Optimal design of energy storage capacity of distributed photovoltaic microgrid based on random error model

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Abstract. The allocation of capacity of distributed photovoltaic energy storage System has always been an urgent problem to be solved, and reasonable capacity allocation plays an important role in stabilizing the power fluctuation of PCC node and smoothing the load output. In order to reasonably configure energy storage, this paper establishes an energy storage model based on the analysis of random error, which combines load prediction error and the randomness of photovoltaic output prediction error to meet the characteristics of normal distribution, and estimates the random error not considered by the original model, so that the results calculated by the model are more accurate. Combining with the example of the Liaoning branch of China Tower, and the capacity configuration of the photovoltaic energy storage system is verified by combining its load power and photovoltaic power curve.

1. Introduction
China has the largest number of thermal power plants in the world, which poses a huge challenge to air quality [1]. New energy power generation came into being, photovoltaic power generation, hydropower generation, tidal energy, nuclear energy has developed rapidly in recent years, photovoltaic power generation due to its own clean, environmentally friendly renewable, flexible and other advantages quickly became the main force in new energy power generation [2]. Distributed photovoltaics are generally built in the load center [3], and the generated electric energy are directly absorbed by the load, saving huge costs such as long-distance transmission lines and towers, and reducing energy loss during transmission lines [4-5]. Since distributed photovoltaic power generation is suitable for combination with buildings and can save a lot of land resources, in recent years, the installed capacity of distributed photovoltaics has been greatly improved. The rational allocation of the capacity of the energy storage system is the key to establish a distributed photovoltaic microgrid. The traditional energy storage model only considers photovoltaic power generation output (PGE) and system load power consumption (PCO) to configure the capacity of the photovoltaic energy storage system. Neglecting the photovoltaic output and load consumption capacity is susceptible to weather, temperature, and even policy, so it is difficult to accurately predict, which will lead to a large deviation between the capacity configuration and the theoretical value.

The on-site field survey of the roof of Liaoning Tower office building is about 1215 square meters, which is suitable for building truss structure photovoltaic power generation system. And the energy storage system model was established according to the literature [6], because both photovoltaic output and load power have randomness and volatility. [7-8]

Since the photovoltaic output and load power are affected by various meteorological and uncertain factors, considering the photovoltaic output and load consumption capacity error both conform to the
normal distribution, the central limit theorem is used to analyze the error of the established model and accurately calculate the result.

Combining the load power curve and photovoltaic power curve of China Tower Liaoning Branch [9-10], analyze various off-grid modes, [11] determine the capacity design of energy storage system. Combined with its load power curve, the correctness of the capacity allocation of the PV energy storage system is verified.

2. Photovoltaic energy storage capacity configuration scheme

2.1. Analysis of photovoltaic energy storage system

To configure the capacity of the PV energy storage system, the energy storage mode should be selected first. The appropriate energy storage mode plays a key role in smoothing the load output, maintaining the power grid power stability and reducing the energy storage cost.

According to the way of energy storage, it is mainly divided into: physical energy storage, chemical energy storage, and electromagnetic energy storage. According to the energy storage performance, it is mainly divided into: energy density type and power density type.

The advantage of the energy density type is that the capacity of the energy storage system is large, and there is still a long battery life when working in the off-grid mode. The power density type energy storage system is charged and discharged very quickly, and can quickly adjust the PCC of the power grid.

Through the comparison of several energy storage methods in the above table, it can be seen that: flywheel energy storage, superconducting energy storage, lithium ion battery energy storage power density is high, can suppress power fluctuations in a short time, suitable for maintaining the stability of power system.

Lithium-ion battery energy storage, sodium-sulfur battery energy storage has good off-grid working ability, comprehensive analysis can be concluded that lithium-ion battery energy storage can ensure high power density, maintain the stability of the power system.

Good energy density ensures that the energy storage system can operate stably in off-grid mode. Therefore, the energy storage system was selected as the lithium ion battery for energy storage.

3. Energy storage capacity configuration based on contingent error model

3.1. Photovoltaic energy storage system modeling

The distributed PV energy storage system consists of distributed photovoltaic array, DC-DC conversion system, inverter control system and energy storage system. The energy storage system has three modes of operation: the grid-connected mode, the energy storage mode and the off-grid mode. As shown in Figure 1 below:
Figure 1. Scheme of distributed arrangement of energy storage.

When the photovoltaic power generation output \((P_{GE})\) is greater than the system load power consumption \((P_{CO})\), \(P_{SU}=P_{GE}-P_{CO}\). The control system sends the remaining energy \((P_{SU})\) into the energy storage system in an energy storage mode. When the photovoltaic power generation \((P_{GE})\) is insufficient to provide the power consumed by the system load \((P_{CO})\), the additional power required by the load will be transferred from the grid to the load by the grid, called the delivery power \((P_{TR})\).

\[
P_{TR}=P_{CO}-P_{GE} \quad (1)
\]

The system is now in the grid mode. The photovoltaic energy storage system will be affected by various factors, such as temperature, weather and wind speed in actual operation. The above mentioned \(P_{TR}\) can be called calculating the transmission power. When the load fluctuates greatly or the PV output is greatly affected by the climate, the actual delivery power \(P_{TR}'\) and the \(P_{TR}\) value also differ greatly, and cannot be ignored. If \(P_{TR}'>P_{TR}\), it indicates that the main grid provides insufficient power, and the surplus power will be provided by the energy storage system: when \(P_{TR}'<P_{TR}\), it can be concluded that the power provided by the main grid is too high, and the surplus power will be absorbed by the energy storage system.

The modified power equation is:

\[
P_{TR}'=\delta P_{CO}-\delta P_{GE} \quad (2)
\]

\(\delta P_{CO}\) for load output error and \(\delta P_{GE}\) is a short-term prediction error for photovoltaics.

3.2. The error analysis of photovoltaic energy storage system

When the theoretical value symbytes of PV output forecast and load power forecast are the same as actual values, the traditional PV energy storage capacity configuration model can be used. However, photovoltaic power generation is vulnerable to weather and other factors, load and PV output will produce fluctuations and thus have a greater impact on the energy storage system, so we based on the random error model of energy storage system capacity to improve accuracy, avoid the negative impact due to error.

| Times  | Actual photovoltaic power /MW | PV power forecast/MW | Power error value/MW | Relative error/MW |
|--------|-------------------------------|---------------------|---------------------|-------------------|
| 06.00  | 1.3265                        | 1.5998              | -0.3352             | -0.2510           |
| 07.00  | 4.1023                        | 5.102               | -1.0223             | -0.2499           |
| 08.00  | 14.0235                       | 12.3654             | 1.2584              | 0.09874           |
| 09.00  | 15.412                        | 16.289              | -1.6588             | -0.1111           |
| 10.00  | 19.5562                       | 18.0221             | 1.6251              | 0.08654           |
| 11.00  | 28.0215                       | 25.3654             | 1.6854              | 0.0598            |
| 12.00  | 27.3965                       | 29.0584             | -1.679              | -0.0692           |
| 13.00  | 30.0258                       | 30.0125             | -0.3584             | -0.01524          |
| 14.00  | 24.369                        | 26.324              | -1.6954             | -0.0694           |
| 15.00  | 19.9845                       | 21.9845             | -1.9547             | -0.09812          |
| 16.00  | 19.6842                       | 18.3021             | 1.0521              | 0.04987           |
| 17.00  | 12.0684                       | 13.2587             | -1.3571             | -0.1422           |
| 18.00  | 6.3199                        | 6.8488              | -0.3332             | -0.0215           |
| 19.00  | 2.6324                        | 2.2324              | 0.3332              | 0.21              |

Mean (expected value) | -0.3432 | -0.04987 |

The analysis data shows that as the measurement time interval becomes shorter, the expectation of the PV output prediction error value gradually decreases. According to the Bernoulli limit theorem, when the time interval approaches 0, the PV predicted power approaches the actual PV power.
By central limit theorem. The law shows that the random variables \( X_1, X_2, \ldots, X_n \) exist independently of each other, the expected value is \( \mu \), the variance is \( \sigma^2 \), \( \sigma \neq 0 \). \( K = 1, 2, 3, \ldots \). The calculation of any normal distribution is easily converted to the standard normal distribution is \( N(0, 1) \). Easy to prove: \( Y = (X - \mu)/\sigma \approx N(0,1) \).

Then random variable:

\[
Y_n = \frac{\sum_{k=1}^{n} X_k - E(\sum_{k=1}^{n} X_k)}{\sqrt{D(\sum_{k=1}^{n} X_k)}} = \frac{\sum_{k=1}^{n} X_k - n\mu}{\sqrt{n}\sigma} \tag{3}
\]

Actually:

\[
P(Y \leq x) = P((X - \mu)/\sigma \leq x) = \left( \sqrt{2\pi} \right)^{-1} e^{-\frac{x^2}{2}} \tag{4}
\]

The expected error of PV output prediction in a certain region within the micro-grid is \( \mu_{Ge} \), variance is \( \sigma_{Ge}^2 \). So its normal distribution can be expressed as:

\[
f(\Delta P_{Ge}) \approx N \left( \mu_{Ge}, \sigma_{Ge}^2 \right). \tag{5}
\]

According to the density function formula of the normal distribution, the probability density function of the normal distribution can be obtained as follows:

\[
f(\Delta P_{Ge}) = \frac{1}{\sqrt{2\pi} \sigma_{Ge}} e^{-\frac{(\Delta P_{Ge} - \mu_{Ge})^2}{2\sigma_{Ge}^2}} \tag{6}
\]

The load forecasting error is mainly affected by the load power situation, weather, geographical location, etc. The impact factor of each influencing factor is less than 0.5, so the load forecasting error is in line with the normal distribution.

The PV output prediction error is mainly affected by temperature, humidity, wind speed, etc. and each impact factor has only a low weight. Similarly, the PV output prediction error is also in line with the normal distribution. As shown in Figure 2 below:

\[\text{Figure 2. Output curves corresponding to different light intensities.}\]
The figure below shows the effects of power and current on different temperatures and light intensities. The expected value of the load power prediction error in a certain area of the microgrid is $\mu_{\text{load}}$, and the variance is $\sigma_{\text{load}}^2$, so its normal distribution can be expressed as:

$$f(\Delta P_{\text{loadi}}) = \frac{1}{\sqrt{2\pi \sigma_{\text{loadi}}}} e^{-\frac{(\Delta P_{\text{loadi}} - \mu_{\text{loadi}})^2}{2\sigma_{\text{loadi}}^2}}$$  \hspace{1cm} (7)

Let M and N respectively represent the PV output prediction error and load prediction error of a microgrid. When the capacity of the energy storage system is configured, the total error is $W=M+N$, and the total error $W$ directly determines the capacity of the energy storage system. The density function is:

$$f_{w_i}(w_i) = \int_{-\infty}^{w_i} f_{m_i}(m_i) f_{n_i}(n_i) dm_i$$

$$f_{w_i}(w_i) = \frac{1}{2\pi \sigma_{\text{Ge}} \sigma_{\text{load}}} \int_{-\infty}^{w_i} e^{-\frac{(\Delta P_{\text{Ge}} - \mu_{\text{Ge}})^2}{2\sigma_{\text{Ge}}^2}} e^{-\frac{\Delta P_{\text{load}} - \mu_{\text{load}})^2}{2\sigma_{\text{load}}^2}} d(\Delta P_{\text{Ge}})$$  \hspace{1cm} (8)

The above equation can be simplified to:

$$f_{w_i}(w_i) = \frac{1}{\sqrt{2\pi \sigma_{\text{Ge}} \sigma_{\text{load}}}^2} e^{-\frac{\Delta P_{\text{load}} - \mu_{\text{load}})^2}{2\sigma_{\text{load}}^2}}$$  \hspace{1cm} (9)

The influence factors of photovoltaic output prediction error and load prediction error are different, so they are independent of each other and do not interfere with each other. The sum of two independent normal distributions is also normal distribution.

$$\Delta P_{TR} = \Delta P_{\text{Ge}} + \Delta P_{\text{load}}$$  \hspace{1cm} (10)

$$Y = \frac{\bar{X} - \mu}{\sigma_{\text{Ge}}/\sqrt{n}} \sim N(0, 1)$$  \hspace{1cm} (11)

Combined with the standard normal distribution definition. The maximum power of the energy storage system is:

$$P_{TR} = \frac{\sigma_{TR} Y}{\sqrt{n}} \sqrt{2}$$  \hspace{1cm} (12)

4. Application analysis

In order to give full play to the flexible and controllable characteristics of distributed PV energy storage systems, reasonable capacity configuration is essential. Excessive capacity configuration will cause the energy storage system to be discharged for a long time, greatly reducing the service life and increasing the cost of the energy storage system. If the selected capacity is too small, the energy storage capacity will be weak, and the ability to cut the peak and fill the valley will be poor, which will greatly affect the effect of suppressing the PPC power countercurrent and adjusting the voltage fluctuation. The available area of the roof of Liaoning Tower office building is about 1215 square meters. However, because the elevator company and the owner’s corporate logo are too high, the installed capacity of the truss structure photovoltaic power generation system is 200KW.
Through the field test to draw the user office building load curve, the maximum load of the user is not more than 150KW. Therefore, according to the normal operation requirements of the user and the installed capacity of the photovoltaic system, the capacity of the energy storage system is 387KWh, and the photovoltaic power station is installed in the roof area provided by the owner. As shown in Figure 3 below:

![Load power curve](image)

**Figure 3.** Load power curve.

The scale of the photovoltaic power station that can be constructed through survey and design is about 234KWp. According to the load power curve of the office building, the maximum load does not exceed 150KW. The power generation curve of the photovoltaic power generation system is approximately parabolic, and the system efficiency is about 80% - 85%, and the photovoltaic installed capacity that meets the stable power generation capacity is 200 KWp.

The 325W double-sided photovoltaic module is installed horizontally in the roof of the available area. It is estimated that the number of PV modules that can be paved is 624. The installed capacity of the photovoltaic power station is 202KWp. The grid connection point selects the nearest TV from the roof of the PV module.

During the peak season of photovoltaic power generation, 400KWh is depleted during the peak period of photovoltaic power generation. The energy storage system is needed for peak clipping and valley filling. The energy supply during the non-working day of the solar energy season can meet the load demand during the peak period, without the energy storage system working, non-power supply. Seasonal PV generation will be greater than the load demand, with a 252 KWh surplus.

According to the above analysis, it can be determined that the installed capacity of the photovoltaic tower of China Railway Tower Liaoning Branch is 400KW.

5. **In conclusion**

Firstly, through the comparison of several energy storage methods, the lithium ion battery with the main energy density is the main energy storage method.

The structure of distributed photovoltaic dispatching energy storage system is analyzed, and the basic mathematical model is established. Since both PV output and load power prediction have randomness and volatility, in order to calculate the accuracy of the result, both errors are obeyed in a normal state. According to the characteristics of the distribution, the error model is integrated and the capacity configuration of the energy storage system is estimated.

Based on the characteristics of China Railway Tower Liaoning Branch, a distributed photovoltaic power station was built on the roof. To ensure reasonable capacity allocation, the capacity of the energy storage system was estimated by the model.
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