Ordered charge-discharge and optimal scheduling of energy storage battery

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Abstract. This paper presents a method to coordinate the discharge depth and charge-discharge times. The method is based on the operation strategy of the partial batteries used alternatively. Under certain premise, the concept of ordered charge-discharge is put forward, and the rules of ordered charge-discharge are explained in this paper. According to the relationship between the number of cycle times and the discharge depth, the number of the corresponding power distribution cell is obtained under maximum lifetime. By considering the balance of battery charge-discharge and state of charge, a power allocation strategy based on ordered charge-discharge is proposed, and the operation cost of the battery energy storage system is used as the evaluation index of the optimal scheduling. It is proved that the battery energy storage system under the ordered charge-discharge is more economical than the power sharing system, which shows the advantage of the battery charge-discharge.

1. Introduction

With the rapid development of distributed generation (DG), represented by wind power and photovoltaic power, the demand for energy storage is also increasing [1]. At present, battery is one of the most widely used energy storage devices, but the cost of battery is high, and its life is easy to be affected by the operation condition [2]. Therefore, based on the consideration of economy, reasonable dispatching of energy storage is particularly important.

The energy storage scheduling problem has been studied at home and abroad and has made some achievements. In [3], the daily scheduling strategy has been optimized by adding the mathematical model of each discharge loss of the reaction battery. In [4], it has proposed a control strategy for real-time smooth fluctuation of energy storage system based on the fluctuation degree of power and the charging state of energy storage system, using weighted moving average filtering algorithm, but did not consider the impact of charge-discharge process on life span. According to the proposed control strategy, real-time dynamic energy distribution can be performed on energy storage, taking into account the voltage and current limits of the energy storage system, but the state-of-charge limitation is not considered [5, 6]. In [7], a control strategy for hybrid energy storage has been proposed, which accelerated the acceptance of wind power and reduced the carbon emissions of mixed energy storage. In [8], a two stages scheduling optimization model for wind energy storage with demand response has been established, which used the demand response and the cooperation effect of the energy storage system, the uncertainty of wind power was suppressed and the efficiency of wind power utilization was improved. In [9], a double-layer structure of control strategy has been designed, including the real-time dispatch method of centralized energy storage station(CESS) in the distribution system and
the power allocation method among all the energy storage devices in CESS, but the effect of frequent charge and discharge on battery life has not been considered.

The battery energy storage system may be composed of multiple battery devices, but most of the existing studies are focused on the research on the control method of single battery equipment and there is not much concern about how to distribute power between multiple batteries. In most energy storage scheduling, the battery uses the average power allocation, without taking the effect of charge and discharge on battery life into account, which will result in more frequent charging and discharging of all the batteries, reducing the operating life of the energy storage system. For the deficiencies of the existing research, this paper proposes a method for prolonging the service life of batteries through ordered charge-discharge and optimal scheduling for multiple battery combinations. First, we put forward the concept of ordered charge-discharge under certain condition, and explained the rules of ordered charge-discharge including the balance of battery charge-discharge times and the balanced state of charge. According to the above rules, the optimal scheduling process of battery was worked out. Finally, a microgrid in a certain area was taken as an example. The analysis verifies that the battery energy storage system under the ordered charge-discharge is more economical than the power sharing system, which shows the advantage of the battery charge-discharge.

2. The concept and advantages of ordered charge-discharge

2.1. The concept of ordered charge-discharge

When a system has multiple energy storage devices of the same type that can be separately controlled and used in parallel, it may be considered that according to certain rules and system prediction or real-time storage demand, some or all of these energy storage devices can selectively participate in the power and energy allocation to improve the efficiency of energy storage systems. In this paper, this operation mode of energy storage battery is called ordered charge-discharge.

The ordered charge-discharge rules used in this paper:

1. According to power demand, power is allocated for some batteries.
2. Each battery is alternately used, and the charge-discharge times of battery is balanced.
3. According to the charged state, the priority of charge and discharge is formulated, and the state of charge is balanced.

2.2. The advantages of ordered charge-discharge

There is a nonlinear negative correlation between the charge-discharge times of the battery and the discharge depth. According to statistical data, the relationship between maximum charge-discharge times $N$ and discharge depth $d$ of a lead-acid battery is as follows [10]:

$$N(d) = -3278d^4 - 5d^3 + 12823d^2 - 14122d + 5112$$

According to the above equation, for a single battery, the smaller the depth of the discharge is, the larger the number of charge-discharge times is. However, when a number of batteries having the same capacity are used at the same time, in addition to reducing the discharging depth, it is also possible to reduce the number of times of charge and discharge by using alternately.

Assuming that the energy storage system has $m$ identical batteries, the number of batteries used for rotation is $m_1$. In the ordered charge and discharge mode, after the $x$-th charge-discharge, the actual number of charge-discharge times of each battery is $x_1$, so according to the total charge-discharge times of these batteries, the following equation can be obtained:

$$m_1 \cdot x = m \cdot x_1$$

According to equation (2), under ordered charge-discharge, once charge-discharge for batteries in rotation can be equivalent to $m_1 / m$ times for all batteries in the storage system. The maximum charge-discharge times $N_{OD}$ of the batteries in the storage system under ordered charge-discharge is:
\[ N_{\text{OD}} = N(d') / (m_1 / m) \]  

where \( d' \) is discharge depth of batteries under ordered charge-discharge.

The cycle life of a battery is related to the number of times of charge-discharge cycles, peak current and temperature [11]. The National Renewable Energy Laboratory (NREL) of the U.S. refers to the amount of energy discharged by a battery at the rated discharge rate and rated discharge depth as the Total Effective Throughput \( \varphi_R \) [12], the formula is:

\[ \varphi_R = N_R D_R C_R \]  

where \( N_R \) is the number of charge-discharge times under the rated discharge current and the rated discharge depth, \( D_R \) is the rated discharge depth, \( C_R \) is the rated capacity of the battery. Each discharge can be converted to the effective throughput. When the effective throughput accumulatively achieves the total effective throughput, it is considered that the battery is scrapped [13]. The effective throughput of each discharge is related to the actual discharge depth and discharge current, the formula is [14]:

\[ \varphi_{\text{eff}} = \left( \frac{d}{D_R} \right)^{r_0} e^{r_1 \left( \frac{d}{D_R} - 1 \right)} \frac{C_R}{C_E} \varphi_{\text{act}} \]  

where \( C_E \) is actual discharge capacity, \( r_0 \) and \( r_1 \) are fitting parameters, which can be fitted according to the relationship between the discharge depth and charge discharge times provided by the manufacturer, \( \varphi_{\text{act}} \) is ampere-hours under actual discharge current.

Under ordered charge-discharge, the effective throughput of each discharge of batteries allocated power is \( \varphi_{\text{eff}}(d') \). The effective throughput under ordered charge-discharge is as follows:

\[ \varphi_{\text{eff,OD}} = \left( \frac{d}{D_R} \right)^{r_0} e^{r_1 \left( \frac{d}{D_R} - 1 \right)} \frac{C_R}{C_E} \varphi_{\text{act}} \left( \frac{m_1}{m} \right) \]  

Assuming that the battery has \( n \) times of charge-discharge during the operation cycle \( T \), its lifetime \( Y_B \) can be expressed as [13]:

\[ Y_B = \frac{\varphi_R}{\sum_{i=1}^{n} \varphi_{\text{eff}}(i) / T} = \frac{N_R D_R C_R}{\sum_{i=1}^{n} \varphi_{\text{eff}}(i)} T \]  

Furthermore, the battery life under ordered charge-discharge can be expressed as:

\[ Y_{\text{BOD}} = \frac{N_R D_R C_R}{\sum_{i=1}^{n} \varphi_{\text{eff,OD}}(i)} T = \frac{\sum_{i=1}^{n} \varphi_{\text{eff}}(i)}{\sum_{i=1}^{n} \varphi_{\text{eff,OD}}(i)} Y_B \]  

Under average power allocation and ordered charge-discharge, the comparison of cycle life of a lead-acid battery corresponding to different number of batteries allocated power is shown in figure 1. It can be seen that for a certain number of batteries allocated power, the cycle life under ordered charge-discharge is larger than that of average power allocation, and the maximum value exists.

Thus, under the ordered charge-discharge, the battery life has the maximum value with the change of the number of batteries. Certain battery quantity and power demand form a certain charge and discharge depth. Therefore, there exists the best charge and discharge depth, which corresponds to the
maximum cycle life of the battery. The number of batteries \( m_i \) corresponding to the maximum cycle life of the battery \( \text{max}(Y_{\text{BOD}}) \) is used as the reference value of the number of batteries allocated power, so that the battery operates under the optimal charge and discharge depth, which provides a theoretical basis for the realization of optimal scheduling.

![Figure 1. Comparison chart of cycle life.](image1)

![Figure 2. Charge state partition of the battery.](image2)

3. The realization of optimal scheduling

Based on the idea of ordered charge-discharge, this paper proposes an optimized scheduling method to coordinate the discharge depth and charge and discharge times. Two rules have been considered, one is the balance of battery charge-discharge times, and the other one is the balance of charge state. Based on the above rules, priority is established to achieve optimal scheduling of energy storage system.

The use of sections to divide the text of the paper is optional and left as a decision for the author. Where the author wishes to divide the paper into sections the formatting shown in table 2 should be used.

3.1. Priority setting based on the balance of battery charge-discharge times

(1) According to the 2.2, the reference value of the power cell in each period is determined.

(2) The charge-discharge times of batteries are counted, and priority of the battery is determined by the charge-discharge times, and the power is allocated to the batteries according to priority.

(3) The batteries allocated are recorded, batteries are put into use alternatively in order to balance the battery charge-discharge times.

3.2. Priority setting based on the balance of charge state

As described in Section 2.2, the charge-discharge depth has great influence on the cycle life of battery. Therefore, as far as possible, we should try to limit the overcharge and overdischarge of the battery. This paper divides current charge state of battery \( S_{\text{OC}} \) into five state intervals. As shown in figure 2, the five intervals is as follows: overdischarge interval \( [0, S_{\text{OCmin}}] \), sub discharge interval \( [S_{\text{OCmin}}, S_{\text{OCmin}]} \), optimal charge-discharge interval, sub charge interval \( [S_{\text{OCmin}}, S_{\text{OCmax}}] \), overcharge interval \( [S_{\text{OCmax}}, S_{\text{OCmax}}] \). Among them, \( S_{\text{OCmax}} \) and \( S_{\text{OCmin}} \) are the upper and lower limits of the charge state of the battery respectively, \( S_{\text{OCmax}} \) and \( S_{\text{OCmin}} \) are the upper and lower limits of the optimal charge state respectively.

In order to make the battery charge and discharge in the optimal charge-discharge interval, the charge-discharge margin corresponding to the five states of the battery is as follows [9]:

\[
\begin{align*}
S_{\text{OC}} &= 1, \\
S_{\text{OCmin}} &= S_{\text{OCmax}}, \quad \text{Overcharge interval} \\
S_{\text{OCmin}} &= S_{\text{OCmax}}, \quad \text{Optimal charge-discharge interval}
\end{align*}
\]
State 1: \( S_{OC} \) is in overdischarge interval \([0, S_{OCmin}]\). The charge margin \( \varepsilon_{c1} \) and discharge margin \( \varepsilon_{d1} \) are as follows:

\[
\begin{align*}
\varepsilon_{c1} &= S_{OCmax}' - S_{OC} \\
\varepsilon_{d1} &= 0
\end{align*}
\]  

(9)

State 2/3/4: \( S_{OC} \) is in sub discharge interval \([S_{OCmin}, S_{OCmax}]\), optimal charge-discharge interval, sub charge interval \([S_{OCmin}', S_{OCmax}']\). The charge margin \( \varepsilon_{c2}/\varepsilon_{c3}/\varepsilon_{c4} \) and discharge margin \( \varepsilon_{d2}/\varepsilon_{d3}/\varepsilon_{d4} \) are as follows:

\[
\begin{align*}
\varepsilon_{c2}/\varepsilon_{c3}/\varepsilon_{c4} &= S_{OCmax}' - S_{OC} \\
\varepsilon_{d2}/\varepsilon_{d3}/\varepsilon_{d4} &= S_{OC} - S_{OCmin}'
\end{align*}
\]  

(10)

State 5: \( S_{OC} \) is in overcharge interval \([S_{OCmax}, 1]\). The charge margin \( \varepsilon_{c5}/\varepsilon_{c3}/\varepsilon_{c4} \) and discharge margin \( \varepsilon_{d2}/\varepsilon_{d3}/\varepsilon_{d4} \) are as follows:

\[
\begin{align*}
\varepsilon_{c5} &= 0 \\
\varepsilon_{d5} &= S_{OC} - S_{OCmin}'
\end{align*}
\]  

(11)

3.3. Optimization of scheduling and implementation process

1. The battery’s charge state \( S_{OC} \), charge-discharge times \( N \), charge-discharge depth \( d \), rated capacity \( E \), rated power \( P \) and quantity \( x \) are initialized.

2. The daily forecast of the load is carried out, and the dispatching power of the battery energy storage system is obtained by averaging the predicted data in the scheduling cycle.

3. In order to prevent the sudden change of power caused by the prediction error, it is judged whether the current \( dP/dt \) is greater than the limit of power change. If the \( dP/dt \) exceeds the limit, the average power allocation is adopted; if it is less than the power change, the ordered charge-discharge is adopted;

4. According to the priority of charge-discharge times and charge state, using ordered charge-discharge scheduling battery to distribute power.

Specific scheduling flow chart is shown in figure 3.

4. Evaluation index of optimal scheduling effect

In this paper, the operating cost \( C \) of the battery energy storage system is regarded as the evaluation index of the optimal scheduling, and the operating costs include the cost of loss \( C_L \), the cost of maintenance \( C_M \) and the cost of punishment \( C_S \):

\[
C = C_L + C_M + C_S
\]  

(12)

1. the cost of loss

The cost of loss of the battery energy storage system is mainly related to the effective throughput \( \varphi_{eff} \) and battery purchase cost \( C_p \) in the scheduling cycle, the specific expressions are as follows:

\[
C_L = \sum_{i=1}^{M} \varphi_{eff}(i,j)C_{pi}
\]  

(13)

\[
C_p = c_e E + c_p P
\]  

(14)
where $M$ is the quantity of batteries, $n_h$ is the charge-discharge times of battery in the $h$-th scheduling cycle, $\varphi_{hi}(i,j)$ is the effective throughput of the $i$-th battery during the $j$-th charge and discharge processes, $c_e$ and $c_p$ is the capacity cost coefficient and the power cost coefficient of energy storage.

(2) the cost of maintenance

The maintenance cost $C_m$ is mainly related to battery types, charge and discharge conditions and battery aging, the specific expressions is as follow:

$$C_M = \sum_{i=1}^{M} \sum_{j=1}^{n_h} (\int_{0}^{t} k_M \cdot P_j \, dt)(1 + \alpha)^{n_{ij}/N_{SBij}}$$

(15)

where $k_M$ is the maintenance coefficient of battery, $P_j$ is the absolute value of active power of charge-discharge of the $i$-th batteries after the $j$-th charge-discharge, $\alpha$ is the aging coefficient, $n_{ij}$ and $N_{SBij}$ are the number of charge-discharge times and total charge-discharge cycles of the $i$-th battery after the $j$-th charge-discharge, $t$ is the scheduling cycle.

![Flow chart of battery scheduling based on ordered charge and discharge.](image)

(3) the cost of punishment

The cost of punishment $C_S$ is related to the price of wind and electricity and the cost of power shortage, which can be calculated by the following formula:

$$C_S = \sum_{j=1}^{m} k_{PE} E_j$$

(16)

where $k_{PE}$ is the punishment coefficient of unit quantity of electricity, which is related to the cost of wind, light and electricity, $E_j$ is the discarded wind/light amount or lack of electricity under the $j$-th loss, $m$ is the total number of times of discarding scenery and power shortage in the scheduling cycle.

5. Example analysis

5.1. Data and model parameters

Taking a microgrid as an example, the correctness and validity of the above models are verified and analyzed. With 1h as the scheduling period and 1d as the scheduling cycle, the number of scheduled periods is 24. The battery energy storage system uses a lead-acid battery with a rated total capacity of 10MW h and a rated power of 5MW. It is composed of 20 battery units with rated capacity of 500kW·h and the rated power of 250kW. Other parameters in the model are selected as shown in table 1 [9, 15]. The net load obtained from the power and load data of the microgrid is shown in figure 4.
### Table 1. Parameter selection in the models.

| Parameter | Physical meaning | Value |
|-----------|------------------|-------|
| $s_{OC\text{min}}$ | the lower limits of the charge state | 0.1 |
| $s_{OC\text{max}}$ | the upper limits of the charge state | 0.9 |
| $c_e$ | the capacity cost coefficient/(yuan/kW·h) | 640 |
| $c_p$ | the power cost coefficient/(yuan/kW) | 270 |
| $k_M$ | the maintenance coefficient | 0.15 |
| $\alpha$ | the aging coefficient | 1 |
| $k_{pl}$ | the punishment coefficient of unit quantity of electricity/(yuan/kW·h) | 0.8 |

![Figure 4. Optimization results.](image)

#### 5.2. Optimization process and result

The model is solved by the above method. The optimization results are shown in figure 4, which are the load of the system, the dispatching power, the number of batteries allocated power and the average discharge depth in the dispatching period.

Table 2 is the optimal result of ordered charge-discharge and power sharing when the optimal charge and discharge threshold is 0.4. It can be seen that the operating cost of energy storage system under the ordered charge-discharge is smaller than that of the average power allocation, because even the average charge and discharge depth of the average power allocation is smaller, but the average charge-discharge times of the battery is much larger than that of the ordered charge-discharge. This verifies the advantage of ordered charge-discharge in energy storage operation, and also reflects the effect of keeping batteries charge and discharge in the optimal charge and discharge area.

### Table 2. Optimization results.

| Parameter | The result of ordered charge-discharge | The result the average power allocation |
|-----------|---------------------------------------|----------------------------------------|
| Average battery charge-discharge times | 2.2500 | 24 |
| Average battery charge-discharge depth | 0.1476 | 0.0261 |
| $C_L$/yuan | $9.4321*10^4$ | $9.7808*10^4$ |
| $C_M$/yuan | $8.8512*10^4$ | $3.0514*10^4$ |
| $C_V$/yuan | $1.0215*10^5$ | $1.2357*10^5$ |
| $C$/yuan | $1.0327*10^5$ | $1.0983*10^5$ |
6. Conclusions
According to the relationship between discharge depth and cycle life of batteries, an ordered charge-discharge method based on partial batteries used alternatively to coordinate discharge depth and charge-discharge times. The power distribution of the battery under ordered charge-discharge is realized by the balance of the charge-discharge times of batteries and the limitation of the discharge depth, and the economy of the system is evaluated by the operating cost of the battery energy storage system. The calculation results show that the operating cost of the energy storage system under ordered charge-discharge is smaller than that of the average power allocation, which proves the advantage of ordered charge-discharge. However, under the scheduling strategy proposed in this paper, the initial state of charge is limited, and the energy storage system with heterogeneous batteries has not been considered, and which can be further improved in subsequent research.

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