Economic Dispatch of Energy Storage System in Micro-grid

Meiyu ZHOU, Qiaozhu ZHAI, Yuzhou ZHOU
MOE KLINNS, System Engineering Institute, Xi’an Jiaotong University, Xi’an 710049, Shannxi Province, China
zzzhy@foxmail.com, qzzhai@sei.xjtu.edu.cn, yzzhou@sei.xjtu.edu.cn

Abstract. Renewable energy and energy storage combined system cannot only realize load transfer, load shifting, energy saving and emission reduction, but also ensure the stability and safety of power grid. Economic dispatch of energy storage system under micro-grid environment is a typical multi-stage stochastic programming problem. The purpose of this paper is to propose an economic dispatch model for the energy storage system satisfying the non-anticipative constraints. The objective function is constructed based on the minimum dispatching cost of the micro-grid, and the accurate mathematical description of the feasible region is given. By solving these problems, we can obtain economic dispatch results of the energy storage system satisfying the non-anticipative constraints. The proposed methods are tested on four different cases, and the results suggest the methods are effective.

1. Introduction

In recent years, with the increasing depletion of fossil energy, global warming and other problems, as well as the adjustment of the global energy structure, the development and utilization of renewable energy, represented by wind power and solar energy, has become an important direction of the global energy industry development [1]. However, due to the intermittent, high output uncertainty and other characteristics of renewable energy generation such as wind power and photovoltaic, the large-scale integration of power grids will significantly affect the safety, stability and economy of power grid operation [2]-[3]. The application of energy storage technology in power grid is an effective way to deal with the intermittence of renewable energy, and it is also a research field closely concerned in China and overseas [4]-[5]. Therefore, the joint dispatch of wind power, photovoltaic and energy storage can protect the environment and improve the utilization rate of renewable energy. At the same time, it is conducive to peak shaving and valley filling and helpful to ensure the stability and safety of power grid operation [6]-[7].

Micro-grid is a small modular and decentralized energy supply network based on distributed generation technology, which is mainly composed of small power plants close to decentralized resources or users, combined with end-user power quality management and energy cascade utilization technology [8]. The combined system of renewable energy and energy storage in micro-grid environment is an effective way to achieve energy saving and emission reduction in power consumption [9]-[10]. Families, residential areas, medium and small-sized enterprises are typical micro-grid environments using renewable energy to generate electricity with uncertain loads. The energy storage equipment in this kind of system stores the electric energy when the micro-grid power surplus, and releases the electric energy when the micro-grid power is not enough to meet the load demand, which is helpful to smooth the fluctuation of the micro-grid load [11]. At the same time, this kind of micro-grid system purchases electricity and stores it in energy storage equipment when the
electricity price of large power grid is low. When the electricity price of large power grid is high, the energy storage equipment discharges electricity to meet the load demand, and even injects it into large power grid through the gateway, thus reducing the electricity cost of micro-grid [12]-[13]. This paper focuses on the economic dispatch of energy storage system in this micro-grid environment.

Economic dispatch of energy storage system in micro-grid environment is a typical multi-stage stochastic programming problem. The main problem in scheduling is to fully consider the non-anticipative of stochastic factors in scheduling plan [14]. That is to say, the charging and discharging decision of the next period can only be determined according to the history of the uncertainty and the current realization value. At the same time, in the case that the information in the future is unknown, the feasibility of decision-making and the optimality in the sense of expectation should be guaranteed. The consideration of non-anticipative constraints is the core difficulty in the economic dispatch of energy storage system and it is still insufficient in the existing methods.

At present, there are four kinds of economic dispatching methods for energy storage system in micro-grid environment: stochastic programming, robust optimization, chance constrained programming and heuristic algorithm. In the literature [15], the scheduling model of energy storage system is established, and the stochastic programming method of scenario analysis is used to realize the economic operation of large-scale energy storage system under the condition of wind power grid connection. Jizhong Z, Pengfei Y, Peizheng X and Pingping X have analyzed the utilization of wind power in three scenarios, and proposed a multi-energy integrated economic dispatch method to ensure the minimum amount of wind power curtailment [16]. In the literature [17], a two-stage decision model is established, which is based on the scenario set and the rolling correction of intraday economic dispatch. The stochastic optimization method is used to solve the economic dispatch problem of energy storage system, which is easy to model and solve, and the physical model is more realistic. This method needs the distribution information of random variables, and the solution time complexity is large.

In [18]-[23], a two-stage robust optimization method is used to solve the economic dispatching and planning problems of energy storage system. This method can guarantee robustness without distributed information. However, it is difficult to solve the multi-layer robust optimization problem. The solution time is long and the solution is conservative. What’s more, it doesn’t meet the non-anticipative constraints.

Jianbo S, Junli W, Buhan Z regard the micro-grid with liquid flow battery as the research object, and establishes the micro-grid environmental economic dispatching model based on chance constrained programming [24]. The objective of the model is to minimize the operation cost and pollutant treatment cost of the micro-grid, and the probabilistic constraint condition is that the rotating reserve capacity satisfies the reliability requirement of the system at a certain confidence level and achieves good results.

Xiu Y, Jie C, Lan Z, Meixie Z and Haibo W have considered a micro-grid with wind power, solar energy, storage system and thermal power loads, and uses the improved genetic algorithm to determine the optimal scheduling of energy storage with the lowest comprehensive cost under the operation mode of grid-connected and isolated grid. In [26] an independent micro-grid economic dispatch optimization method based on particle swarm optimization (PSO) algorithm is proposed with dynamic cooperation of two main controllers. Hao W and Yansong W have used intelligent single particle algorithm to search the optimal solution of scheduling variables, and compares it with conventional particle swarm optimization algorithm.

However, none of the methods in the literature can satisfy the full-scenario-feasibility and non-anticipative constraints. The purpose of this paper is to propose an economic dispatch model for energy storage system in micro-grid environment which meets non-anticipative constraints. The model considers the constraints of micro-grid operation and energy storage system, including the non-anticipative constraints of economic dispatch. The objective function is constructed based on the criterion of minimizing the power consumption cost of micro-grid. And the accurate mathematical description of the feasible region of energy storage system is given. By solving the model, we can
obtain a full-scenario-feasibility economic dispatch for energy storage system. The performance of the proposed scheduling method has been tested in three cases.

The structure of this paper is as follows: The second section gives the mathematical model of economic dispatch of energy storage system under micro-grid environment and its model transformation. The third section introduces the feasibility analysis and solution process of the model. The fourth section proposes the optimal decision solution. The fifth section gives the numerical test results. And the last section summarizes the full paper.

2. Economic dispatch model of energy storage system in micro-grid

The economic dispatch of energy storage system in micro-grid is a typical multi-stage stochastic programming problem. The main difficulty is to fully consider the non-anticipative constraints of stochastic factors in the scheduling plan.

2.1. Mathematical models

The objective function is constructed on the criterion of minimum scheduling cost of micro-grid. The scheduling cost of micro-grid includes two items, namely, the cost of purchasing and selling electricity in each period in each period. The objective function is expressed as follows:

\[
\min_{E_i, p_i^{ch}, p_i^{dis}, \lambda_i^b, \lambda_i^s} \sum_{t=1}^{T} \tau \cdot \lambda_i^b \cdot \max\{I_t, 0\} + \tau \cdot \lambda_i^s \cdot \min\{I_t, 0\}
\]  

where, \( t, t \in \{1, 2, ..., T\} \) is the index of time periods, \( \tau \) is the length of each period (h), \( \lambda_i^b \) is the purchase price (¥/MWh) of electricity in the period \( t \) from the main grid to micro-grid, \( l_i \) is exchange power of stage gate between main grid and micro-grid (MW), micro-grid gets electricity from main grid when \( l_i > 0 \), micro-grid provides electricity to main grid when \( l_i < 0 \), \( \lambda_i^s \) is the sale price (¥/MWh) of electricity in the period \( t \) from the micro-grid to main grid. By default, the sale price of electricity is not higher than the purchase price of electricity in the same period, that is \( \lambda_i^s \leq \lambda_i^b \).

The objective function should satisfy the following constraints:

1) Power balance constraint

\[
l_i = d_i + p_i^{ch} - p_i^{dis} - (w_i - w_i^{cw})
\]  

where, \( d_i \) is the load demand (MW) in the period \( t \), \( p_i^{ch} \) is the charging power (MW) of energy storage equipment in the period \( t \), \( w_i \) is the photovoltaic power (MW) in the period \( t \), \( w_i^{cw} \) is the photovoltaic power curtailment (MW) in the period \( t \), \( p_i^{dis} \) is the discharging power (MW) of energy storage equipment in the period \( t \).

2) Stage gate power constraint

\[
l_L \leq l_i \leq l_U
\]  

where, \( l_L \) is the lower limit of the stage gate power (MW) between the main grid and micro-grid in the period \( t \), \( l_U \) is the upper limit of the stage gate power (MW).

3) Energy storage constraint for adjacent periods of energy storage equipment

\[
E_i = E_{i-1} + (\eta_c p_i^{ch} - \frac{1}{\eta_d} p_i^{dis}) \tau
\]  

where, \( E_i \) is the energy storage (MWh) at the end of the period \( t \), \( \eta_c \) is the charging efficiency coefficient of energy storage equipment and \( 0 < \eta_c < 1 \), \( \eta_d \) is the discharging efficiency coefficient of energy storage equipment and \( 0 < \eta_d < 1 \).

4) Energy storage constraint of energy storage equipment
where, $E_i$ is the lower limit of the energy storage (MWh) at the end of the period $t$, $E_i$ is the upper limit of the energy storage (MWh) at the end of the period $t$.

5) Charging and discharging power constraints of energy storage equipment

$$\eta_i p_{i}^{ch} \leq \Delta^+, \frac{1}{\eta_d} p_{i}^{dis} \leq \Delta^-$$

$$p_{i}^{ch} \geq 0, p_{i}^{dis} \geq 0, p_{i}^{ch} \cdot p_{i}^{dis} = 0$$

where, $\Delta^+, \Delta^-$ are the upper limit of charging and discharging power of energy storage (MW). Here’s the illustration: there is always one between $p_{i}^{ch}$ and $p_{i}^{dis}$ that should be zero. When $p_{i}^{ch} = 0, p_{i}^{dis} \neq 0$, the energy storage equipment has discharged in the period $t$; when $p_{i}^{ch} \neq 0, p_{i}^{dis} = 0$, the energy storage equipment has charged in the period $t$.

There are two random variables in the model. One is load demand $d_i$:

$$d_i \leq d_i \leq \bar{d}_i$$

where $d_i$ is the lower limit of load demand (MW), $\bar{d}_i$ is the upper limit of load demand (MW) in the period $t$, $0 \leq d_i \leq \bar{d}_i$.

The other is photovoltaic power $w_i$:

$$w_i \leq w_i \leq \bar{w}_i$$

where, $w_i$ is the lower limit of photovoltaic power (MW), $\bar{w}_i$ is the upper limit of photovoltaic power (MW) in the period $t$, $0 \leq w_i \leq \bar{w}_i$.

In the problem of economic dispatch of energy storage system in micro-grid, the decision-making process of each period is as follows: On the premise of knowing the realization value of load demand power $d_i$ and photovoltaic power $w_i$ and the energy storage of the last period $E_{i-1}$, the optimal decision is made on the energy storage $E_i$ at the end of this period, so that the charging power $p_{i}^{ch}$ or discharging power $p_{i}^{dis}$ of energy storage equipment and the optimal decision of gate power $l_i$ can be obtained. Decision process is shown in Figure 1.

![Figure 1. Decision process of energy storage system in micro-grid](image)

Therefore, this paper proposes that only the optimal $E_i^*$ needs to be searched with the breakthrough of this problem $E_i$. Furthermore, $E_i$ and $w_i^{cw}$ are taken as decision variables, especially $E_i$ as core decision variable. And $l_i$, $p_{i}^{ch}$, $p_{i}^{dis}$ and $w_i^{cu}$ are taken as state variables to complete the decision-making process. Here is the following constraint on $w_i^{cu}$:

$$0 \leq w_i^{cu} \leq w_i$$

where, $w_i$ is unknown before the period $t$.

2.2. Model transformation

According to (4) and (7) in 2.1, we can obtain:
\[ p_{ch}^i = \max \left\{ 0, \frac{1}{\eta_c \tau} (E_i - E_{i-1}) \right\} \] (11)

\[ p_{dis}^i = \max \left\{ 0, \frac{\eta_t}{\tau} (E_{i-1} - E_i) \right\} \] (12)

Therefore, we know that:

\[ p_{ch}^i - p_{dis}^i = \begin{cases} \frac{\eta_c}{\tau} (E_i - E_{i-1}), & \text{if } E_i \leq E_{i-1} \\ \frac{1}{\eta_c \tau} (E_{i-1} - E_i), & \text{if } E_i \geq E_{i-1} \end{cases} \]

Then we introduce an auxiliary function:

\[ f(x) = \begin{cases} \frac{\eta_c}{\tau} x, & \text{if } x \leq 0 \\ \frac{1}{\eta_t \tau} x, & \text{if } x \geq 0 \end{cases} \]

In Figure 2, we can see that \( f(x) \) is a continuous and strictly monotonically increasing convex function and \( f^{-1}(y) \) is a continuous and strictly monotonically increasing concave function.

![Figure 2. Auxiliary function and its inverse](image)

Then we obtain:

\[ p_{ch}^i - p_{dis}^i = f(E_i - E_{i-1}) \] (13)

Based on the above symbols, constraints (2) - (7) can be changed to:

\[ I_l = d_i + f(E_i - E_{i-1}) - w_i + w_{dis}^i \]

\[ I_l \leq l, E_i \leq E, E_i - \Delta^+ \tau \leq E_i - E_{i-1} \leq \Delta^+ \tau \]

Therefore, the necessary and sufficient conditions for the solution of \( E_i \) and \( w_{dis}^i \) to be feasible in the period \( t \) are as follow:

\[ \begin{cases} I_l \leq d_i + f(E_i - E_{i-1}) - w_i + w_{dis}^i \leq l_i \\ 0 \leq w_{dis}^i \leq w_i \\ E_i \leq E_i \leq E \\ -\Delta^+ \tau \leq E_i - E_{i-1} \leq \Delta^+ \tau \end{cases} \] (14)

By solving (1) and (14), we can obtain the optimal economic dispatch solution of energy storage system in micro-grid.

### 3. Feasibility Analysis and Solution

#### 3.1. Feasibility Analysis

From the first and second formulas in (14), we obtain:
\[
\begin{align*}
\begin{cases}
L_i - d_i + w_i - f(E_i - E_{i-1}) \leq w_i

w_i \leq \bar{L}_i - d_i + w_i - f(E_i - E_{i-1})

0 \leq w_i \leq w_i
\end{cases}
\end{align*}
\]

Therefore, \( w_i \) has a solution if and only if:

\[
\max \{0, L_i - d_i + w_i - f(E_i - E_{i-1})\} \leq \min \{w_i, \bar{L}_i - d_i + w_i - f(E_i - E_{i-1})\}
\]

After simplifying formula (15), we can get:

\[
L_i - d_i \leq f(E_i - E_{i-1}) \leq \bar{L}_i - d_i + w_i
\]

According to the monotony of \( f(\cdot) \), we obtain that:

\[
f^{-1}(L_i - d_i) \leq E_i - E_{i-1} \leq f^{-1}(\bar{L}_i - d_i + w_i)
\]

From this, we can see that for the realization values \( d_i, w_i \) and the energy storage system state \( E_{i-1} \) at the beginning of the period \( t \), the original problem has a solution if and only if the following system has feasible solution to \( E_i \):

\[
\begin{align*}
f^{-1}(L_i - d_i) &\leq E_i - E_{i-1} \leq f^{-1}(\bar{L}_i - d_i + w_i) \\
\bar{E}_i &\leq E_i \leq E_i \\
-\Delta^\tau &\leq E_i - E_{i-1} \leq \Delta^\tau
\end{align*}
\]

After proper transpositions of the terms, formula (19) can be regarded as three sets of upper and lower bounds constraints. The sufficient and necessary condition for the system mentioned above to have feasible solutions is that the intersection of three sets of upper and lower bounds is not empty, that is, the maximum lower bound does not exceed the minimum upper bound:

\[
\max \{E_{i-1} + f^{-1}(L_i - d_i), \bar{E}_i, E_{i-1} - \Delta^\tau\} \leq \min \{E_{i-1} + f^{-1}(\bar{L}_i - d_i + w_i), E_i, E_{i-1} + \Delta^\tau\}
\]

The formula above gives the exact upper and lower bounds of the feasible range of decision variable \( E_i \) for a given \( d_i, w_i, E_{i-1} \).

\( E_i \) is a decision made after knowing \( d_i, w_i \), and \( E_{i-1} \) is a decision made before \( d_i, w_i \) known. Therefore, improper selection of \( E_{i-1} \) may make the formula (20) false. For some realization values of \( d_i, w_i \), the scheduling problem has no solution. So, what kind of \( E_{i-1} \) value can guarantee “full-scenario-feasibility”? In formula (20), min, max parentheses contain three terms, which are equivalent to nine inequalities valid. However, three of them are naturally valid, so only the other six inequalities should be valid:

\[
\begin{align*}
E_{i-1} &\leq \bar{E}_i - f^{-1}(L_i - d_i) \\
f^{-1}(L_i - d_i) &\leq \Delta^\tau
E_i - f^{-1}(\bar{L}_i - d_i + w_i) \leq E_{i-1} \\
E_i - \Delta^\tau &\leq E_{i-1} \\
0 &\leq f^{-1}(\bar{L}_i - d_i + w_i) + \Delta^\tau
E_{i-1} &\leq \bar{E}_i + \Delta^\tau
\end{align*}
\]

where, each formula has a clear physical meaning.

In (21), the first, third, fourth and sixth formulas can be regarded as boundary constraints. In order to make the above formulas valid for any realizations, the monotonicity of functions can be used to obtain:
The second and fifth formulas in (21) can be changed into:

\[
f^{-1}(l_t - d_t) - \Delta^+ \tau \leq 0 \leq f^{-1}(\bar{t}_t - \bar{d}_t + w_t) + \Delta^- \tau
\]

The formula (23) should be valid for each period, therefore the monotonicity of functions can be used to obtain:

\[
f^{-1}(\max_{t \in T} (l_t - d_t)) - \Delta^+ \tau \leq 0 \\
\leq f^{-1}(\min_{t \in T} (\bar{t}_t - \bar{d}_t + w_t)) + \Delta^- \tau
\]

The range of \( E_{t-1} \) is as follows:

\[
\max\left\{ E_{t-1} - \Delta^+ \tau, E_{t-1} - f^{-1}(\bar{t}_t - \bar{d}_t + w_t) \right\} \leq E_{t-1} \\
\leq \min\left\{ E_{t-1} + \Delta^- \tau, E_{t-1} - f^{-1}(l_t - d_t) \right\}
\]

### 3.2. Feasibility Solution

Under the conditions discussed above, the feasible upper and lower bounds of \( E_{t-1} \) can be defined by reverse inversion:

S1. Initialize the parameters. Let \( T = T \). Set the initial values of the feasible upper and lower limit of energy storage equipment: \( E_{T_t}^{true} = E_{T_t}, E_{T_t}^{true} = E_{T_t} \).

S2. Given \( T_t, l_t, \bar{d}_t, d_t, w_t, E_{t-1}, E_{t-1} \) and the feasible upper and lower limit of energy storage for energy storage equipment \( E_{t-1}^{true}, E_{t-1}^{true} \) in the period \( t \), then the feasible upper and lower limit of energy storage in the time period \( t-1 \) can be calculated:

\[
E_{t-1}^{true} = \max\left\{ E_{t-1}^{true} - \Delta^+ \tau, E_{t-1}^{true} - f^{-1}(\bar{t}_t - \bar{d}_t + w_t) \right\} \\
E_{t-1}^{true} = \min\left\{ E_{t-1}^{true} + \Delta^- \tau, E_{t-1}^{true} - f^{-1}(l_t - d_t) \right\}
\]

S3. If \( E_{t-1}^{true} \geq E_{t-1}^{true} \), then let \( t = t-1 \), jump to S2 and execute; otherwise, stop.

According to the inversion algorithm above, the feasible interval of \( E_{t-1} \), which satisfies the full-scenario-feasibility and non-anticipative constraints can be obtained.

### 4. Optimal Decision Solution

As can be seen from the objective function (1) in Section 2.1, in the time period \( t \) the cost

\[
C_t = \tau \cdot \lambda_t^0 \cdot \max\{l_t, 0\} + \tau \cdot \lambda_t^0 \cdot \min\{l_t, 0\}
\]

is a piecewise linear function of \( l_t \), which is shown in the Figure 3.

![Figure 3. Cost function of each period](image-url)
Therefore, the cost of the time period \( t \) is about \( l_t \) monotonically incremented, and when \( l_t \) take the minimum value, the cost of the time period \( t \) is minimized. From (17), we can obtain:

\[
w_t^{\text{true}} = \max \{0, l_t - d_t + w_t - f(E_t - E_{t+1})\}
\]

Combining (14) and (27), we can get:

\[
l_t = \max \{d_t - w_t + f(E_t - E_{t+1}), l_t\}
\]

When \( d_t - w_t + f(E_t^{\text{true}} - E_{t+1}) > l_t \), \( E_t^* = E_t^{\text{true}} \); when \( d_t - w_t + f(E_t^{\text{true}} - E_{t+1}) < l_t \), \( E_t^* = \overline{E}_t^{\text{true}} \); when \( d_t - w_t + f(E_t^{\text{true}} - E_{t+1}) < l_t < d_t - w_t + f(E_t^{\text{true}} - E_{t+1}) \), \( E_t^* = E_{t+1} + f^{-1}(l_t - d_t + w_t) \).

In summary, the optimal solution for energy storage is as follow:

\[
E_t^* = \max \left\{ F_t^{\text{true}}, \min \left\{ E_t^{\text{true}}, E_{t+1} + f^{-1}(l_t - d_t + w_t) \right\} \right\}
\]

(28)

5. Numerical testing

In this section, we build four cases to test the economic scheduling of energy storage system in micro-grid. Test environment: Intel (R) Xeon (R) CPU E3-1226 v3 @ 3.30GHz PC (8GB RAM), MATLAB R2014a.

Considering a micro-grid system with sufficient photovoltaic energy, the installed capacity and maximum photovoltaic output of the photovoltaic power plant can basically meet the peak load demand. However, due to the fluctuation of the photovoltaic power in the day-to-day cycle and the randomness affected by weather conditions, the system is equipped with energy storage equipment to suppress this fluctuation and uncertainty. Consider an economic scheduling problem of 24-period in micro-grid: \( \eta_c = 0.90 \), \( \eta_d = 0.90 \), \( \Delta^+ = 10MW \), \( \Delta^- = 10MW \), \( \overline{E}_t = 280MW \), \( l_t = -30MW \). The upper, lower limit and expectation of load demand power for each period are shown in Figure 4; the upper, lower limit and expectation of photovoltaic power are shown in Figure 5. The price information for each period is shown in Table 1.

The change of load demand, photovoltaic power, the upper and lower limits of energy storage or the upper and lower limits of the stage gate may have an impact on the feasibility, optimality and power decision-making of energy storage equipment. Therefore, we design three cases to test the scheduling results of this method under the circumstances above.

![Figure 4. Load demand power](image)

![Figure 5. Photovoltaic power](image)

| Time period/h | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 |
|---------------|----|----|----|----|----|----|----|----|----|----|----|----|
| \( x_t \)    | 364.7 | 364.7 | 364.7 | 364.7 | 364.7 | 364.7 | 700 | 700 | 700 | 700 | 700 | 700 |
| \( y_t \)    | 349.6 | 349.6 | 349.6 | 349.6 | 349.6 | 349.6 | 635 | 635 | 635 | 635 | 635 | 635 |

| Time period/h | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---------------|----|----|----|----|----|----|----|----|----|----|----|----|
| \( x_t^+ \)   | 700 | 1136 | 1136 | 1136 | 1136 | 700 | 700 | 1136 | 1136 | 1136 | 700 | 700 |
| \( y_t^+ \)   | 635 | 928.4 | 928.4 | 928.4 | 928.4 | 635 | 635 | 928.4 | 928.4 | 928.4 | 635 | 635 |
5.1. Rationality of test results in different scenarios

5.1.1. Scheduling results in the expected scenario. In the expected scenario, the upper and lower limits of energy storage for each time period and the feasible upper and lower limits of energy storage obtained by this algorithm are shown in Figure 6.

According to the information in Table 1, Figure 4, Figure 5 and Figure 6, the economic dispatching problem of energy storage system in micro-grid is solved. The photovoltaic curves with and without curtailment, the energy curves of energy storage equipment at the end of each period, the histogram of stage gate power and the histogram of load demand power are shown in Figure 7. It can be seen that when the load demand power is large, the energy storage equipment discharges, the stage gate power is bigger than 0 or equal to 0, and the electricity is purchased from main grid (e.g. period 7, 17, 20); when the load demand power is small, the energy storage equipment charges, the stage gate power is less than 0 or equal to 0, and the electricity is sold to main grid (e.g. time periods 11, 12). Due to the energy storage equipment reaching the upper limit of energy storage and the stage gate power reaching its lower limit, the photovoltaic curtailment has occurred during the period 13-15. In this scenario, the cost of micro-grid scheduling is 283,056.6 yuan.

5.1.2. Scheduling results in random scenarios.
When the load demand power and photovoltaic power fluctuate greatly, the feasible energy storage area of energy storage equipment in each period is exactly the same as the standard case. Compared Figure 8 and Figure 7, it has a certain impact on energy storage decision-making, photovoltaic power decision-making and gate power decision-making in each period. In this random scenario, load and photovoltaic value fluctuate greatly, and the cost increases, which is 221,849.09 yuan.

5.2. The influence of energy storage’s upper limit on feasibility and economy

5.2.1. The influence of energy storage’s upper limit on feasibility.
When the upper limit of energy storage is 140 MWh, 100 MWh and 60 MWh respectively, the feasible energy storage area of energy storage equipment in each period is obtained as shown in Figure 9. It can be seen that the upper limit of the feasible energy storage area decreases with the decreasing of the upper limit of the energy storage equipment, and the lower limit of the feasible energy storage area decreases obviously in the period of 19-23. Generally speaking, the feasible range of energy
storage becomes smaller. When the energy storage limit of energy storage equipment is less than 55MWh, there is no feasible interval.

![a. The upper limit of energy storage is 140 MW](image1)

![b. The upper limit of energy storage is 100 MW](image2)

![c. The upper limit of energy storage is 60 MW](image3)

Figure 9. The upper limit, lower limit and the feasible interval of energy storage equipment

5.2.2. The influence of energy storage’s upper limit on feasibility. When the upper limit of energy storage equipment changes, the dispatching cost is shown in Table 2. It can be seen that the dispatching cost of micro-grid increases with the decreasing of upper limit of energy storage equipment. From Section 4.2.1, with the upper limit of energy storage becoming smaller, the feasible range of energy storage becomes smaller. Therefore, when the load demand is large and the photovoltaic power is difficult to balance the load, it needs to rely more on buying electricity from the main grid through the gateway, resulting in increased costs. Therefore, choosing energy storage equipment with large energy storage cap can improve the economy of micro-grid dispatching.

| $E_r$ (MWh) | 140 | 120 | 100 | 80 | 60 |
|------------|-----|-----|-----|----|----|
| Cost (¥)   | 2056044.0 | 2069550.3 | 2083056.6 | 2094164.7 | 2105272.7 |

Table 2. Cost under the different upper limits of energy storage equipment

5.3. The impact of gate power’s upper and lower limits on feasibility and economy

5.3.1. The impact of gate power’s upper limit on feasibility. When the upper limit of the gateway is 300 MW and 270 MW respectively, the feasible energy storage area in each period can be obtained as shown in Figure 10. It can be seen that with the decreasing of the upper limit of the gateway, the feasible energy storage area becomes smaller, especially in the period 2-6 and 16-19, the feasible area shrinks obviously. When the upper limit is less than 265 MW, there is no feasible interval.
5.3.2. The impact of gate power’s upper limit on economy. When the upper limit of the gateway is 330MW, 320MW, 310MW and 300MW respectively, the dispatching cost can be obtained as shown in Table 3. It can be seen that with the increasing of the upper limit of the gateway, the dispatching cost of the micro-grid decreases due to the enlargement of the feasible energy storage area; when the upper limit of the gateway power is more than 320MW, the dispatching cost of the micro-grid remains unchanged. Therefore, properly increasing the upper limit of the gateway power can improve the economy of micro-grid scheduling.

Table 3. Cost under the different upper limits of stage gate

| $I_u$ (MWh) | 300   | 310   | 320   | 330   |
|-------------|-------|-------|-------|-------|
| Cost(¥)     | 2086238.1 | 2085382.7 | 2085230.6 | 2085230.6 |

5.3.3. The impact of gate power’s lower limit on economy. When the lower limit of the gateway is -30MW, -40MW and -50MW respectively, the dispatching cost is obtained as shown in Table 4. It can be seen that as the lower limit of the gateway decreasing, the power supplied from the micro-grid to the main grid through the gateway increases, thus the dispatching cost of the micro-grid decreases, and the speed of reduction becomes slower. When the lower limit is greater than or equal to the feasible upper limit of energy storage, the cost will not be reduced. Therefore, the economy of micro-grid dispatching can be improved by reducing the lower limit of the gateway appropriately.

Table 4. Cost under the different lower limits of stage gate

| $I_l$ (MWh) | -30    | -40     | -50     |
|-------------|--------|---------|---------|
| Cost(¥)     | 2083056.6 | 2047514.6 | 2017828.7 |

6. Conclusion

In the problem of economic dispatching of energy storage equipment in micro-grid, considering the non-anticipative constraints of stochastic programming properly is the key to ensure the rational utilization of energy storage system and the least cost of electricity consumption.

In this paper, 1) The economic dispatching model of energy storage system in micro-grid which satisfies the non-anticipative constraints is established, 2) considering the operation constraints of the micro-grid, including the non-anticipative economic dispatching decision, and the constraints of the energy storage system, the objective function is constructed based on the minimum scheduling cost of micro-grid, and the accurate mathematical description is given, 3) the proposed model is solved, and by solving it, we can get the economic dispatching scheme of energy storage system which satisfies the full-scenario-feasibility. Numerical tests show that the model and the algorithm of this paper have good performance, and the important factors affecting the economic dispatching decision of energy storage equipment are analysed, and the conclusion is of great significance to the economic dispatching of energy storage system in micro-grid.

References

[1] National Development and Reform Commission 2017 Renewable energy development “Thirteen-Five” planning (3):5-12.
[2] Yusheng X, Xing L, Feng X and Chen Y 2014 A Review on Impacts of Wind Power
Uncertainties on Power Systems Proceedings of the CSEE 34(29):5029-5040.
[3] Jun L 2013 Status and Trend Analysis on Grid Integration Key Technologies of Renewable Energy Power Generation Shaanxi Electric Power.
[4] Barton J, Infield D 2004 Energy storage and its use with intermittent renewable energy IEEE Trans on Energy Conversion 19(2): 441-448.
[5] Abbey C, Strunz K, Chahwan J and Joos G 2007 Impact and control of energy storage systems in wind power generation Proceedings of the 4th Power Conversion Conference (Nagoya, Japan: IEEE) 1201-1206.
[6] Yin Y, Hongde T, Jiabao G 2010 Application Prospect of Wind-PV-ES Hybrid Power System East China Electric Power.
[7] Wang S, Lai X, Cheng S 2013 An Analysis of Prospects for Application of Large-scale Energy Storage Technology in Power Systems Automation of Electric Power Systems 37(1):3-8+30.
[8] Lasseter R 2002 MicroGrids Power Engineering Society Winter Meeting IEE, 2002:305-308 vol.1.
[9] Denholm P, Ela E, Kirby B and Milligan M 2010 Role of Energy Storage with Renewable Electricity Generation Office of Scientific & Technical Information Technical Reports 48(48):563-575.
[10] Katayoun R, Chinchoy C, Rui Z 2016 Energy Cooperation Optimization in Microgrids with Renewable Energy Integration IEEE Transactions on Smart Grid PP(99):1-1.
[11] Xisheng T, Wei D, Ningning L and Zhiping Q 2012 Control technologies of micro-grid operation based on energy storage Electric Power Automation Equipment 32(3).
[12] Jiajun Z 2013 Research on Coordinated Control Strategies of Micro-sources for Wind/PV/Battery Micro-grid North China Electric Power University.
[13] Rufeng Z, Linquan B, Houhe C, Guoqing L and Fangxing L 2016 Economic dispatch of wind integrated power systems with energy storage considering composite operating costs Iet Generation Transmission & Distribution 10(5): 1294-1303.
[14] Qiaozhu Z, Xuan L, Xuejiao L and Xiaohong G 2016 Transmission Constrained UC with Wind Power: An All-Scenario-Feasible MILP Formulation with Strong Nonanticipativity IEEE Transactions on Power Systems PP(99):1-1.
[15] Wei L, Ning Y, Bo Z, Shaohua M, Yangyang G and Wanqiu X 2018 Economic dispatch of energy storage system in wind farm based on scenario analysis method Advanced Technology of Electrical Engineering & Energy.
[16] Jizhong Z, Pengfei Y, Peizheng X and Pingping X 2017 Comprehensive Economic Dispatch Method with Energy Storage and Wind Power Generation Southern Power System Technology.
[17] Hongjun G, Junyong L, Zhenbo W, Youbo L, Wei W and Xia L 2014 Multi-scenario two-stage dispatch decision-making model for wind farm with integrated energy storage Electric Power Automation Equipment 34(1):135-140.
[18] Christos D, Simone B, Michailidis I and Elias B 2016 Occupancy-based demand response and thermal comfort optimization in microgrids with renewable energy sources and energy storage Applied Energy 163:93-104.
[19] Liwei J, Zhongfu T, Jinyun Y, Qingkun T, Huanhuan L and Fugui D 2016 A bi-level stochastic scheduling optimization model for a virtual power plant connected to a wind-photovoltaic-energy storage system considering the uncertainty and demand response Applied Energy 171:184-199.
[20] Wenjian S 2015 Research on Economic Operation Optimization of Photovoltaic Storage Micro-Grid Shandong University.
[21] Shengwei M, Yingying W and Zhengquan S 2012 Robust economic dispatch considering renewable generation Innovative Smart Grid Technologies Asia.
[22] Binge J 2016 Research on Methodologies of Planning and Operation of Microgrids under Uncertainty Tianjin University.
[23] Ruifeng S, Changhao S, Zhenyu Z and Li Z 2016 A robust economic dispatch of residential microgrid with wind power and electric vehicle integration Control and Decision Conference IEEE, 2016:3672-3676.

[24] Jianbo S, Junli W, Buhan Z 2013 Economic Environmental Dispatch Model of Microgrid Including Redox Flow Battery and Its Application Water Resources & Power 77(44):168-168.

[25] Xiu Y, Jie C, Lan Z, Meixia Z and Haibo W 2013 Optimization allocation of energy storage for microgrid based on economic dispatch Power System Protection & Control 41(1):53-60.

[26] Yiwei M 2016 Economic dispatch optimization method of independent micro-power network based on dual master dynamic collaboration.

[27] Hao W, Yansong W 2016 Economic dispatch of microgrid using intelligent single particle optimizer algorithm Power System Protection & Control.