Optimal Allocation Method of Energy Storage Considering Probability Distribution of New Energy Power Fluctuation

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Abstract. With constantly increased penetration of new energy power generation such as wind and pv, it has imposed the challenges on operation and control of power systems due to power fluctuations. In order to reduce the influences, an optimal allocation method of energy storage considering probability distribution of new energy fluctuation is proposed. The probability distribution characteristics of different time-scale power fluctuations of new energy power are obtained by probability statistics. According to the probability distribution characteristics and fluctuation index, a probability indicator calculation model which contains time-scale and fluctuation amplitude is set up. The model is then solved by iterative calculations to get minimum compensation power of the required energy storage. Thus, its rated power, capacity and initial state of charge are calculated. This method only compensates the fluctuated power that does not meet the fluctuation index, and has no impact on the power already satisfied. Through calculation and analysis using the data measured from a 50MW photovoltaic power station, the method is proved to be correct and effective.

Keywords: new energy, power fluctuation, probability, energy storage, optimal allocation.

1. Introduction
At present, there are mainly two kinds of methods to smooth the output power fluctuation of new energy. One is to improve the self-control system of new energy\textsuperscript{[1]}, which will sacrifice the active power output of new energy and is affected by the control capacity and resources of the unit. Second, the energy storage system (ESS) is used to compensate and adjust the power fluctuation of new energy. Through the rapid charging and discharging capacity of energy storage, the power leveling is more flexible, and there is no need to change the control of the unit, which has become one of the effective means to solve the power fluctuation of new energy\textsuperscript{[2-12]}. According to present research, realization of the fluctuation limit index by ESS is no longer a technical problem, but the power and capacity of ESS are most larger, and the output power is more or less phase shift. So, due to the high cost of ESS, how to reduce the energy storage capacity at the same time of fluctuation smoothing become the key technical problems to be resolved.
An optimal allocation method of energy storage considering probability distribution of new energy fluctuation is proposed in this paper. And through calculation and analysis using the data measured from a 50MW photovoltaic power station, the method is proved to be correct and effective.

2. Probability analysis of new energy power fluctuation

The goal of smoothing the output power fluctuation of new energy with energy storage is to make the output active power fluctuation connected to the grid meet certain requirements. The maximum variation of the output active power of new energy power station within a certain time scale $T$ is defined as follows:

$$\Delta P_T = \max P(\tau) - \min P(\tau), \tau \in [t-T, t)$$  \hspace{1cm} (1)

where: $T$ is the time window, available for 1min, 10min, etc. $\max P(\tau)$, $\min P(\tau)$ respectively are the maximum and minimum output power in the continuous time period $T$, and $\Delta P_T$ are the maximum power variation in the time period $T$.

According to formula (1), the $T$ time-scale power fluctuation is a discrete random variable, the probability of each possible value of the variable is calculated, and the obtained result is the distribution law of the fluctuation, as follows:

$$p(\Delta P_{i}) = \frac{\text{Num}_i(\Delta P_i)}{N}$$  \hspace{1cm} (2)

where, $\Delta P_{i}$ is the $i$ value of power fluctuation ($i = 1, 2, ..., N$ ), $p(\Delta P_{i})$ is the probability of $\Delta P_{i}$, $\text{Num}_i(\Delta P_i)$ is the number of power fluctuation equal to the $i$ value, meets $0 \leq p(\Delta P_{i}) \leq 1$, $\sum_{i=1}^{N} p(\Delta P_{i}) = 1$, and $N$ is the number of discrete variables.

The cumulative probability distribution of power fluctuation at $T$ time scale is as follows:

$$F(\Delta P_{j}) = P(\Delta P_{j} \leq \Delta P_{j}) = \sum_{i=1}^{j} p(\Delta P_{i}) = \frac{1}{N} \sum_{i=1}^{j} \text{Num}_i(P_i \leq \Delta P)$$  \hspace{1cm} (3)

where: $\Delta P_{j}$ is the $j$ value of power fluctuation, $1 \leq j \leq N$.

According to formula (2) and (3), the probability distribution and cumulative probability distribution of new energy output power variation in a cycle can be computed, so the original power characteristics is obtained. If the characteristics meet the requirement of interconnection, the energy storage not need, otherwise, the energy storage should be configured to smooth the power fluctuation.

3. Energy storage optimal configuration method

3.1. Optimal configuration model

If the probability that the maximum power fluctuation of $T$ time scale is less than a constant is reached, the cumulative probability distribution of the maximum power fluctuation of $T$ time period of new energy should meet the following formula:

$$\frac{1}{N} \sum_{i=1}^{j} \text{Num}_i[(\max P(\tau) - \min P(\tau)) \leq \Delta P] \geq \alpha$$  \hspace{1cm} (4)

where: select the value equal to or less than the value closest to the limit value.

The process of solving equation (4) through iterative calculation are as follows:

(1) Calculate the cumulative probability distribution of the output power fluctuation according to formula (3). If $F(\Delta P) \geq \alpha$, it doesn’t need to configure the energy storage. Otherwise, the energy storage needs to be configured, and the next step is to compensate the $\max P(\tau)$ and $\min P(\tau)$ that does not meet the requirements;
When $\Delta P_T > \Delta P$, adjust the maximum and minimum power values corresponding to the T time-scale fluctuation to compensate, set the maximum power value to reduce $\Delta P_c$ (energy storage charging power), and the minimum power value to increase $\Delta P_d$ (energy storage discharge power), so that the adjusted fluctuation quantity meets the following formula:

$$\left( \max P(\tau) - \Delta P_c \right) - \left( \min P(\tau) + \Delta P_d \right) \leq \Delta P$$

(5)

In order to minimize the compensation power required for energy storage, and the configuration capacity meets the constraint of the balance of charge and discharge in a data cycle, that is, according to formula (5), the minimum compensation easily obtained is:

$$\Delta P_c = \Delta P_d = \frac{(\Delta P_T - \Delta P)}{2}$$

(6)

After adjusting the power, recalculate and check whether the power change in the time scale T meets the limit requirement. If so, increase the number by 1; if not, continue to adjust until meets.

According to the above calculation, the reference compensation power value of energy storage can be obtained as $P_{E,i}[i]$, which is the output power of the power converter system (PCS).

### 3.2. The energy storage rated power and capacity calculation

After the energy storage reference compensation power is obtained, it still needs to be considered the following factors to calculate the rated power and capacity of energy storage.

1. Charging and discharging efficiency constraint

With the energy storage discharge power as positive and the charging power as negative, the output power of the energy storage body considering the charge-discharge efficiency is as follows:

$$P_E[i] = \begin{cases} P_{E0}[i] & \text{if } P_{E0}[i] \geq 0 \\ (1 - \eta_d) P_{E0}[i] & \text{if } P_{E0}[i] < 0 \end{cases}, \quad i = 1, 2, \ldots, N$$

(7)

where, $P_E[i]$ is the actual charge-discharge power of energy storage, $P_{E0}[i]$ is the reference charge-discharge power of energy storage obtained after probability calculation, $\eta_d$ is the discharge efficiency, $\eta_c$ is the charging efficiency, and $N$ is the number of sampled data.

2. Energy storage SOC constraint

In real-time operation, the real-time charging state of the energy storage system should meet:

$$SOC_{max} \leq SOC = SOC_0 - \left( \frac{\sum_{i=0}^{N} P_E[i]}{3600} \right) / E_N \leq SOC_{max}$$

(8)

Among them: $E_N$ is the energy storage rated capacity, $SOC_0$ is the initial state of charged, $SOC_{max}$ and $SOC_{min}$ are respectively the charged state of minimum and maximum allowed.

3. The rated power value

Throughout the cycle, energy storage needs to compensate the maximum absolute value, that is the energy storage power rating:

$$P_{EN} = \max \left\{|P_E[n]|\right\}$$

(9)

4. The rated capacity and initial state of energy storage calculation

According to the constraint conditions of equations (7) and (8), the following can be obtained:
\[
E_N = \frac{\max\{E[n]\}}{SOC_0 - SOC_{low}}
\]
\[
E_N = \frac{\left|\min\{E[n]\}\right|}{SOC_{up} - SOC_0}
\]
\[
0 \leq \min\{E[n]\} \leq -N \leq \max\{E[n]\} \leq 0
\]

The rated capacity and initial state of charge are solved as follows:

\[
E_N = \frac{\max\{E[n]\} + \left|\min\{E[n]\}\right|}{SOC_{up} - SOC_{low}}
\]

(11)

\[
SOC_0 = \frac{\max\{E[n]\}SOC_{up} - \min\{E[n]\}SOC_{low}}{\max\{E[n]\} - \min\{E[n]\}}
\]

(12)

4. Case study

Taking the actual output of a 50MW large photovoltaic power station as an example, take the power generation data from 6 AM to 18 PM on any given day, as shown in figure 1. The sampling period is 1s. Assuming the charge and discharge efficiency of energy storage is 0.95, the upper and lower limit of SOC is 0.9 and 0.1. According to the current standard, 1min and 10min time scales are respectively taken to analyze the output fluctuation of power for energy storage configuration.

![Figure 1. PV output, ES power and grid power.](image)

According to equations (1) - (3), the maximum active power variation of the pv power station at 1min and 10min stages is calculated respectively, as shown in figure 2. It can be seen that the maximum variation value of the 1min active power is about 6.5 MW, and the volatility is 13%, exceeding the standard limitation. The maximum variation value of 10min active power is about 12.59 MW, and the volatility is 25.2%, which does not exceed the standard limitation. Therefore, it is necessary to configure energy storage to smooth the 1min active power fluctuation of the power.

The probability distribution and cumulative probability distribution of the maximum active power variation at 1min were shown in figure 3. It can be obtained that the probability of the 1min active power fluctuation that exceed the limitation is 0.25%.
In order to verify the influence of the fluctuation index of different time scales on the energy storage configuration capacity, the maximum active power variation of 1 min and 10 min was respectively taken.
as different limits to solve the corresponding compensation power of energy storage and configuration capacity, typical values are shown in table 1.

Table 1. ES allocation corresponding to different time-scale and fluctuation indexes.

| variables | Fluctuation limitation $\Delta P/(MW)$ | Fluctuation ratio $Fr/(%)$ | 1min rated power $PEN/(MW)$ | 10min rated power $PEN/(MW)$ | 1min rated capacity $EN/(MWh)$ | 10min rated capacity $EN/(MWh)$ |
|-----------|--------------------------------------|---------------------------|-----------------------------|-------------------------------|-------------------------------|-------------------------------|
| values    | 5                                    | 10                        | 0.73                        | 5.92                          | 0.006                         | 0.6                           |
|           | 4                                    | 8                         | 1.59                        | 6.6                           | 0.021                         | 0.74                          |
|           | 3                                    | 6                         | 2.59                        | 7.26                          | 0.048                         | 0.91                          |
|           | 2                                    | 4                         | 3.43                        | 7.29                          | 0.125                         | 2.45                          |
|           | 1                                    | 2                         | 4.97                        | 8.41                          | 0.296                         | 34.86                         |
|           | 0.5                                   | 1                         | 6.59                        | 14.15                         | 0.5                           | 100.72                        |

The energy storage capacity curves corresponding to different volatility indicators are shown in figure 4 and figure 5. As can be seen, for the same output power, 1min short time scale fluctuation and suppression have a large demand for energy storage power, and the total charge and discharge energy is small. The charge and discharge time is minute or second, so it is necessary to select a power-type energy storage system capable of frequent charge and discharge switching. Fluctuations in 10 min demand for more energy storage capacity, the increase of the time scale in the growth of demand for energy storage capacity is greater than demand for power, as more and more small amount of volatility index, energy storage capacity increase jump, so for a long time scale volume of volatility is low, the combination of power and energy hybrid energy storage system is necessary.

Figure 4. 1min power and capacity.  
Figure 5. 10min power and capacity.

5. Summary
Based on the method and case results, the following conclusions can be drawn:

(1) The method proposed in this paper gives consideration to both the time scale and amplitude of fluctuations, and only compensates the power value that does not meet the volatility index, but does not affect the power value that meets the conditions. The smoothed grid-connected power will not be offset, and the required energy storage power and capacity are minimal.

(2) For the same pv output power, short time scale fluctuations demand for large energy storage power, it is necessary to choose the power type energy storage system that can be frequently switched between charge and discharge; There is a large demand for energy storage capacity for long time scale fluctuations, so energy-type energy storage system should be selected.
(3) The increase in the growth of demand for energy storage capacity is greater than the growth of demand for power, in the long time scales as smaller and smaller amount of volatility index, the increase of the energy storage capacity will be jump, so for a long time scale, the combination of power and energy hybrid energy storage system should be selected.

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