Risk Assessment of Power Systems Dispatching Decision Considering Photovoltaic Systems Penetration

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Abstract. Grid-connected photovoltaic power generation is an important form of new energy utilization, which can effectively reduce the dependence of power system on traditional energy sources. However, the randomness and uncertainty of the output of photovoltaic power generation system will also pose some risks to power grid dispatching decision-making. The source of dispatching decision risk is analyzed, and a risk index system including line overload risk, reserve shortage risk, load shedding risk and light abandonment risk is established. Then a risk assessment model for optimal dispatch of grid-connected photovoltaic power generation is established. The time of power flow calculation is greatly simplified by using power flow distribution factor. Finally, through the risk assessment of IEEE RTS-79 system scheduling decision-making, the risk of scheduling decision-making under different photovoltaic acceptance is analyzed, and the feasibility of the model is verified.

1. Introduction
At present, photovoltaic power generation has become one of the efficient ways to use solar energy, and the scale of grid connection is increasing day by day. Limited by the prediction accuracy of photovoltaic output, the uncertainty of photovoltaic output will have a certain impact on power system dispatching decision. Therefore, it is very important to assess the risk of power grid dispatching decision with photovoltaic power generation.

The security analysis methods of power system can be roughly divided into three categories: deterministic analysis method, probabilistic analysis method and risk assessment method. Deterministic analysis method was applied earlier, and $N-1$, $N-2$ and so on are widely used at present. The literature [1] analyzes the development process of power grid cascading failures, and proposes a risk assessment method for power grid $N-K$ ($K \geq 2$) failures, but this method only analyzes the safety of power network structure, and cannot analyze factors other than the grid structure. Probabilistic analysis method can well reflect the fault probability information of power grid components, but this method does not consider the influence of the severity of fault consequences on power grid security. In order to comprehensively consider the possibility of accidents and the severity of accident consequences, the concept of risk was first proposed at the International Conference on Large High Voltage Electric System (CIGRE) in 1997, and the concept of risk assessment was introduced into the safety analysis of power systems.

At present, there are many researches on risk assessment of conventional unit power grid and wind power grid. The literature [2] analyzes various factors of large-scale blackouts, and establishes a set of safety risk assessment system by using fault tree analysis and hierarchical analysis, but does not
analyze the specific method of risk assessment; the literature [3] establishes a reliability model of power generation system including wind power, photovoltaic and energy storage, but does not involve the analysis of the risk state of the power grid.

The above literatures are all analysis and modeling of power system operation risks. At present, there are few researches on risk assessment of power grid dispatching decision with photovoltaic power generation. Limited by the climbing ability of units, the risk situation of power grid will be quite different under different dispatching decisions. Therefore, it is of great significance to assess the risk of power grid dispatching decision with photovoltaic power generation. This paper first studies the causes of risks in photovoltaic power systems, and then establishes a risk index system including line overload risk, reserve shortage risk, load shedding risk and light abandonment risk, and establishes a dispatching decision risk assessment model considering photovoltaic power generation. Finally, an example of IEEE RTS-79 system is given to verify the feasibility of the model.

2. Risk Assessment Model of Power System Dispatching Decision with Photovoltaic

Analysis of Influencing Factors of Power System Dispatching Decision Risk

The risk consequences of traditional power systems generally mainly refer to system load shedding, line overload and other events. For photovoltaic grid-connected power systems, the phenomenon of light abandonment in photovoltaic systems has attracted more and more attention. These power system risks are mainly caused by the imbalance between power supply and demand in the power grid and the change of power grid topology, which leads to risks in dispatching decision-making. The influencing factors of grid-connected photovoltaic power system dispatching decision risk are mainly the prediction error and accidental disturbance of photovoltaic power or climbing events.

2.1. Analysis of Influencing Factors of Power System Dispatching Decision Risk

2.1.1. Analysis of Prediction Error Distribution Characteristics of Photovoltaic Output. In this paper, Gaussian mixture distribution is used to fit the prediction error of photovoltaic output. The expression of $n$-order Gaussian mixture distribution is as follows:

$$f(x) = \sum_{i=1}^{n} a_i e^{-\frac{(x-b_i)^2}{c_i}}$$

where $a_i$, $b_i$ and $c_i$ are parameters to be fitted.

2.1.2. Analysis of Distribution Characteristics of Load Forecasting Errors. Generally, it is assumed that the load output forecasting error obeys the normal distribution. In this paper, it is assumed that the load forecasting error obeys the normal distribution expected to be 0. According to the literature [4], the standard deviation of load forecasting error can be obtained as follows:

$$\sigma = k \cdot P_{L_a}(t) / 100$$

where $P_{L_a}(t)$ is the load forecast value at time $t$ and $k$ is generally taken as 1.

2.2. Fast power flow calculation method

In the process of risk assessment, the speed of power flow calculation is an important factor affecting the assessment time. This paper uses Monte Carlo simulation method to simulate the system state. In view of the fact that the data prediction error and the failure rate of components in the actual power grid are both small values, the simulated system state and the system state when the dispatching decision is generated will not change too much. Therefore, the generation transfer distribution factor, the load transfer distribution factor and the branch outage distribution factor are used to solve the line power flow.

2.2.1. Generation transfer distribution factor. Generation transfer distribution factor refers to the variation of branch power flow caused by the increase of unit active power output of generator[5]. The
GSDF of generator node \( i \) to line \( k \) is denoted as \( G_{k-i} \), and the variation of power flow \( \Delta P_k \) on branch can be obtained from the variation of power flow \( \Delta P_i \) injected by node \( i \):

\[ \Delta P_k = G_{k-i} \cdot \Delta P_i \]  \hspace{1cm} (3)

\[ G_{k-i} = M^T_k \cdot X_i \]  \hspace{1cm} (4)

where \( M_k \) is the \( k \)-th branch node association vector; \( X_i \) is the \( i \)-th column vector of \( X \) matrix in DC power flow calculation; \( x_k \) is the reactance value of the \( k \)-th branch.

The literature [6] extends the concept of GSDF to the variation of load nodes and deduces the load transfer distribution factor (LSDF). The LSDF of load node \( i \) to line \( k \) is denoted as \( L_{k-i} \), then:

\[ L_{k-i} = G_{k-i} \]  \hspace{1cm} (5)

2.2.2. Branch outage distribution factor. For a given power system, when a branch \( l \) in the network is disconnected, the variation of power flow \( \Delta P_k \) on the branch \( k \) can be regarded as a linear function of the initial power flow \( P_l^0 \) on the branch \( l \):

\[ \Delta P_k = D_{k-l} \cdot P_l^0 \]  \hspace{1cm} (6)

where \( D_{k-l} \) is the branch outage distribution factor of branch \( k \) to branch \( l \).

The variation of power flow \( \Delta P_{i-lk} \) on branch \( i \) caused by the simultaneous disconnection of two branches \( l \) and \( k \) in the power grid can be regarded as a linear function of the initial power flow \( P_l^0 \) and \( P_k^0 \) on branches \( l \) and \( k \):

\[ \Delta P_{i-lk} = D_{i-lk}^{N-2} \cdot \begin{bmatrix} P_l^0 \\ P_k^0 \end{bmatrix} \]  \hspace{1cm} (7)

where \( D_{i-lk}^{N-2} \) is the power flow transfer sensitivity vector of branch \( i \) to branch \( l \) and \( k \).

3. Risk assessment index

3.1. Line overload risk

The formula for calculating the load rate of the \( i \)-th line in the power grid is as follows:

\[ \omega_i = \frac{P_{\text{acc},i}}{P_{\text{max},i}} \times 100\% \]  \hspace{1cm} (8)

The load rate expectation and overload probability of the \( i \)-th line at time \( t \) are:

\[ E_0^t_{\text{ol},i} = \frac{1}{K} \sum_{j=1}^{K} \omega^j_i \]  \hspace{1cm} (9)

\[ P_0^t_{\text{ol},i} = \frac{N_{\text{ol},i}^t}{K} \]  \hspace{1cm} (10)

where \( N_{\text{ol},i}^t \) is the number of samples of overload events on the \( i \)-th line in the simulation process under the scheduling decision at time \( t \); \( K \) is the total number of analog samples.

3.2. Reserve shortage risk

The formula for calculating the total positive and negative reserve capacity of the system at time \( t \) are:

\[ \text{rep}^t = \sum_{l_0} \left( P^t_{0,\text{max},i} - P^t_{0,i} \right) \]  \hspace{1cm} (11)
\[ ren'_i = \sum_{j=1}^{K} \left( P_{Gj}' - P_{\min,j}' \right) \]  

(12)

where \( P_{Gj}' \) is the actual output value of the \( i \)-th generator at time \( t \). In Monte Carlo simulation, the expected values of positive and negative reserve capacity of the system at time \( t \) are calculated by Equations (17) and (18) respectively:

\[ E_{\text{rep}}^t = \frac{1}{K} \sum_{j=1}^{K} rep'_j \]  

(13)

\[ E_{\text{ren}}^t = \frac{1}{K} \sum_{j=1}^{K} ren'_j \]  

(14)

where \( rep'_j \) and \( ren'_j \) are the positive and negative reserve capacity of the conventional unit in the \( j \)-th sample at time \( t \), respectively. In the following, the critical values for judging whether the positive and negative reserve capacity of the system is sufficient are expressed by \( rep_0 \) and \( ren_0 \) respectively. The expectation of positive and negative reserve capacity shortage value of the system are defined as follows:

\[ E_{\text{rep}_{\text{sa}}}^t = \frac{1}{K} \sum_{j=1}^{K} \max \left\{ \text{rep}_0 - rep'_j, 0 \right\} \]  

(15)

\[ E_{\text{ren}_{\text{sa}}}^t = \frac{1}{K} \sum_{j=1}^{K} \max \left\{ ren_0 - ren'_j, 0 \right\} \]  

(16)

3.3. Load shedding risk

The formula for calculating the expected load shedding at time \( t \) is:

\[ E_{\text{cut}}^t = \frac{1}{K} \sum_{j=1}^{K} l_{\text{cut},j} \]  

(17)

where \( l_{\text{cut},j} \) is the load shedding amount corresponding to the \( j \)-th sampling sample at time \( t \). The probability of load shedding at time \( t \) is:

\[ P_{\text{cut}}^t = \frac{N_{\text{cut},t}}{K} \]  

(18)

where \( N_{\text{cut},t} \) is the number of samples of load shedding events occurring in the simulation process under the decision of time \( t \).

3.4. Risk of light abandonment

The definitions of light abandonment expectation and light abandonment probability at time \( t \) are respectively:

\[ E_{\text{pva}}^t = \frac{1}{K} \sum_{j=1}^{K} A_{\text{pva},j} \]  

(19)

\[ P_{\text{pva}}^t = \frac{N_{\text{pva}}^t}{K} \]  

(20)

where \( A_{\text{pva},j} \) is the amount of abandoned light in the \( j \)-th sample at time \( t \); \( N_{\text{pva}}^t \) is the number of samples of light abandonment events in the simulation process under the decision of time \( t \).

4. Specific Process of Risk Assessment Model for Dispatching Decision of Photovoltaic Power System

In this paper, the risks caused by photovoltaic output prediction error, load prediction error, generator fault outage and line fault outage are considered, and the risk degree is randomly simulated by Monte
Carlo simulation method. The generation transfer distribution factor and Branch outage distribution factor are used to calculate the active power flow of the line, and then the amount of abandoned light, load shedding and the positive and negative reserve capacity of conventional units are calculated, and then the values of each risk index are calculated.

5. Example analysis

5.1. Parameter Setting
In order to verify the feasibility of the proposed risk assessment model, the modified IEEE RTS-79 system is used for example analysis. Photovoltaic is connected from node 18, and its capacity is 400 MW.

5.2. Scheduling decision scheme
According to the willingness to absorb photovoltaic, two dispatching decision schemes are set, and the output value of photovoltaic power generation system in the two dispatching decisions is shown in Figure 2. As can be seen from Figure 2, scheduling decision 2 basically accepts photovoltaic output in full, and decision 1 accepts photovoltaic output in part.

5.3. Results of risk assessment
According to the established risk assessment model, the total number of simulations is set. The risk assessment of decision 1 and decision 2 is carried out respectively, and the results of four types of risk indicators are obtained. The results of line overload risk assessment are shown in Fig.3.

During the period when the predicted photovoltaic output is zero, because the two scheduling decisions are basically the same, the corresponding risk assessment results are basically the same. During the period when the predicted output of photovoltaic is not zero, since the photovoltaic power generation system is connected to the power grid at node 18 and the access position is far away from the load concentration area, the higher the photovoltaic acceptance degree, the higher the power transmitted by some lines (such as line 28), and the higher the load rate expectation and overload probability of the lines. The risk assessment results of insufficient reserve capacity are shown in Fig.4.

Fig.1 PV output value under different scheduling decision

Fig.2 The comparison of line overload risk

Fig.3 The comparison of reserve shortage risk

In the period when the photovoltaic output is zero, the four moments of 25th, 29th, 31st and 65th all correspond to the sudden increase of load, and the photovoltaic power generation system has no output in the first three moments, while the photovoltaic output in the fourth moment is very small although it has output. Limited by the climbing ability of conventional units, the expectation of
positive reserve capacity is obviously reduced and the expectation of negative reserve capacity is obviously increased. The four moments of 77th, 81st, 85th, 89th and 93rd correspond to the sudden drop of load, the change trend is opposite. The load shedding risk assessment results are shown in Fig.5.

During the period when the predicted photovoltaic output is zero, the positive reserve capacity at the 25th, 29th, 31st and 65th moments is lower, so the load shedding expectation and load shedding probability are higher. During the period when the photovoltaic output is not zero, the risk of load shedding is generally small when the positive reserve capacity is large. However, from the 52nd to 57th moments, the load shedding expectation of decision 2 is higher than that of decision 1 because the positive reserve capacity of the two decisions is not much different, and the planned output of photovoltaic in decision 2 is much higher than that of decision 1, and the failure rate of photovoltaic power generation system is higher. The results of light abandonment risk assessment are shown in Fig.6. Scheduling decision 1 is to partially accept photovoltaic output, and there is light abandonment in the decision itself. Therefore, at the 40th to 60th moments, its light abandonment expectation and probability are higher than those of decision 2, which fully accepts photovoltaic output.

6. Conclusion
In this paper, the dispatching decision of power grid with photovoltaic power generation is taken as the research object, the source of dispatching decision risk is analyzed, and a risk assessment model based on Monte Carlo simulation is established. The method of solving line power flow by power generation transfer distribution factor, load transfer distribution factor and branch outage distribution factor solves the problem that it takes too long to evaluate the risk of dispatching decision. The risk index system including line overload risk, reserve shortage risk, load shedding risk and light abandonment risk is established. Finally, two dispatching decisions are generated according to the different acceptance degree of photovoltaic output. By analyzing the risk assessment results of the two dispatching decisions, the accuracy and applicability of the model are verified, which can provide reference for the dispatching decision of the actual power grid.

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