Research on calculation of spinning reserve capacity of wind power system considering multiple uncertainties

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Abstract. With the development of artificial intelligence technology, power system has gradually adopted this technology. In order to better promote the application of artificial intelligence in power system, various algorithms for power system need to be further optimized and improved. After a large-scale wind power grid-connected, its random fluctuation characteristics significantly increase the uncertainty of power system operation. The traditional deterministic reserve capacity determination method has been difficult to meet the needs of the safe and economic operation of the system. It is necessary to comprehensively consider all kinds of uncertain factors that may change the operation state of the system, so as to accurately obtain the rotational reserve demand of the system. Based on this, considering the multiple uncertainties of wind power forecasting error, load forecasting error and conventional outage, this paper proposes a method to determine the reserve capacity of power system including wind power, and deduces the quantitative relationship between upper reserve capacity and loss of load probability (LOLP), lower reserve capacity and wind curtailment probability (WCP). Finally, a case study is given. The research in this paper can be used as the basis of coordinated dispatching and reserve sharing of interconnected power systems.

Keywords: Reserve capacity, Wind power system, Multiple uncertainties, LOLP and WCP

1. Introduction
With the construction and commissioning of large-scale modern wind power bases in the world, the proportion of wind power installed in the power system has increased year by year [1-2]. After a large-scale wind power grid-connected, its random fluctuation characteristics significantly increase the uncertainty of power system operation. The traditional deterministic reserve capacity determination method has been difficult to meet the needs of the safe and economic operation of the system [3-4]. Some literature has also studied this issue [6-7]. However, the influence of multiple uncertainties is less considered. Actually, it is necessary to comprehensively consider all kinds of uncertain factors that may change the operation state of the system, so as to accurately obtain the rotational reserve demand of the system.

Considering the multiple uncertainties of wind power forecasting error, load forecasting error, and conventional outage, this paper proposes a method to determine the reserve capacity of power systems including wind power.
2. Characterization of multiple uncertain factors

2.1. Load uncertainty
Accurate load forecasting is helpful for the dispatching department to make an economic and reasonable generation plan. However, due to the influence of seasonal climate, environmental temperature, and plant production plan changes, load forecasting errors are always unavoidable. At present, studies have shown that the load forecasting error obeys the normal distribution the expectation of 0 and variance $\sigma_a^2$, as in (1),

$$
\begin{align*}
\epsilon^a_t &= X^a_t - X^f_t \\
\epsilon^a_t &\sim N(0, \sigma_a^2)
\end{align*}
$$

Where $X^a_t$ is the load forecast value of period $t$, $X^a_t$ is the actual load value of period $t$, and $\epsilon^a_t$ is the load forecasting error of period $t$. The standard deviation of load forecasting error in each period can be calculated according to the load forecast value, as in (2). The value of $k$ is generally 1.

$$
\sigma^a_t = \frac{k}{100} X^f_t
$$

2.2. Uncertainty of wind power output
Due to the lack of understanding of wind power output law and the limitations of prediction technology, short-term wind power forecasting still has large errors. For a wind farm composed of a large number of wind turbines in wide-area distribution, it can be considered that the output prediction error obeys the normal distribution the expectation of 0 and variance $\sigma_w^2$, as in (3),

$$
\begin{align*}
\epsilon^w_t &= Y^a_t - Y^f_t \\
\epsilon^w_t &\sim N(0, \sigma_w^2)
\end{align*}
$$

Where, $Y^a_t$ is the predicted value of wind power for period $t$, $Y^a_t$ is the actual wind power value of period $t$, and $\epsilon^w_t$ is the wind power prediction error of period $t$. The standard deviation of wind power prediction in each period can be calculated according to the installed capacity of the wind farm and the predicted value of wind power,

$$
\sigma^w_t = k_1 Y^f_t + k_2 Y^a_t
$$

Where $k_1$ and $k_2$ are the prediction error coefficients, $Y_f$ is the installed capacity of the wind farm.

2.3. Net load uncertainty
In view of the current policy requirements of wind power priority and the poor controllability of wind turbines, wind power is usually regarded as uncontrollable "negative" load to participate in dispatching, and the concepts of net load and its prediction error are defined,

$$
\begin{align*}
Z^a_t &= X^a_t - Y^a_t \\
Z^f_t &= X^f_t - Y^f_t
\end{align*}
$$
\[ \varepsilon^t_z = Z^t_a - Z^t_f = X^t_a - Y^t_a - (X^t_y - Y^t_y) = \varepsilon^t_x - \varepsilon^t_y \]  

Where, \( Z^t_f \) is the predicted value of the net load of period \( t \), \( Z^t_a \) is the actual value of the net load of period \( t \), and \( \varepsilon^t_x \) is the forecast error of the net load of period \( t \).

It is generally assumed that load forecasting error and wind power forecasting error are two unrelated random variables. According to probability theory and statistical knowledge, any linear combination of multiple independent normal random variables still obeys normal distribution. Therefore, it is considered that the net load forecasting error follows the normal distribution with the expectation of 0 and variance of \( \sigma^2_z \), and the standard deviation can be given,

\[ \sigma^t_z = \left( \left( \sigma^t_x \right)^2 + \left( \sigma^t_y \right)^2 \right)^{\frac{1}{2}} \]  

### 2.4. Uncertainty of forced outage of generating units

Considering that the probability of multiple units failure at the same time is very low in the dispatching operation time scale, this chapter only considers two cases: no-fault for all units and fault for a single unit, and all units adopt two-state model, that is, there are only two states of normal operation and fault shutdown.

On the basis of known forced outage rate of units, the probability that all units in the whole network have no fault is,

\[ P^0 = \prod_{i=1}^{N} (1 - \lambda_i) \]  

The probability of a single failure of unit \( i \) is,

\[ P^1_i = \lambda_i \prod_{j=1}^{N} (1 - \lambda_j) \quad j \neq i \]  

Where \( n \) is the total number of generating units, and \( \lambda_i \) is the forced outage rate of generator set \( i \).

### 3. Calculation of spinning reserve capacity

In this paper, the most commonly used reliability index of the power system, LOLP, is used to quantify the function relationship between loss of load risk and reserve capacity, so as to determine the minimum upper reserve requirement meeting the expected risk level.

Considering the net load forecasting error and the N-1 fault of the generator set, when the reserve capacity of the system is \( R^U_t \), the load loss probability LOLP of system period \( t \) can be calculated,

\[ \text{LOLP}_t = \prod_{i=1}^{N} (1 - \lambda_i) \times P(R^U_t < \varepsilon^t_z) \]

\[ + \sum_{i=1}^{N} \lambda_i \times \prod_{j=1}^{N} \left( 1 - \lambda_j \right) \times P(R^U_t < \varepsilon^t_z + P_{t,\text{max}}) \]  

Where \( R^U_t \) is the available upper reserve capacity of the system at \( t \), and \( P_{t,\text{max}} \) is the maximum generation capacity of the outage generator set \( i \).
In this paper, the prediction error of net load is considered to be a random variable with a normal distribution. Based on the concept of the quantile of the distribution function of $\varepsilon^t_i$, equation (11) can be further expressed as,

$$LOLP_t = \prod_{i=1}^{N} (1-\lambda_i) \times \left[ 1 - \Phi \left( R^U_i \right) \right] + \sum_{i=1}^{N} \lambda_i \times \prod_{j=1, i\neq j}^{N} \left( 1 - \lambda_j \right) \times \left( 1 - \phi \left( R^U_i - P_{\text{max}} \right) \right)$$

(12)

Where $\Phi(\cdot)$ is the probability distribution function of net load forecasting error $\varepsilon^t_i$. Given the system load and wind power prediction information, according to formula (1) - (8), the expression $\Phi(\cdot)$ of the net load forecast error could be determined. Then $LOLP_t$ is only a univariate function of the upper reserve capacity $R^U_t$.

When the criterion of system loss probability is set as $\alpha$, the reliability constraint of upper reserve capacity on the system is

$$LOLP_t \leq \alpha, \quad \forall t$$

(13)

By solving the univariate inequality equation (13), the minimum upper reserve capacity of the system can be determined considering the probabilistic characteristics of the load, wind power, and generator set.

In this paper, the WCP index of wind curtailment probability is introduced to quantify the functional relationship between the risk of wind curtailment and the reserve capacity, so as to determine the minimum reserve demand meeting the expected risk level.

Considering the uncertainty of net load forecasting error, when the reserve capacity is $R^L_t$, the wind curtailment probability WCP of system period $t$ can be calculated,

$$WCP_t = P \left( R^L_t < -\varepsilon^t_i \right) = \phi \left( -R^L_t \right)$$

(14)

Where $\Phi(\cdot)$ is the probability distribution function of the net load forecasting error. When the system load and wind power forecasting information is given, according to formula (1) - formula (8), the expression $\Phi(\cdot)$ in the probability distribution function of net load forecasting error is also uniquely determined, then $WCP_t$ is only a univariate function of the lower reserve capacity $R^L_t$.

When the criterion of wind curtailment probability is set as $\beta$, the reliability constraint of reserve capacity is,

$$WCP_t \leq \beta, \quad \forall t$$

(15)

By solving the univariate inequality equation (15), the minimum down reserve demand of the system in each period which meets the target reliability level considering the load and wind power probability characteristics can be determined.

It is worth pointing out that the method proposed in this paper based on the reliability index can calculate the minimum reserve demand of the system off-line under the condition that the wind power is fully absorbed, according to the given load, wind power prediction information and forced outage rate of generating units, the minimum reserve demand of the system can be calculated off-line. When the reserve capacity of the system is not enough to absorb all the wind power, the actual dispatching output of wind power can replace the predicted value of wind power in the above formula, and the influence of abandoned wind power can be taken into account in the determination of reserve capacity, and the reserve demand and its distribution can be optimized online.
4. Case study
In order to verify the effectiveness of the reserve capacity determination method proposed in this chapter, and analyze the impact of wind power uncertainty on the reserve demand of the system after the wind power is connected, this section studies the reserve demand of the power system with wind power based on a five-unit system with a 1000MW wind farm.

The system includes four thermal power units and one hydropower unit. The installed capacity of the water turbine is 500MW, and the forced outage rate is 0.0013. The maximum generating capacity of the four thermal power units is 500MW, 460 MW, 340 MW, and 300 MW respectively. The forced outage rates are 0.0022, 0.0024, 0.0028 and 0.0031 respectively. The load and wind power forecasting curve is shown in Fig. 1. The standard deviation of load and wind power prediction error is determined by the formula (2) and formula (4).

![Figure 1. Forecast load power](image1)

When the load loss probability and wind abandonment probability of each period of the day is required to not exceed 0.05, the minimum upper and lower reserve capacity curve of the whole day can be obtained, as shown in Fig. 2. The reason why the minimum upper reserve capacity is higher than the lower is that the influence of forced outage is considered.

![Figure 2. The minimum upper and lower reserve capacity](image2)
The difference in wind power forecasting accuracy will also significantly affect the reserve demand. Taking the standard deviation of wind power prediction error as 0.5 times and 2 times of equation (4), the reserve demand curve under each prediction level is obtained, as shown in Fig.3.

It can be seen from the figure that with the increase of wind power prediction error, the uncertainty of power system operation increases significantly. In order to achieve the same level of reliability, more reserve has to be reserved.

![Figure 3. Reserve demand under different prediction levels](image)

The National Energy Administration recently released the national statistical data of wind power grid connected operation in 2018. Yunnan's clean energy continues to develop, with wind power utilization hours leading the country, reaching 2654 hours, far exceeding the national average of 2095 hours of wind power utilization. In 2019, the utilization hours of wind power in Yunnan will reach 2808 hours, which will continue to rank first among all provinces and regions in China.

![Figure 4. Reserve demand under different prediction levels of a case in Yunnan](image)

In view of the high utilization rate of wind power in Yunnan power grid, taking a wind power system in Yunnan power grid as an example, the minimum reserve capacity is calculated, as shown in Figure 4. The calculation results can provide reference for practical application.
5. Conclusion
Considering the multiple uncertainties of wind power forecasting error, load forecasting error, and conventional outage, this paper proposes a method to determine the reserve capacity of power systems including wind power.

This method can realize the off-line calculation of reserve capacity when wind power is fully absorbed, and can also be used for online reserve optimization considering the impact of wind curtailment. The results of this paper lay a foundation for the research of inter regional coordinated scheduling and reserve sharing.

Acknowledgments
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