Probability Density Analysis of Wind Storage Output Based on Monte Carlo Simulation

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Abstract: Due to the relatively large fluctuation amplitude of the output power of wind farms, when using energy storage to stabilize the output characteristics of wind power, the impact of the addition of energy storage on the probability density of wind power output needs to be further analyzed. This paper uses Monte Carlo simulation algorithm to analyze the probability density of active power output in consideration of the operating state of wind power and compares the change of the output probability density curve after adding energy storage. According to the output probability density curve obtained by the algorithm, the abscissa of the curve is shifted to the right by one energy storage capacity unit after the addition of energy storage, so that the output probability density curve of the wind storage system can reach the required value by adding energy storage.

1. Introduction

Nowadays, wind power has penetrated into many application fields, but the operation of wind power is very susceptible to the influence of environmental wind speed, so the power output has greater random fluctuations than other types of power generation devices. In order to improve the stable output characteristics of wind farms, in actual projects, wind farms are usually equipped with energy storage systems to stabilize the output characteristics of wind power. The addition of energy storage makes the influence of the probability density of wind power output have a close relationship with the output reliability of wind storage. Based on Monte Carlo sampling, this paper analyzes the output characteristics of energy storage boosting wind power.

Monte Carlo simulation is a commonly used research method in statistics. Its basic principle is to estimate the probability density of the sample by a given statistical sample set, and subject to a known specific probability distribution, from a randomly sampled numerical sequence. Literature\textsuperscript{[1]} does not consider the time sequence of the system in wind farm output evaluation, so the non-sequential Monte Carlo simulation method can be used to establish a wind farm output probability model. Literature\textsuperscript{[2]} considers the state of operation, shutdown and derating, establishes a multi-state fault model for wind turbines; combines the randomness of wind speed, wind farm wake effects and the failure of the wind turbine itself to establish a wind farm reliability model. Relevant programs are written in MATLAB by the sequential Monte Carlo method, and the reliability of the active output of the wind farm is evaluated. Literature\textsuperscript{[3]} established a Monte Carlo simulation-based simulation program for the probability evaluation of the output of wind turbines in MATLAB, and evaluated the probability of the output of a wind farm, and gave the probability density of this type of wind turbine under different output states. Literature\textsuperscript{[4]} uses the strategy of combining Monte Carlo sampling and the equivalent power function method to calculate the power supply reliability of the power system with a high
proportion of wind power grid-connected under different network environments.

The active power output of a wind farm is affected by the scale of the wind farm, wind speed and the operating status of the unit. The addition of energy storage will change the probability density curve of wind farms, which is the focus of this paper, guiding us to improve the output characteristics of wind farms.

2. Energy storage system supports wind power output

The energy storage system of a wind farm is mainly composed of energy storage units, power conversion systems and control equipment. Energy storage unit is the main carrier of energy storage system to realize electric energy storage and release, and its capacity is directly related to the energy storage capacity of energy storage system. Restricted by factors such as low battery cell terminal voltage, limited energy density and power density, in order to expand the capacity, the battery system is generally composed of thousands of battery cells in series and parallel. The power conversion system is an important part of the energy storage system. The two-way energy transfer between the energy storage system and the external grid can be realized through the control equipment and the power conversion system.

The energy storage system provides additional power to the system when the wind farm's output is insufficient. The greater the power capacity of energy storage can compensate for the insufficient output of the wind farm, the greater the capacity. When the probability of continuous output power shortage of the wind farm is higher, the configuration of a certain capacity of energy storage can reduce the insufficient output of the wind farm. As shown in Figure 1, the 24-hour output power density curve of wind farms is relatively sparse.

![Fig. 1 24-hour output active power characteristics of wind farms](image1)

The addition of energy storage increases the minimum output power of wind power by one unit of the maximum output capacity of energy storage.

![Fig. 2 24-hour active power output characteristics of the wind farm after the configuration of energy storage](image2)
3. Wind farm operation status and output

The change between the available state and the unavailable state of the wind power equipment in a wind farm is considered to be an independent event. Considering the natural aging of the equipment and the intervention of maintenance personnel, the random changes in these two states are considered. Analyzing the state of the system components and the transitions between the states of the system components need to be expressed by the conversion rate. Commonly used conversion rates include failure rate $\lambda(t)$ and repair rate $\mu(t)$. The expression of failure rate is as follows:

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{1}{\Delta t} P[t < T \leq t + \Delta t | T > t]$$ (1)

In the formula: $T$ is the failure time of the component. The expression of the repair rate is as follows:

$$\mu(t) = \lim_{\Delta t \to 0} \frac{1}{\Delta t} P[t < T_D \leq t + \Delta t | T_D > t]$$ (2)

In the formula: $T_D$ is the repair time of the element. The state model of the system components needs to choose a two-state model or a three-state model for analysis according to actual research needs.

The state probability of each element in the wind farm can be simulated with random numbers in the interval $[0,1]$. The research object has two independent states of failure and work. Let $S_i$ denote the state of the system element $i$, $Q_i$ denote the failure rate of the element, and generate a random number $R_i$ in the interval $[0,1]$ for the element $i$ to obtain:

$$S_i = \begin{cases} 0, & R_i > Q_i \quad \text{(Working status)} \\ 1, & 0 \leq R_i \leq Q_i \quad \text{(Failure state)} \end{cases}$$ (3)

The state of the system with $N$ elements is represented by the vector $S$, as shown in the following formula:

$$S = (s_1, \cdots, s_i, \cdots, s_N)$$ (4)

When the state of the component is selected, the state is judged whether it is in the invalid state, and if it is, the value of the state is accumulated.

Since wind power does not always run at rated power, this paper considers the output state of wind power to be a three-state model, and outages and derating are considered random events. From the Markov state transition probability, the following formula can be obtained:

$$P_{fo} = \frac{\mu_2 \lambda_2}{\lambda_1 \mu_2 + \lambda_2 \mu_1 + \mu_1 \mu_2}$$ (5)

$$P_{do} = \frac{\mu_1 \lambda_1}{\lambda_1 \mu_2 + \lambda_2 \mu_1 + \mu_1 \mu_2}$$ (6)

In the formula: $\lambda_1$ and $\lambda_2$ are the fault migration rates of derating and outage respectively; $\mu_2$ and $\mu_1$ are the repair migration rates of outage and derating respectively. $P_{fo}$ is the probability of outage state; $P_{do}$ is the probability of derating state; refer to equation (3) A three-state probability model can be obtained, as follows:

$$S_i = \begin{cases} 0 \quad \text{(run)} & P_{do} + P_{fo} < U \leq 1 \\ 1 \quad \text{(Out of service)} & P_{do} < U \leq P_{do} + P_{fo} \\ 2 \quad \text{(Derating)} & 0 \leq U \leq P_{do} \end{cases}$$ (7)

In the formula: $U$ is a random number randomly selected in the interval $[0,1]$; the output state of the wind farm can be obtained by formula (7) combined with the classic wind power output model[5]:

$$P_{gi} = \begin{cases} P(U_w) & P_{do} + P_{fo} < U \leq 1 \\ 0 & P_{fo} < U \leq P_{do} + P_{fo} \\ aP(U_w) & 0 \leq U \leq P_{do} \end{cases}$$ (8)

In the formula: $P_{gi}$ is the output of the $i$-th typhoon; $a$ is the derating factor of the wind power.
4. Wind power output evaluation based on Monte Carlo simulation

According to the basic knowledge of probability statistics, when the required quantity $X$ is the mathematical expectation $E(\zeta)$ of the random variable $\zeta$, then the method of approximately determining $X$ is to repeat the sampling of $\zeta$ for $N$ times to generate a sequence of mutually independent $\zeta$ values $\zeta_1, \zeta_2, \ldots, \zeta_N$, and calculate its arithmetic mean:

$$\zeta_N = \frac{1}{N} \sum_{n=1}^{N} \zeta_n$$  \hspace{1cm} (9)

From the theory of large numbers:

$$P(\lim_{N \to \infty} \overline{\zeta}_N = x) = 1$$  \hspace{1cm} (10)

Thus when $N$ is sufficiently large, the following formula can be obtained:

$$\overline{\zeta}_N \approx E(\zeta) = \infty$$  \hspace{1cm} (11)

The probability that this formula holds is 1. According to the above theory, it is assumed that the probability of a random event $A$ is $p$, the value of the random variable $\zeta$ is 1, and the value of $\zeta$ is 0 when $A$ does not appear. In $N$ experiments, assuming that $A$ appears $V$ times, the frequency of its appearance is also considered as a random variable. Its mathematical expectation is $E(v) = Np$, variance $\sigma^2(v) = Npq$, where $q = 1 - p$. Let $p = v/N$, which means the frequency of occurrence of the event. When $N$ is sufficiently large, the following formula is obtained:

$$\overline{p} = \frac{v}{N} \approx E(\zeta) = p$$  \hspace{1cm} (12)

The probability that the above formula holds is 1. Thus $\overline{p} = v/N$ can be obtained approximately to obtain the required quantity, and the sample variance is:

$$\sigma^2(\overline{p}) = \frac{\overline{p}(1-\overline{p})}{N-1}$$  \hspace{1cm} (13)

The Monte Carlo algorithm continuously samples from the system state parameter $S$ and counts the number of different states. When the number of states obtained by sampling reaches a certain value, the sampling frequency of the system state $S$ is used as an unbiased estimation of the sampling, which can be obtained:

$$\hat{P}(S) = \frac{n(s)}{N_s}$$  \hspace{1cm} (14)

In the formula: $N_s$ is the sampling times of the system; $n(s)$ is the number of appearances of the state $s$; from the unbiased estimation of the system, the mean value of the reliability index of the system can be calculated, and the expression is:

$$E(J_R) = \sum_{s \in \text{fail}} F(S) \times \hat{P}(S)$$  \hspace{1cm} (15)

In the formula: $J_r$ is the value of the reliability index; $F(s)$ is the index function of the state $S$; $P(s)$ is the probability of the appearance of the state $S$; The uncertainty is measured by the mean sample variance, as shown in the following formula:

$$V\left(\bar{E}(J_R)\right) = \frac{1}{N_s(N_s-1)} \sum_{s \in \text{fail}} \left(\hat{P}(S) - \bar{E}(J_R)\right)^2$$  \hspace{1cm} (16)

The accuracy achieved by Monte Carlo simulation is measured by the coefficient of variance $\eta$, as shown in the following formula:

$$\eta = \sqrt{V\left(\bar{E}(J_R)\right)} \quad \frac{E(J_R)}{E(J_R)}$$  \hspace{1cm} (17)

The specific steps of the Monte Carlo simulation wind power output evaluation algorithm process are as follows:
① Enter the relevant data of the wind farm: time series wind speed, number of wind power, wind power outage rate, derating rate, maximum sampling times and minimum variance.

② Randomly drawn values in the interval [0,1] are used as the values of $U_w$ and $U$, where $U_w$ represents the working state of the wind power, and $U$ represents the sampled wind speed.

③ Calculate the output of the $K$-th sampled wind farm, and determine the attribution range of the divided output state.

④ Calculate the coefficient of variance and judge whether its accuracy meets the requirements, then the sampling ends; otherwise, $K=K+1$, go to step ② until the maximum sampling value.

⑤ Judge whether the evaluation of all output states is completed, calculate and output the probability of all output states.

Fig. 3 Monte Carlo simulation algorithm flow

5. Simulation analysis

Take a wind farm in Inner Mongolia as an example, the wind farm scale is 30 3MW double-fed wind turbines, the cut-in wind speed of the wind power is 3m/s, the cut-out wind speed is 25m/s, the rated wind speed is 11.4m/s, and the wind power outage rate is 0.052. The derating rate is 0.25 and the derating factor is 0.6. It is considered that the arrangement of all wind power plants is a regular arrangement without obstruction, and the wind speed of the wind farm is fitted using the Wilber distribution [6], the scale parameter $c=5.218$, the shape parameter $k=1.637$. The annual wind speed frequency distribution of this wind farm is shown in the figure below:
Fig. 4 Wind speed frequency distribution

According to MATLAB statistics of wind power output, the probability density of wind farm output can be obtained as shown in the figure below:

![Wind Speed Frequency Distribution]

Fig. 5 Annual output power probability density distribution of wind farms

It can be seen from the above figure that the probability density of wind power output is lower in the power range of 5MW~85MW, and the probability density is higher in the power range of 0MW~5MW. After adding energy storage to the wind farm, the output probability density curve of the wind farm can be obtained as shown in the figure below:

![Annual Output Power Probability Density]

Fig. 6 Comparison of the output probability density of a wind farm with 2MW energy storage and that of a wind farm without energy storage

After the wind farm is equipped with 2MW energy storage, its probability density curve shifts to the right, and the trend of its probability density does not change. When the capacity or wind speed environment of the wind farm is fixed, the probability density curve of wind farm output can be moved to the required power range by increasing the energy storage capacity.
6. Conclusion
According to the above analysis, as the power capacity of energy storage increases, the output probability density curve of wind storage shifts to the right. The increase in energy storage capacity increases the basic output power of the wind farm at low wind speeds, and does not affect the output of the wind farm. The trend of the probability density curve. In order to make the output probability density curve of the wind storage power station reach the required power capacity range, increasing energy storage is a more direct method. Due to the high selling price and maintenance costs of energy storage units, investors in actual projects hope that the energy storage capacity is as economical as possible. By gradually increasing the energy storage capacity, the output curve reaches the power output range we need.

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