 \leq v < v_{ci} \\
\frac{a + b v^3}{v_{cr}^3} v_{ci} \leq v < v_{cr} \\
\frac{P_{w,\max}}{v_{cr}^3} v_{co} \leq v < v_{co} \\
0, & v \geq v_{co}
\end{cases}
\]  

(6)

The relationship between wind power and the increase in the failure rate may be determined through Equations (5) and (6).

3.2. Failure Model of the Battery System

The battery system consists of the battery module group, the power conversion system (PCS), a filter, a battery management system (BMS), the control unit and energy management system (EMS), and other parts, connected in series [18]. Failures of the battery system can be divided into integral failures and partial failures. Figure 2 shows the structure of the battery energy storage system.

![Figure 2. The structure of the battery energy storage system.](image)

For an integral failure of the energy storage system, its failure rate is the sum of that of the system units, among which the integral failure rate of the energy storage module is concluded from the statistics data. Meanwhile, the failure rate of powered electronic devices (including the transistor, diode, filter, and transformer) in the battery energy storage system is calculated as per the methods given in the literature [19]. On such a basis, the failure rate of each unit is calculated as per the physical structure of each unit.

Partial failure of the energy storage system indicates the sub-module failure or shutdown of the battery, while the sub-module is subject to independent control of the battery management system. Although the failure or repair and shutdown of a certain sub-module does not affect the integral operation of the battery energy storage system, the rated capacity and rated power will be reduced, which will cause a partial power loss of energy storage.

The partial failure rate of the battery system consisting of \( n \) battery sub-modules is shown as below, in Equation (7):

\[
\lambda_{Bess,j}^{part} = C_n^i \lambda_{Bess,j}^{nol}
\]  

(7)

With the increase of service life, the probability distribution of its failure will obey the two-parameter exponential function \( F_k(k) \) [20] shown as below in Equation (8):

\[
F_k(k) = 1 - e^{-\lambda_k(k-k_0)}
\]  

(8)

4. Operation Risk Model

The operation risk is the comprehensive measurement of the possibility and severity given by the uncertainty factors of a power system, which indicates that the risk includes two aspects, the event
occurrence probability and the serious consequences resulting from the event. The mathematical expression [21] is shown as below in Equation (9):

$$R_{\text{Risk}}(X) = \sum P(E_i) \cdot S(E_i)$$  \hspace{1cm} (9)

1. The occurrence probability of uncertain factors: The operation risk probability $P(E_i)$ of the power system containing a power station with integrated wind power and energy storage includes the partial power loss probability of the battery system, the failure probability, the wind turbine failure probability, and the forced outage probability of the thermal power-generating unit.

2. Serious consequences are caused by the uncertainty: serious consequences that result from the aforesaid uncertainties $S(E_i)$ include energy storage and wind turbine failures, as well as the value of load shedding and wind power curtailment resulting from post-scheduling, and the value of the lost load caused after the shutdown of the system’s thermal power-generating unit.

Considering the unreliability of the energy storage of the battery and the wind turbine operation, the equations of the system’s wind power curtailment $P_{\text{wBess\_dis}, LW}$, the amount of load shedding $P_{\text{wBess\_dis}, LL}$, and the total amount of active power imbalance $P_{\text{wBess\_dis}}$ are respectively shown as below in Equations (10)–(12):

$$P_{\text{wBess\_dis}, LW} = \max \left\{ \sum_{i=1}^{N_G} P_{G,i} + P_{\text{dam\_wBess}} - P_L + R_{\text{Bess},0} \right\}$$  \hspace{1cm} (10)

$$P_{\text{wBess\_dis}, LL} = \max \left\{ P_L - \left( \sum_{i=1}^{N_G} P_{G,i} + P_{\text{dam\_wBess}} \right) + R_{\text{Bess},0} \right\}$$  \hspace{1cm} (11)

$$P_{\text{wBess\_dis}} = P_{\text{wBess\_dis}, LW} + P_{\text{wBess\_dis}, LL}$$  \hspace{1cm} (12)

Given the lost load value of serious consequences resulting from a forced shutdown of the thermal power generators $P_{\text{P\_G\_dis}}$, the equation is shown as below in Equation (13):

$$P_{\text{P\_G\_dis}} = P_L - \left( \sum_{i=1}^{N_G} P_{G,i} + P_{\text{wBess}} \right)$$  \hspace{1cm} (13)

3. Risk index of system operation: the equation of the risk index of system operation $R_{\text{Risk}}$ is shown as below in Equation (14):

$$R_{\text{Risk}} = \lambda_{\text{Bess}} P_{\text{Bess\_dis}} + \sum_{i=1}^{n} \lambda_{i}^{\text{part\_Bess\_dis}} P_{\text{Bess\_part\_dis}} + \lambda_{\text{wind}} P_{\text{wind\_dis}} + \sum_{j=1}^{N_G} \lambda_{P_G,j} P_{\text{P\_G\_dis}}$$  \hspace{1cm} (14)

5. A Multi-Objective Optimization Scheduling Model of the System, Considering the Operation Risk of Power Stations with Integrated Wind Power and Energy Storage

In a power station with integrated wind power and energy storage, uncertainties simultaneously exist in the wind turbine and battery systems, which significantly increase the system operation risk. Therefore, when the optimized scheduling model of the power system is established, it is necessary to consider the impact of the operation risk of a power station with integrated wind power and energy
storage on the scheduling plan. The decline of power generation costs, and the increase in wind power capacity are at the cost of enhancing the system risk. In order to balance the relationships among the three issues, and to solve corresponding contradictions and conflicts, this paper adopts system operation coal consumption, risk, and wind power curtailment as the objective for establishing an optimized scheduling model. The multi-objective solving method is used to reduce the system operation coal consumption, enhance the utilization rate of wind power, and minimize the system operation risk.

5.1. Objective Functions

Objective function 1: The coal consumption index of the thermal power-generating unit is the power generation when the coal consumption of thermal power plant is the lowest. It can be expressed as follows in Equation (15):

$$\min F_1 = \sum_{t=1}^{T} \sum_{i=1}^{NG} a_i P_{i,t}^2 + b_i P_{i,t} + c_i$$  \hspace{1cm} (15)

Objective function 2: The risk index refers to the risk accumulation of each time interval of the system at present in Equation (16):

$$\min F_2 = \sum_{t=1}^{T} R_{Risk,t}$$  \hspace{1cm} (16)

Objective function 3: Wind power curtailment: when the amount of wind power curtailment at each time interval of the system is at a minimum, it represents the utilization rate of the wind power being at maximum. This paper does not consider the stochastic wind power, and it supposes that the fluctuation wind power may be set off by the emergency power supply as in Equation (17):

$$\min F_3 = \sum_{t=1}^{T} (P_{w0,t} - P_{w,t})$$  \hspace{1cm} (17)

According to the fuzzy set theory, this paper adopts the degree of the membership function $F$ to describe the optimization results [22] of each objective function, while its value is taken within the range of 0–1. $F = 0$ represents it being closest to the optimal result, which is the most satisfactory; $F = 1$ represents the result being the most unsatisfactory. The expression of $F$ is shown as below in Equation (18):

$$F_i(X) = \frac{f_i(X) - f_i(X^*_i)}{f_{iw} - f_i(X^*_i)}$$  \hspace{1cm} (18)

where $F_i(X)$ is the objective function, while $f_i(X)$ is the membership degree function that is taken as the optimal function when the single objective of the objective function $f_i(X)$ is optimized. $f_{iw}$ refers to the worst value of the objective function $f_i(X)$ in the optimal strategy $X^*_i$ of each single objective.

The linear-weighted-sum method is used to convert the multi-objective optimization issue into a single-objective optimization issue, as in Equation (19):

$$F = \min \sum_{i=1}^{3} \omega_i F_i$$  \hspace{1cm} (19)

where $\omega_i$ refers to the weight, which is the emphasis degree of the scheduling upon each objective, and can be calculated as per the variable risk level. Meanwhile, $\sum_{i=1}^{3} \omega_i = 1$. 
5.2. Constraint Conditions

1. Output constraint of the thermal power units as in Equation (20):

\[ p_{\text{min}}^{\text{Gi}} \leq P_i,t \leq p_{\text{max}}^{\text{Gi}} \]  

(20)

2. Ramp rate constraint of the thermal power units, as in Equation (21):

\[
\begin{align*}
P_i,t - P_{i,t-1} &\leq u_i \Delta t \\
P_{i,t-1} - P_i,t &\leq d_i \Delta t
\end{align*}
\]

(21)

3. Reserve constraint, as in Equations (22) and (23):

\[
\sum_{t=1}^{T} \min\left(p^\text{max}_{\text{Gi},t} - \frac{u_i}{6}\right) \geq 0.02P_{L,t} + 0.15P_{w0,t}
\]

(22)

\[
\sum_{t=1}^{T} \min\left(P_i,t - p^\text{min}_{\text{Gi},t}\right) \cdot \frac{u_i}{6} \geq 0.15P_{w0,t}
\]

(23)

Equations (22) and (23) represent the upper and lower reserve constraints of the system, respectively, while the upper reserve constraint takes 2% of the load power and 15% of forecasting wind power, and the lower reserve constraint takes 15% of the forecasting wind power. Being divided by 6 as shown in the equation, it represents the reserved 10 min response.

4. The output constraint of power stations with integrated wind power and energy storage can be expressed as in the Equations (24) and (25):

\[ 0 \leq P_{w\text{Bess},t} \leq P_{w\text{max}} \]  

(24)

The output constraint of the wind turbine is shown as below:

\[ 0 \leq P_{w,t} \leq \min(P_{w0,t}, P_{w\text{max}}) \]  

(25)

5. Energy storage constraint: During normal operation, the interaction relationship exists before and after energy storage, which is shown by the following equation:

\[
E_{\text{Bess},t_e} = \begin{cases} 
E_{\text{Bess},t_e-1} - P_{\text{Bess},t} \Delta t \cdot \eta_{\text{ch}} P_{\text{Bess},t} &\leq 0 \\
E_{\text{Bess},t_e-1} - \frac{P_{\text{Bess},t}}{\eta_{\text{dis}}} \Delta t &> 0
\end{cases}
\]

(26)

In the case of failures, the time interval before and after energy storage should satisfy the following constraints in Equation (27):

\[
E_{\text{Bess},t_e} = \begin{cases} 
E_{\text{Bess},t_e-1} - P_{\text{dam Bess},t} \Delta t \cdot \eta_{\text{ch}} P_{\text{Bess},t} &\leq 0 \\
E_{\text{Bess},t_e-1} - \frac{P_{\text{dam Bess},t}}{\eta_{\text{dis}}} \Delta t &> 0
\end{cases}
\]

(27)

During the entire time interval, the power is balanced, and this will not have any impact on the next scheduling period, as in Equation (28):

\[ E_{\text{Bess},0} = E_{\text{Bess},T} \]  

(28)

For the long-term operation of a battery energy storage system, its maximum charging and discharging power will be affected by the charge–discharge rate after a certain number of years [23], shown as below in Equation (29):

\[-\alpha_{\text{ch}}(I_{\text{ch}}) \leq P_{\text{Bess},t} \leq \alpha_{\text{dis}}(I_{\text{dis}})P_{\text{Bess}}^{\text{max}} \]  

(29)
The battery capacity will be subject to the depth of charge and discharge, battery health status, and temperature, shown as below as in Equation (30):

\[ \alpha \text{Edown}(D, H)E_{\text{Bess}}^{\text{max}} \leq E_{\text{Bess}}(t) \leq \alpha \text{Eup}(D, H)E_{\text{Bess}}^{\text{max}} \] (30)

Formula (29) and Formula (30) represent the charge–discharge output constraint and the upper and lower limits of the capacity, considering the long-term operation properties of the energy storage of the battery, respectively.

6. The active power balance constraint of the system is shown in Equation (31):

\[ \sum_{i=1}^{N_G} P_{G,i,t} + P_{w,\text{Bess},t} - P_{L,t} = 0 \] (31)

5.3. The Adjustment of the Optimization Objective of Scheduling Problem Based on Conditional Value at Risk

When considering the randomness of power stations with integrated wind power and energy storage, the objective function \( F_3 \) herein, can be given as follows below in Equation (32):

\[ F_3 = \sum_{i=1}^{T} (P_{\text{real},w,t} - P_{w,t}) \] (32)

The method of the conditional value at risk is used to deal with random variables of wind power. The conditional value-at-risk theory is developed on the basis of the value-at-risk theory. The value-at-risk (VaR) refers to the loss threshold that is faced by a certain financial asset or portfolio in a certain future period under certain confidence level and normal market fluctuations, the equation is shown as below in the Equation (33):

\[ \text{porb}\{\Delta V \leq \text{VaR}\} = \beta \] (33)

The conditional risk value refers to the conditional expectation value that the loss is greater than the value-at-risk. According to the definition of the conditional risk value, the probability that the loss function \( f(x, y) \) caused by \( y \) does not exceed the critical value \( a \) is given below in Equation (34):

\[ \psi(x, a) = \int_{f(x,y) \leq a} \phi(y)dy \] (34)

For a fixed \( x \), \( \psi(x, a) \) is the cumulative distribution function of the function of \( a \) under the decision variable \( x \), which is non-subtracted and right-continuous for \( a \). For a given confidence level \( \beta \), there is a corresponding set of \( a \), and the minimum value is the value at risk, as in Equation (35) below:

\[ f_{\text{VaR}}(x) = \min\{a \in R : \psi(x, a) \geq \beta\} \] (35)

The confidence level \( \beta \) represents the decision-maker’s attitude towards risk. The larger the \( \beta \), the higher the level of safety required by decision makers and the more excluded the risk. The expression of conditional value at risk is given below in the Equation (36):

\[ f_{\text{CVaR}}(x) = f_{\text{VaR}} + \mathbb{E}\left[f(x, y) - f_{\text{VaR}} \mid f(x,y) > f_{\text{VaR}} \right] \]

\[ = \mathbb{E}\left[f(x, y) \mid f(x,y) \geq f_{\text{VaR}} \right] \]

\[ = \frac{1}{1-\beta} \int_{f(x,y) \geq f_{\text{VaR}}} f(x, y)\phi(y)dy \] (36)
By introducing an equivalent continuous convex function, the integral terms are approximated
by the sample average method. Taking the objective function $F_3$ as the loss function, the equivalent
conditional value at risk of the scheduling problem is given as follows in Equation (37):

$$
\tilde{F}_\beta(P_{w,t}, \alpha_t) = \sum_{t=1}^{T} (\alpha_t + \frac{1}{N(1-\beta)} \sum_{k=1}^{N} [f(P_{w,t}, P_{real}^{\text{rel}}) - \alpha_t]^-)
$$

The coagulation function is used to smooth the expression, so that the classical optimization
algorithm can be used.

5.4. Optimization Methods and Procedures

The objective function of the model in this paper is a non-linear and continuous differential
convex function, and the primal–dual interior point method is applied in order to obtain the solution. The solution procedures are shown as below:

- Determine the initial status of the system, including the wind power, energy storage, and load power of the power station with integrated thermal power, wind power, and energy storage within each time interval.
- Select the system failure set, including the wind turbine failure, full failure, and partial failure of energy storage.
- Calculate the single-objective function and adopt the description of the degree of the membership function, respectively, and then convert the multi-objective function into the single-objective function by utilizing the linear weight method.
- Calculate the optimal solution within the constraint conditions by adopting the primal–dual interior point method.

6. Case Study and Discussion

By taking a 6-unit system as an example (Tables 1 and 2), an additional power station with integrated wind power and energy storage is included, where the rated power of the station is 250 MW, and the wind power station has priority of access to the grid. The grid-access power of the power station is restricted to 15% of the load power of the current time interval. The battery energy storage scale is 70 MW/210 MW·h, consisting of four sub-modules. For the related data for the battery, please see Figures 3–5. Tables 1–3 show respectively: the parameters of the thermal power unit, the data of the system load and wind power-forecasting output, and the binary contrast weighting method, to calculate the weights of the different risk levels. Figures 3–5 show respectively, the inefficiency of power electronic components, the inefficiency of the cell storage system and the partially inefficient of battery storage.

| Table 1. Parameters of the thermal power unit. |
|-----------------------------------------------|
| Unit 1 | 1 | 2 | 3 | 4 | 5 | 6 |
| Maximum power generation (MW) | 350 | 240 | 200 | 250 | 350 | 230 |
| Minimum power generation (MW) | 50 | 50 | 80 | 50 | 50 | 50 |
| $10^5a$ (t·MW$^{-2}$·h$^{-1}$) | 275 | 295 | 225 | 334 | 450 | 215 |
| $10^5b$ (t·MW$^{-2}$·h$^{-1}$) | 96 | 122 | 137 | 115 | 95 | 126 |
| $c$ (t·MW$^{-2}$·h$^{-1}$) | 130 | 110 | 120 | 110 | 120 | 100 |
| Maximum uphill climb (MW) | 138 | 90 | 72 | 96 | 162 | 114 |
| Maximum downhill climb (MW) | 138 | 90 | 72 | 96 | 162 | 114 |
Table 2. Data of the system load and the wind power-forecasting output.

| Time interval | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     |
|---------------|-------|-------|-------|-------|-------|-------|-------|-------|
| System load (MW) | 689.4 | 661.5 | 655.7 | 665.9 | 663.7 | 687.5 | 752.4 | 820.4 |
| Wind power-forecasting output (MW) | 234.1 | 241.9 | 249.5 | 236.6 | 225.9 | 191.4 | 211.2 | 166.5 |
| Time interval | 9     | 10    | 11    | 12    | 13    | 14    | 15    | 16    |
| System load (MW) | 900.6 | 1050.1| 1201.9| 1263  | 1228.8| 1289.6| 1310.4| 1298.2|
| Wind power-forecasting output (MW) | 103.5 | 84.9  | 92.3  | 78.5  | 111.7 | 141.5 | 183.5 | 197.2 |
| Time interval | 17    | 18    | 19    | 20    | 21    | 22    | 23    | 24    |
| System load (MW) | 1170.1| 987.5 | 1048.3| 1198.8| 1174.6| 1012.2| 829.8 | 721.6 |
| Wind power-forecasting output (MW) | 160.1 | 131.5 | 179.7 | 188.5 | 201.5 | 222.1 | 230.2 | 245.5 |

Figure 3. Inefficiency of power electronic components.

Figure 4. Inefficiency of the cell storage system.
6.1. Scheduling Results and Analysis, Considering the Operation Risks of Power Stations with Integrated Wind Power and Energy Storage

Assume that the system risk and coal consumption weight are the same and higher than the wind power curtailment index, while the values are taken as follows: \( w_1 = 0.41 \), \( w_2 = 0.41 \), and \( w_3 = 0.18 \). It is required to carry out the comparison analysis as per three scenarios, and in terms of multi-index: the scenario 1 will not consider the risk, while the scenario 2 will not consider the battery energy storage risk and the scenario 3 will not consider the risk of the integrated wind power and energy storage. The following Figure 6. shows the variety of indexes of the scheduling results in three scenarios.

As shown in Figure 6, the scheduling results of the coal consumption index and the wind power curtailment index in scenario 3 are higher than that in scenario 1, but the system risk declines by 20.2\%, compared with scenario 1. The scheduling results of coal consumption index and wind power curtailment index in scenario 2 are lower than that in scenario 3, but the risk values of the energy storage system, wind power station, thermal power plant and system are higher than that in scenario 3. If the energy storage system does not consider its operation risk, wind power accommodation power and wind power utilization rate will be increased, together with the output rise. However, the increased system risk that results from the output of energy storage and wind power cannot be ignored.

The impact of the energy storage failure rate increase of variable years in scenario 3 upon scheduling should be considered. With a 3-year failure rate risk as the benchmark, an increase of the energy storage failure rate of the battery after its operation for five and 10 years will respectively, bring about a 3.7\% and 10.2\% increase in risk value to the system. Therefore, with an increase in the battery service life, it is necessary to consider the risks of system scheduling that result from the energy storage failure.
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In order to analyze the impact of wind speed variation upon the scheduling results, this paper will respectively increase or decrease the forecasting wind power by 5%. As shown in Figure 7, the wind turbine failure rate variation and scheduling results corresponding to the forecasting wind power peak hour (the third time interval) are presented. The following Figure 7 shows the scheduling results with different forecasting wind power.

As shown from the scheduling results, with the increase of wind power, the failure rate of wind turbine will slightly increase, while the system operation risk will grow dramatically. Figure 8 shows the residual capacity of the battery energy storage and the abandoned air volume of the wind power station each time in the three scenarios.
As shown from the scheduling results, with the increase of wind power, the failure rate of wind turbine will slightly increase, while the system operation risk will grow dramatically. Figure 8 shows the residual capacity of the battery energy storage and the abandoned air volume of the wind power station each time in the three scenarios.

Figure 8a shows the residual capacity scheduling results of the energy storage of the battery within variable time intervals. The output of the energy storage is related to the risk index. Within the scheduling period, when the risk is considered by the energy storage system, the variation of the residual capacity will become gentler. Figure 8b shows the comparison results of wind power curtailment of three scenarios within variable time intervals. According to the examples, the wind power has anti-peak shaving features. When the wind power restriction access load is 15%, the wind power curtailment will be centralized within the valley load time interval. In order to decline the risks, the...
wind turbine and energy storage output are declined accordingly, which leads to the increase of wind power curtailment within the valley load time interval.

Considering the operation risk of the battery system and the integrated wind power and energy storage makes the coal consumption and wind power utilization rate of the system operation relatively conservative. The calculation results show the risk of the system operation is significantly reduced. It shows that considering the risk of integrated operation of wind and storage is beneficial to the safe operation of the system.

6.2. Comparison Analysis of Risk Scheduling Results between Variable Operation Mode with Integrated Wind Power and Energy Storage

Considering the risk factors, this paper carries out risk scheduling between two operation modes with dispatchable energy storage and integrated wind power and energy storage; the results are as shown in Figure 9 below.

![Figure 9](image_url)

**Figure 9.** Comparison of the risk scheduling results between two kinds of operation modes with integrated wind power and energy storage.

When the restrictive access load of wind power is 15%, the integrated wind power and energy storage mode tends to have lower economical efficiency and less wind power curtailment than the dispatchable energy storage mode, which suggests that the utilization rate of wind power is high. When the output of wind power and energy storage increases, the scheduling results of the system considering the risks will be less declined, compared with that of the system that does not consider the risks.

Figure 10a,b present the wind power output and wind power station output under two operation modes, respectively. Within the valley load time interval, the outputs of the wind power station under the two operation modes are the same, while the wind power output under the integrated wind power and energy storage mode is larger than that under the dispatchable energy storage mode with a high utilization rate of wind power. Within the load peak time interval, the wind power outputs are the same, while the output of the wind power station under the integrated wind power and energy storage mode is larger than that under the dispatchable energy storage mode. Therefore, the integrated wind power and energy storage mode can enhance the utilization rate of wind power, while the dispatchable energy storage mode reduces the system’s coal consumption. Figure 10 shows the every period of wind power, and power of the wind power stations for two kinds of wind power and energy storage in combined operation mode.
Figure 10. Every period of wind power and power of wind power station of two kinds of wind power and energy storage in combined operation mode.

6.3 Risk Scheduling of Battery Energy Storage under Variable Management Strategies

The state of charge (SOC) and storage capability of the battery system are restricted by charge–discharge management strategies, so as to ensure the safety of the energy storage system. The variation of the charge–discharge strategies will have different impacts on the power station with
integrated wind power and energy storage and system operation. The charge–discharge strategies of three sorts of battery systems are compared and elaborated in this paper.

Strategy 1: The charge–discharge of the energy storage is without the constraints of the charging times and the charging duration.

Strategy 2: In order to reduce battery life loss, and to reduce the switch times of the battery charge–discharge status, or additional increases in the battery energy storage constraint, namely, within one day, the switch times of the actual charge–discharge status $N_{dBess}$ shall be no more than the regulated times $N_{dBess}$, as in the following Equation (38):

$$N_{dBess} \leq N_{dBess}$$ (38)

Strategy 3: In order to reduce the difference between the peak load and the valley load of wind power, the battery system is only allowed to be charged within the forecasting wind power peak time interval set $t_{peak}$, and discharged within the forecasting wind power valley time interval set $t_{tro}$. In addition, additional increase of the energy storage constraints is required, as per the following Equation (39):

$$\begin{cases} P_{Bess,t} \leq \alpha, t \in t_{tro} \\ P_{Bess,t} > \alpha, t \in t_{peak} \end{cases}$$ (39)

Under an operation mode with integrated wind power and energy storage, to ensure the service life of the battery system, strategy 2 ($N_{dBess} = 2$) is generally adopted. In order to reduce the impact of the anti-peak shaving features of wind power on the system, strategy 3 is generally adopted ($t_{peak} = 1, 2, \ldots, 7, 21, 22, 23, 24; t_{tro} = 9, 10, \ldots, 14$).

This paper carries out risk scheduling under different management strategies for the energy storage, the results are as shown in Figure 11. It can be seen that the different strategies have little effects on the economics index. The system security is the highest under strategy 3, because the wind power at the peak and valley times are suppressed, which decreases the uncertainty. However, the amount of wind power curtailment is the largest under strategy 2, because of the increase of the battery energy constraint.

**Figure 11.** Scheduling results under different management strategies for battery energy storage.

6.4. Scheduling Results and Analysis under Variable Weights of Risks and Coal Consumption Objectives

In order to balance the risks of power stations, with integrated wind power and energy storage being brought to system operation, this paper selects the variable risks and coal consumption weights, and determines the weight coefficients of each objective with the qualitative sorting and quantitative
scale-combined dualistic factor contrast for index weight calculations, while weight selection is as shown in Table 3.

The scenarios (a), (b) and (c) in Figure 12 represent the scheduling results of the system’s wind power curtailment, coal consumption, and risk index under variable weights, respectively. Among these scenarios, the weight of wind power curtailment is kept almost constant. With the risk weight decreases and the economics weight increases, the risk index will decline. The cause is that the power system pays attention to the optimal goal of reliability. Therefore, in order to guarantee safe operation, the amount of wind power curtailment will rise because of the power uncertainty. Also, then the total cost of the system will increase, due to the lack of low-cost wind power.

![Figure 12. Cont.](image-url)
wind power. However, the amount of wind power curtailment is the largest under the strategy of reducing the difference between the peak load and the valley load of wind power. The following conclusions can be drawn:

(1) Compared with the dispatchable energy storage mode, the operation mode with integrated wind power and energy storage accommodates more wind power through the coordination of wind power and energy storage within the wind power station, which reduces the coal consumption cost but increases the risks.

(2) The different strategies have few effects on the economics index. The system security is the highest under the strategy of reducing the difference between the peak load and the valley load of wind power. However, the amount of wind power curtailment is the largest under the strategy of increasing the battery energy constraint.

(3) An increase in the risk weight in the model, and the enhancement of the utilization rate of the wind power and battery protection energy storage strategy will reduce the system risk. During the scheduling operation, it full consideration of the operation risks of the system resulting from the failure and unreliability of the wind turbines and energy storage will have non-ignorable impacts on the safe operation of the system.

Author Contributions: H.H. and H.S. developed the ideas; F.P. and W.Z. conducted the simulation tests; H.H. and Z.G. wrote the manuscript; X.L. and S.H. carried out the analysis; S.H. reviewed the literature and proofread the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

\( a_i, b_i, c_i \) the coal consumption coefficients

\( D \) the charge–discharge depth

\( E_i \) the number \( i \) of uncertain factors of the system

Figure 12. Scheduling results under different risk levels.

7. Conclusions

Based on the operation risk model of the battery energy storage system and the wind turbine, this paper proposed the risk index of a power system containing a power station with an integrated wind power and energy storage, established an optimization scheduling model considering the coal consumption, risks, and wind power curtailment of the system thermal power-generating unit, and applied a multi-objective handling method to solve the contradictions of the three objectives mentioned above, which not only reduces the risk, but also enhances the system economy and the utilization rate of wind power. The following conclusions can be drawn:

(1) Compared with the dispatchable energy storage mode, the operation mode with integrated wind power and energy storage accommodates more wind power through the coordination of wind power and energy storage within the wind power station, which reduces the coal consumption cost but increases the risks.

(2) The different strategies have few effects on the economics index. The system security is the highest under the strategy of reducing the difference between the peak load and the valley load of wind power. However, the amount of wind power curtailment is the largest under the strategy of increasing the battery energy constraint.

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Figure 12. Scheduling results under different risk levels.
the residual capacity of energy storage at the hour of \( t_e \)

the capacity of energy storage at the beginning of the entire time interval

the capacity of energy storage at the end of the entire time interval

the initial rated capacity of energy storage of the battery

the membership degree function

the worst value of the objective function \( f_i(X) \) in the optimal strategy \( X_i^* \) of each single objective

a loss function with \( x, y \)

a two-parameter exponential function

the objective function

the objective function

the battery health status

the number of failure sub-modules

the charge rate

the discharge rate

the failure-generating unit

the constant related to the cut-out speed and the cut-in speed

the guaranteed minimum battery life

number of battery sub-modules

the number of samples

the number of thermal power-generating units

the switch times of the actual charge–discharge status

the regulated times

the output power of the power stations with integrated wind power and energy storage

the wind power output

the battery power output

the predictive wind power

the rated power of the wind turbine

the power limitation of the wind power grid connection

the occurrence probability of a number \( i \) of uncertain factors

the system's wind power curtailment

the amount of load shedding

the total amount of active power imbalance

the power of the power station with integrated wind power and energy storage with a battery system and wind turbine failures taken into account within

the total load power of the system

given the lost load value of serious consequences resulting from a forced shutdown of the thermal power generators

the active power imbalance after the complete failure of the battery system

the system's active power imbalance after the failure of the number \( i \) sub-module of the battery

the system's active power imbalance after a wind power failure

the system's power imbalance after the failure of a number \( j \) of generator units

the output of a number \( i \) of thermal power-generating units under a time interval \( t \)

the wind power output under a time interval \( t \)

the predictive wind power under a time interval \( t \)

the upper limit of the thermal power unit output

the lower limit of the thermal power unit output

the output power of the power stations with integrated wind power and energy storage at the time interval \( t \)

the energy storage power within time interval \( t \)

the power within the time interval \( t \) after energy storage failure, including the total loss and the partial loss

the rated maximum charge and discharge power of the battery

the system load at the time interval \( t \)
$P_{G,i,t}$ the power output of number $i$ of a thermal power-generating unit under the time interval $t$

$P_{wind}$ the actual wind power

$R_{Risk}(X)$ the operation risk function

$R_{Bess}$ the emergency response power

$R_{Risk}$ the risk index of the system operation

$S(E_i)$ the risk index of a power system containing a power station with integrated wind power and energy storage under the time interval $t$

$t$ the value of each physical quantity under the time interval

$t_{peak}$ the hours charged within the forecasting wind power peak time interval set

$t_{tro}$ discharged within the forecasting wind power valley time interval set

$\Delta t$ the possession period

$T$ the total time interval

$v$ the wind speed

$v_{co}$ the cut-out speed

$v_{ci}$ the cut-in speed

$v_{cr}$ the rated wind speed

$\Delta V$ the loss of financial assets in the possession period $\Delta t$

$\omega_i$ the degree of scheduling upon each objective

$x \in X$ an-dimensional decision variable

$X$ the current system status

$X^*_i$ the optimal strategy

$y \in R^m$ an m-dimensional random variable, representing the uncertainty factor related to $Z$

$Z \subset R^n$

$\alpha$ the critical value

$\alpha_{ch}$ the influence coefficient of the charge rate related to $I_{ch}$

$\alpha_{dis}$ the influence coefficient of the discharge rate related to $I_{dis}$

$\alpha_{Eup}$ the energy storage capacity coefficient related to $H$

$\alpha_{Edown}$ the energy storage capacity coefficient related to $D$

$\beta$ the confidence level

$\lambda_{wind}$ the extra failure rate resulting from different wind speeds

$\lambda_0$ the basic failure rate of the wind turbine

$\Delta \lambda_{wind}(v)$ the quadratic relations with wind speed $v$

$\lambda_{max}$ the corresponding failure rate

$\lambda_{min}$ the corresponding failure rate

$\lambda_{part}$ the failure rate of simultaneous fault of $i$ sub-modules

$\lambda_{Bess,j}$ the failure rate of a single sub-module

$\lambda_k$ the probability of failure occurring during the unit time after $k$

$\lambda_{Bess}$ the complete failure probability of the energy storage of the battery

$\lambda_{wind}$ the failure probability of the wind turbine

$\lambda_{P_{G,j}}$ the forced shutdown rate of the $j$th generating unit

$\lambda_{part,i}$ the failure probability of the $i$th sub-module of the battery

$\eta_{ch}$ the charging efficiency of the battery

$\eta_{dis}$ the discharging efficiency of the battery

$\varphi(y)$ a probability density function with $y$

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