

Distribution Network Risk Evaluation of Photovoltaic Power Cascaded Tripping-off Based on Low Voltage Ride Through Uncertainty

Li Ma, Zi-Rui Li, Yan-Hu Zhang, Yi-Fan Pang, Di Xiao, Xin-Yu Deng, Wen-Zhe Li

Abstract—In order to effectively quantify the risks that may be brought by photovoltaic power trip, a risk evaluation method of distribution network considering photovoltaic power cascaded tripping-off is proposed in this paper. Firstly, the multi-stage voltage sag waveform caused by photovoltaic power cascaded tripping-off under short-circuit fault is analyzed. Secondly, combined with the low voltage ride through curve(LVRTC) of photovoltaic power, considering the uncertainty of low voltage ride through, the virtual upper and lower limit curves of the uncertain area are described according to the characteristics of the normal distribution function, and the trip probability evaluation method of photovoltaic power is proposed. Then, from the two aspects of the possibility of the event and the severity of the consequences, a risk evaluation method of distribution network under photovoltaic power cascaded tripping-off is proposed. Finally, the multi-scenario simulation is carried out by the modified IEEE-30 system. The results show that the risk evaluation method proposed in this paper is reasonable, and provides a basis for reasonably quantifying the risk of distribution network.

Index Terms—Photovoltaic power, Multi-stage voltage sag, Low voltage ride through, Trip probability evaluation, Risk evaluation

I. INTRODUCTION

Photovoltaic power has developed rapidly because of its green environmental protection and economic advantages. Its large-scale access to distribution network is an important way to achieve energy diversification and low

carbonization[1]. However, the access of photovoltaic power also poses new challenges to the reliability and stability of distribution network. Especially when the voltage sag occurs, some photovoltaic powers reach the low voltage ride through limit and occur trip, which may cause a cascade reaction in some cases, resulting in more photovoltaic power trip[2]. Therefore, it is of great significance to accurately evaluate the system risk caused by cascaded tripping-off of photovoltaic power under short-circuit fault.

When the voltage sag occurs at the point of common coupling (PCC) of photovoltaic power, it may cause photovoltaic power reaches the low voltage through limit and trip. In [3], it is pointed out that due to the differences in manufacturing processes of different manufacturers, the low voltage ride through capability of photovoltaic power is ambiguous and uncertain. In [4], the voltage sag tolerance characteristics of photovoltaic power were tested, and the tolerance curves under different voltage sag were drawn, which proved that the low voltage ride through capability of photovoltaic power was different under different voltage sag. In [5], considering the uncertainty of photovoltaic low voltage ride through, some types of photovoltaic inverters were tested for low voltage ride through. Using the test data, only the uncertainty area of photovoltaic low voltage ride through within 0.4s was established. Although the above literature analyzes the uncertainty of the low voltage ride through capability of photovoltaic power, there are still limitations in the study of its uncertainty area.

The large-scale photovoltaic power cascaded tripping-off accident has seriously affected the safety and stability of distribution network, and has caused many scholars to attach great importance to photovoltaic power cascaded tripping-off. In [6], the influence of photovoltaic power trip for the voltage stability of distribution network is analyzed based on the structure and characteristics of photovoltaic grid-connected system. In [7], it is pointed out that photovoltaic power trip will affect the regulated power and frequency of the system, and then affect the stability of the system. The above literature cannot distinguish the working state of each photovoltaic power under fault conditions and the correlation between photovoltaic power. In [8], the voltage distribution model and event timing algorithm are used to analyze the mechanism of photovoltaic power cascaded tripping-off. In [9], it is pointed out that the voltage sag event causes the partial grid-connected photovoltaic power trip, which leads to multi-stage voltage

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sag, resulting in photovoltaic power and sensitive users suffer more serious losses. The above literature ignores the change of the tolerance of photovoltaic power under multi-stage voltage sag. However, its tolerance has a great influence for photovoltaic power cascaded tripping-off under multi-stage voltage sag, so its tolerance must be considered when analyzing photovoltaic power cascaded tripping-off.

Photovoltaic power trip not only affects the economic benefits of distribution network, but also brings risks to the safe and stable operation of distribution network[10]. In [11], the risk evaluation of distribution network with large-scale distributed photovoltaics was carried out from the probability of the system state and the corresponding severity of the consequences. In [12], the outage risk index of distribution network is obtained by the probability of various emergencies in distribution network and the outage consequence index generated by the event. However, there is no relevant literature to systematically evaluate the risk caused by photovoltaic power cascaded tripping-off.

In view of the above problems, a risk evaluation method of distribution network considering photovoltaic power cascaded tripping-off is proposed in this paper. The following sections are organized as follows: Section 2 analyzes the multi-stage voltage sag waveform caused by photovoltaic power cascaded tripping-off under short-circuit fault. Section 3 proposes a method for evaluating the trip probability of photovoltaic power based on the uncertainty of low voltage ride through. Section 4 proposes a risk evaluation method of distribution network considering photovoltaic power cascaded tripping-off. Section 5 uses the modified IEEE-30 system to verify the proposed evaluation method by multi-scenario simulation. Section 6 gives the conclusion.

II. ANALYSIS OF MULTI-STAGE VOLTAGE SAG WAVEFORM CAUSED BY PHOTOVOLTAIC POWER CASCADED TRIPPING-OFF UNDER SHORT-CIRCUIT FAULT

The photovoltaic power cascaded tripping-off is the phenomenon that photovoltaic power connected at other nodes trip is caused by photovoltaic power trip. Taking the modified IEEE-30 system (in Fig.7) as an example, the photovoltaic power is connected at nodes 27 and 26, and the node 26 is set as the voltage observation point. The simulation is carried out by PSCAD, and the simulation result is shown in Fig.1.

Without considering photovoltaic power cascaded tripping-off, the voltage change trend of node 26 is shown in the red line in Fig.1. A three-phase short-circuit fault occurs at a node 50 % away from node 8 on the 8-28 line at time 0. At this time, the voltage amplitude of node 26 drops to 0.401p.u., and the first-stage voltage sag occurs. The photovoltaic power at node 27 trips at time t_{DG1} . At this time, the voltage amplitude of node 26 is further reduced to 0.203p.u., and the second-stage voltage sag occurs. The line protection action at time t_1 . At this time, the fault is removed, and the voltage amplitude of node 26 recovers to 0.88p.u.. However, since the photovoltaic power at node 27 occurs trip, the voltage amplitude of node 26 is not restored to the normal value.

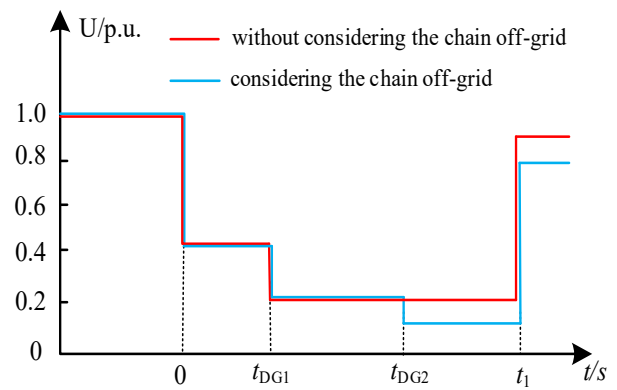


Fig.1. Multi-stage voltage sag waveform under cascaded tripping-off

However, the photovoltaic power at node 27 trips at time t_{DG1} , and the voltage amplitude of node 26 drops to 0.203p.u., resulting in the photovoltaic power at node 26 reaching the low voltage crossing limit and trips at time t_{DG2} . Therefore, considering photovoltaic power cascaded tripping-off, the voltage change trend of node 26 should be changed from the red line to the blue line in Fig.1. The photovoltaic power at node 26 trips at time t_{DG2} . At this time, the voltage amplitude of node 26 is further reduced to 0.151p.u., and the third-stage voltage sag occurs. The line protection action at time t_1 . At this time, the fault is removed, and the voltage amplitude of node 26 recovers to 0.8p.u.. However, since the photovoltaic power at nodes 27 and 26 trip, the voltage amplitude at node 26 is not restored to the normal value.

III. THE TRIP PROBABILITY EVALUATION METHOD OF PHOTOVOLTAIC POWER BASED ON LOW VOLTAGE RIDE THROUGH UNCERTAINTY

A. Multi-stage voltage sag amplitude equivalent method

When the multi-stage voltage sag occurs, the initial process parameters of photovoltaic power under each stage of voltage sag are different[13]. In order to accurately evaluate the trip probability of photovoltaic power under multi-stage voltage sag, it is necessary to reasonably characterize the voltage sag tolerance of photovoltaic power. Process immune time (PIT) is used to reflect the variation of process parameters[14], which can effectively measure the response characteristics of photovoltaic power to voltage sag. Taking the three-stage voltage sag under photovoltaic power cascaded tripping-off as an example, the PIT curve of photovoltaic power under multi-stage voltage sag is reasonably characterized. The results is shown in Fig. 2.

In Fig.2, t_0 is the occurrence time of voltage sag. $t_0 + \Delta t$ is the time when the process parameter deviates from the rated value. L_1 is the PIT characteristic curve of photovoltaic power under the first-stage sag, and its initial process parameter is P_{nom} . t_{DG1} is the occurrence time of the second-stage sag. L_2 is the PIT characteristic curve of photovoltaic power under the second-stage sag, and its initial process parameter is P_1 . t_{DG2} is the occurrence

time of the third-stage sag. L_3 is the PIT characteristic curve of photovoltaic power under the third-stage sag, and its initial process parameter is P_2 . The fault is removed at time t_1 , and the process parameter gradually returns to P_{nom} .

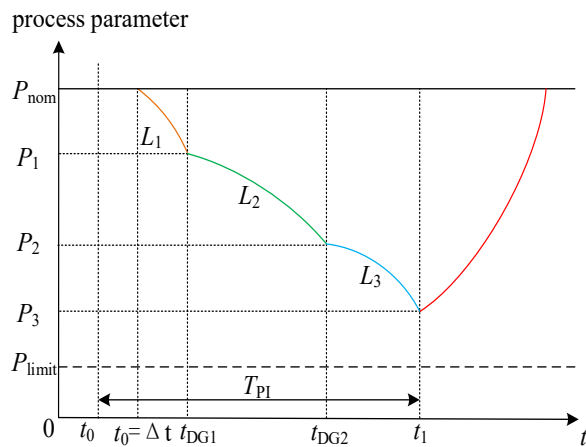


Fig.2. PIT curve of photovoltaic power under three-stage voltage sag

The above analysis shows that there is a correlation between each stage sag. Therefore, when evaluating the trip probability of photovoltaic power under multi-stage voltage sag, in order to make the evaluation results closer to the real situation, it is necessary to fully consider the correlation between each stage sag and reasonably determine the importance proportion of each stage sag. According to the importance proportion of each stage sag, the voltage amplitude of the second-stage sag and the third-stage sag is equivalently calculated. The equivalent voltage amplitude is used to evaluate the trip probability of photovoltaic power, which makes the evaluation results closer to the actual situation. In [15], the initial process parameters of each stage sag in the multi-stage voltage sag PIT curve of sensitive equipment are analyzed, and the analytic hierarchy process is improved by using the correlation and severity index of each stage sag, so as to evaluate the severity of multi-stage voltage sag. Based on the improved analytic hierarchy process in [15], the importance proportion of each stage sag in the multi-stage voltage sag evaluation is solved as $\varepsilon_1, \varepsilon_2, \varepsilon_3$ ($\varepsilon_1 < \varepsilon_2 < \varepsilon_3$). The amplitude of each stage sag is equivalently calculated, and the duration remains unchanged. Because the initial process parameter of photovoltaic power under the first-stage sag is P_{nom} equivalent calculation of its amplitude is not carried out. The initial process parameter of photovoltaic power under the second-stage sag is smaller than P_{nom} . The disturbance caused by the second-stage sag to photovoltaic power is more serious than that caused by the independent sag with the same eigenvalue. Therefore, when the risk evaluation of the second-stage sag is carried out, it can not be regarded as an independent sag. The equivalent calculation should be carried out according to the disturbance caused by voltage sag to photovoltaic power. Considering the correlation of each stage sag, the second-stage sag should be regarded as the independent sag

with a lower amplitude. Therefore, equivalent calculation of multi-stage voltage sag amplitude is carried out by using the weight of each stage sag. In the multi-stage voltage sag, the second stage sag amplitude is equivalent based on the first-stage sag. If the second-stage sag amplitude is U_2 , the equivalent sag amplitude is $U'_2 = \frac{\varepsilon_1}{\varepsilon_2} U_2$. Similarly, if the third-stage sag amplitude is U_3 , the equivalent sag amplitude is $U'_3 = \frac{\varepsilon_1}{\varepsilon_3} U_3$. The equivalent form of multi-stage voltage sag is shown in Fig.3.

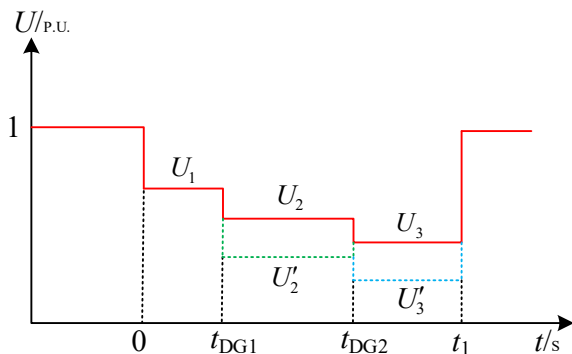


Fig.3. Equivalent of multi-stage voltage sag under photovoltaic power cascaded tripping-off

B. Analysis of uncertainty area of low voltage ride through photovoltaic power

The LVRTC of photovoltaic power can be determined by four inflection points (t_1, U_1) , (t_2, U_2) , (t_3, U_3) , and (t_4, U_4) to determine the characteristic contour of the curve, as shown by the red curve in Fig.4. In order to cope with the main protection rejection caused by communication channel failure, this paper considers the operation of photovoltaic power within 1s.

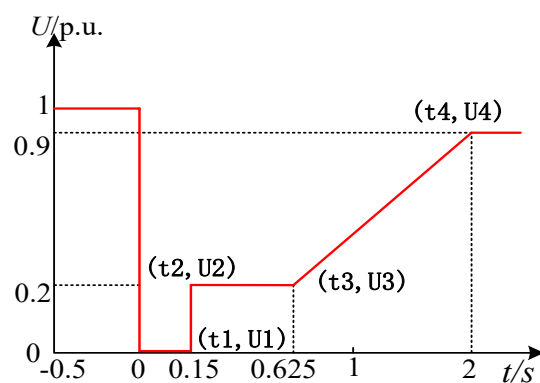


Fig.4. LVRTC of photovoltaic power

Through the low voltage ride through capability test of photovoltaic inverters, it is found that there are great differences in the low voltage ride through capability test of different types of inverters, that is, the PCC of the inverter may trip when it is above the low voltage ride through curve, and may remain grid-connected when it is below. Considering the above situation, it can be approximately considered that its low voltage ride through capability fluctuates in the area near the national standard curve. In

order to more reasonably evaluate the low voltage ride through capability of photovoltaic power, a representation method of virtual upper and lower limit LVRTC is proposed in this paper, as shown in the dashed line in Fig.5.

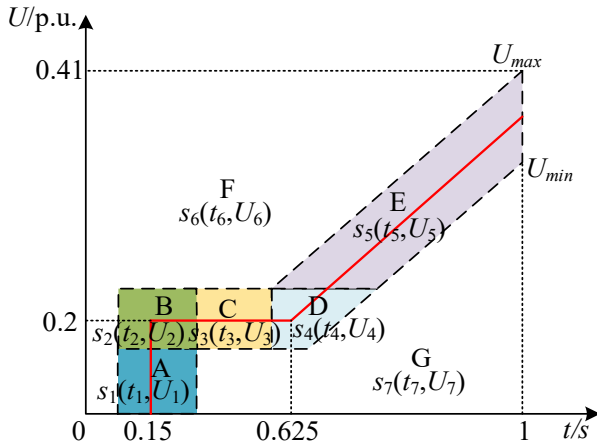


Fig.5. Low voltage ride through uncertainty area of photovoltaic power

When adopting the virtual upper and lower limit curves form with uncertainty area, considering the uncertainty of the low voltage ride through capability of photovoltaic power, the inflection points of the LVRTC can be randomly obtained by changing the values of their t -axis and U -axis according to the normal distribution of the preset given mean and variance. Therefore, the inflection points of the virtual upper and lower limit curves considering uncertainty can be determined by randomly changing the normal distribution function of a set of given parameter values U_i and t_i . That is, the definition of U_1, U_2, U_3, U_4 and t_1, t_2, t_3, t_4 should satisfy the normal distribution with the inflection point value of the standard LVRTC as the expected value.

$$U_1 = f(0, \theta_{u1}) \quad (1)$$

$$t_1 = f(0.15, \theta_{t1}) \quad (2)$$

$$U_2 = f(20\%, \theta_{u2}) \quad (3)$$

$$t_2 = f(0.15, \theta_{t2}) \quad (4)$$

$$U_3 = f(20\%, \theta_{u3}) \quad (5)$$

$$t_3 = f(0.625, \theta_{t3}) \quad (6)$$

$$U_4 = f(90\%, \theta_{u4}) \quad (7)$$

$$t_4 = f(2, \theta_{t4}) \quad (8)$$

Where θ_i is the variance of the normal distribution when i satisfies the inflection point value of the LVRTC of photovoltaic power as the expected value.

The normal distribution function is used to determine the upper and lower limits of each area. Taking the variance of the positive and negative three times of the LVRTC as the upper and lower limits of each area, the probability of voltage sag outside the upper and lower limits of each area does not exceed 0.3 %. Taking the B area (in Fig.5) as an example, the voltage sag amplitude and duration can be defined as:

$$\begin{cases} U_{2\max} = 0.2 + 3\theta_{u2} \\ U_{2\min} = 0.2 - 3\theta_{u2} \\ t_{2\max} = 0.15 + 3\theta_{t2} \\ t_{2\min} = 0.15 - 3\theta_{t2} \end{cases} \quad (9)$$

In order to facilitate analysis and expression, the uncertainty area of low voltage ride through of photovoltaic power is divided into five sub-areas A, B, C, D and E in this paper. Among them, A and C areas are one-dimensional function of t and U respectively, and B, D and E areas are two-dimensional function of t and U . In addition, the F area above the uncertain area is photovoltaic power grid-connected operation area, and the lower area G is photovoltaic power trip area.

C. Evaluation method of trip probability of photovoltaic power under low voltage

Whether the photovoltaic power trip is determined by the voltage sag amplitude and duration of the PCC of photovoltaic power, which can be converted into a probability problem in uncertainty area. The probability model is used to describe the randomness of the low voltage ride through capability, and then the trip probability of photovoltaic power under known fault conditions is evaluated.

Due to the influence of manufacturers, equipment models, operating environment and other factors, the trip probability of photovoltaic power in uncertainty area is uncertain, that is, t and U are random variables. In this paper, based on the research of load voltage tolerance curve[16], the randomness of random variables t and U is characterized by the normal distribution function. It is assumed that the probability density functions of one-dimensional random variables t and U in areas A and C are $f_x(t)$ and $f_y(U)$, respectively, which are expressed as:

$$f_x(t) = \frac{1}{\sqrt{2\pi}\sigma_1} \exp\left[-\frac{(t-0.15)^2}{2\sigma_1^2}\right] \quad (10)$$

$$f_y(U) = \frac{1}{\sqrt{2\pi}\sigma_2} \exp\left[-\frac{(U-0.2)^2}{2\sigma_2^2}\right] \quad (11)$$

Where $t \in [0, 1]$, $U \in [U_{\min}, U_{\max}]$, σ_1 and σ_2 are the distribution densities of t and U , respectively. Since t and U are two independent random variables, the joint probability density function of random variables t and U in areas B, D and E can be expressed as:

$$f_{xy}(t, U) = f_x(t)f_y(U) = \frac{1}{\sqrt{2\pi}\sigma_1\sigma_2} \exp\left\{-\frac{1}{2}\left[\frac{(t-0.15)^2}{\sigma_1^2} + \frac{(U-0.2)^2}{\sigma_2^2}\right]\right\} \quad (12)$$

According to the characteristics of the normal distribution function, the values of σ_1 and σ_2 can be further solved as follows:

$$\begin{cases} \sigma_1 = (0.15-0)/3 = 0.05 \\ \sigma_2 = (0.2-U_{\min})/3 \end{cases} \quad (13)$$

It is assumed that the voltage sag of the PCC of photovoltaic power has seven cases of $s_1 \sim s_7$, which are located in the A, B, C, D, E, F, and G areas, as shown in Fig. 5. U_i and t_i are the voltage sag amplitude and duration of s_i , respectively. When $s_1 \sim s_7$ sag occurs, the trip

probabilities of photovoltaic power are expressed as:

$$\begin{cases} P_{s1} = \int_{t_{\min}}^{t_1} f_x(t) dt, 0.14 \leq t \leq t_1 \\ P_{s2} = \int_{t_{\min}}^{t_2} \int_{U_2}^{U_{\max}} f_{x,y}(t, U) dt dU, 0.14 \leq t \leq t_2, U_2 \leq U \leq U_{\max} \\ P_{s3} = \int_{U_3}^{U_{\max}} f_y(U) dU, U_3 \leq U \leq U_{\max} \\ P_{s4} = \int_{U_4}^{t_4} \int_{U_4}^{U_{\max}} f_{x,y}(t, U) dt dU, 0.59 \leq t \leq t_4, U_4 \leq U \leq U_{\max} \\ P_{s5} = \int_{t_{i5}}^{t_5} \int_{U_5}^{U_{\max}} f_{x,y}(t, U) dt dU, 0.66 \leq t \leq t_5, U_5 \leq U \leq U_{\max} \\ P_{s6} = 0, U_{\max} \leq U \\ P_{s7} = 1, U \leq U_{\min} \end{cases} \quad (14)$$

IV. DISTRIBUTION NETWORK RISK EVALUATION METHOD OF PHOTOVOLTAIC POWER CASCADED TRIPPING-OFF

The photovoltaic power cascaded tripping-off will not only affect the economic benefits of distribution network, but also affect the operation of distribution network. When the power grid loses part of its power generation capacity, it will change the power flow of the local power grid, causing the node voltage and line current to exceed the limit. Risk refers to the harm of an event with lossy consequences that may occur in a certain period of time. It is usually expressed as the product of the probability of the event that causes this harm and the severity of the consequences caused by the event. A risk evaluation method with three risk categories for distribution network of photovoltaic power cascaded tripping-off is proposed in this paper. The events in the evaluation method include short-circuit fault occurs on the line and photovoltaic power trip. The three risk categories are node voltage over-limit risk, branch current over-limit risk, and photovoltaic power trip capacity loss risk.

A. Consequence severity model

The calculation formulas of the over-limit loss values of the above three risk categories are as follows:

1) *The first risk: the node voltage over-limit loss value*

$$\tau_u = \begin{cases} \frac{u_{\min} - u_i}{u_{\min}}, u_i \leq u_{\min} \\ 0, u_{\min} \leq u_i \leq u_{\max} \\ \frac{u_i - u_{\max}}{u_{\max}}, u_i \geq u_{\max} \end{cases} \quad (15)$$

Where u is the bus voltage; $u_{\min}$ and $u_{\max}$ are the lower and upper limits of system operation voltage, respectively.

2) *The second risk: the branch current over-limit loss value* τ_I

$$\tau_I = \begin{cases} \frac{I_i - I_r}{I_r}, I_i \geq I_r \\ 0, I_i \leq I_r \end{cases} \quad (16)$$

Where, I_i and I_r are the system branch bus current and the branch current threshold of the low-voltage distribution network, respectively.

3) *The third risk: the photovoltaic power trip capacity loss value* τ_c

$$\tau_{c_i} = \begin{cases} 0, c_i \leq 0 \\ \frac{c_i}{c_p}, c_i > 0 \end{cases} \quad (17)$$

Where c_i is the capacity of photovoltaic power trip; c_p is the total capacity of the system photovoltaic power.

For the above three risk categories, the severity of the consequences of the three risks is calculated respectively. In this paper, the risk-oriented utility function [17] is used to construct the consequence severity model, and the expression is:

$$S_{ev} = \frac{e^{\tau} - 1}{e - 1} \quad (18)$$

Where τ is the over-limit loss value of the m -th type risk.

B. The establishment of risk index

In order to make the risk evaluation results of distribution network reasonable and accurate, the constructed risk index usually cover two aspects: the probability of event and the severity of the consequences caused by the event. In this paper, the probability of event includes the probability of a short-circuit fault on the line and the probability of photovoltaic power trip under this short-circuit fault. The severity of the consequences of the three risks caused by the event is calculated by section A. In summary, the risk index of distribution network is established, and the specific calculation formula is shown in Equation (19):

$$R_m = \sum_{N_l=1}^N \sum_{K=1}^4 \sum_{i=1}^n \delta_K P_i S_{ev-m} \quad (19)$$

Where R_m is the m -th type risk index; N is the total number of lines; K is the type of short-circuit fault; n is the total number of photovoltaic power in distribution network; δ_K is the probability of line failure; P_i is the probability of the i -th photovoltaic power trip; S_{ev-m} is the severity of the consequence of the m -th type risk caused by the event.

C. Determination of risk index weight

Due to the differences in the significance and units of each risk index, it is difficult to determine the relative weights. The above risk index are to evaluate the impact of photovoltaic power cascaded tripping-off to distribution network from one aspect. In order to comprehensively evaluate the impact of photovoltaic power cascaded tripping-off to distribution network, BWM method and CRITIC method are used to further quantify the above risk index from both subjective and objective aspects. In summary, the above three risk index are weighted, and the combined weights are determined by the Lagrange multiplier method [18]. After calculation, the weights of the three risk index are 0.20, 0.33 and 0.47, respectively.

D. Total risk evaluation

Considering the three risk index and their corresponding weights, the calculation formula of the total risk value under photovoltaic power cascaded tripping-off is:

$$R = \sum_{m=1}^3 R_m \omega_m \quad (20)$$

Where R_m is the total risk value of distribution network of photovoltaic power cascaded tripping-off; ω_m is the weight of the m -th type risk index.

The risk evaluation process is shown in Fig.6:

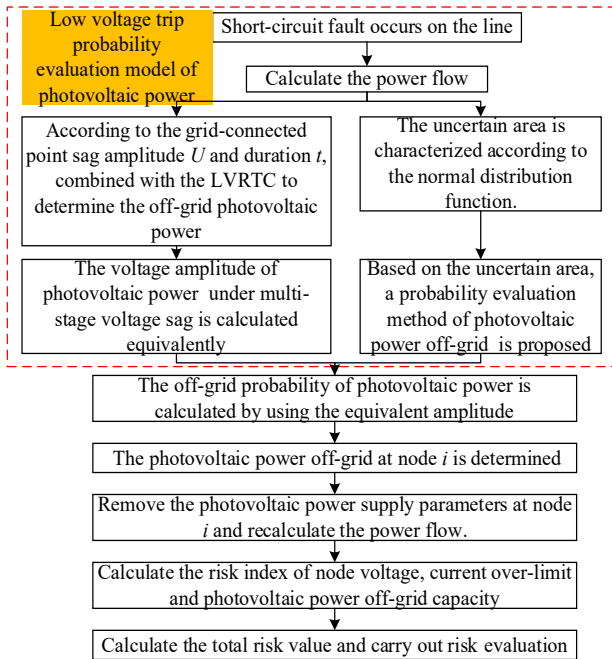


Fig.6. Risk evaluation process of distribution network of photovoltaic power cascaded tripping-off

V. CASE ANALYSIS

The risk evaluation method proposed in this paper is applied to the modified IEEE-30 node system as an example for simulation. The probability of single-phase grounding fault, two-phase grounding fault, two-phase interphase fault and three-phase short circuit fault on the line is 78 %, 11 %, 7 % and 4 % respectively[19].

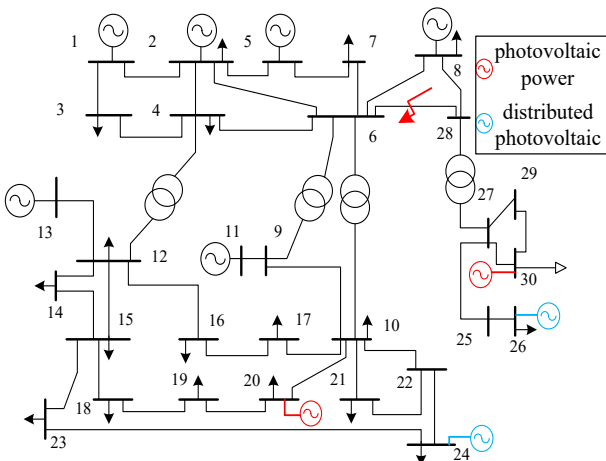


Fig.7. IEEE-30 bus system with photovoltaic

As shown in Fig7, the photovoltaic power with low voltage ride through capability is connected at nodes 20 and 30, and the capacity is 10 MW each. The distributed photovoltaic with only under-voltage protection is connected at nodes 24 and 26, and the capacity is 1MW each. The under-voltage protection threshold is 0.7p.u., and the protection delay action time is 0.2s[20]. In order to simplify the calculation, it is assumed that U_{max} 、 U_{min} and

T_{max} of all photovoltaic power are 0.3.p.u 、0.1.p.u and 0.2s respectively in low voltage ride through uncertain area, and the parameters in the probability density function are determined according to the equation (10)-(13), that is, $\sigma_2 = 0.33$.The voltage sag amplitude in the case analysis is per unit value. The following scenarios are simulated and analyzed.

1) Scenario 1: Risk evaluation of distribution network without considering photovoltaic cascaded tripping-off

In the modified IEEE-30 node system, a short-circuit fault is set at a node 50% away from node 6 on the 6-28 line, and the fault duration is 0.6 s. The voltage sag amplitude of each photovoltaic node under different fault types is shown in Table I.

TABLE I
VOLTAGE SAG AMPLITUDE OF EACH PHOTOVOLTAIC NODE UNDER DIFFERENT FAULTS ON THE 6-28 LINE

The location of the photovoltaic node	single-phase grounding	two-phase grounding	two-phase interphase	three-phase
20	0.788	0.677	0.656	0.474
24	0.765	0.582	0.551	0.428
26	0.691	0.517	0.495	0.394
30	0.654	0.408	0.336	0.279

According to Table 1, it can be seen that the voltage sag amplitude of the distributed photovoltaic at node 26 under the single-phase grounding fault is 0.691p.u., which is less than the under-voltage protection threshold, and the distributed photovoltaic at node 26 occurs trip. The voltage sag amplitude of the distributed photovoltaic at node 24 is 0.765p.u., which is larger than the under-voltage protection threshold, and the distributed photovoltaic at node 24 remains grid-connected operation. The voltage sag amplitudes of photovoltaic power at nodes 20 and 30 are 0.788p.u. and 0.654p.u., respectively, both of which fall in the F area of the low voltage ride through uncertain area of photovoltaic power, so both of them remain grid-connected operation. Similarly, under the two-phase grounding and two-phase interphase faults, the distributed photovoltaic at nodes 26 and 24 trip. The photovoltaic power at nodes 20 and 30 remain grid-connected operation. Under the three-phase short circuit fault, the distributed photovoltaic at nodes 26 and 24 trip. The photovoltaic power at node 20 remain grid-connected operation. The voltage sag amplitude of the photovoltaic power at node 30 is 0.279p.u., which falls in the C area of the uncertain area, and the trip probability is calculated to be 7.88%. The trip probability of each photovoltaic without considering photovoltaic cascaded tripping-off is shown in Fig.8.

In summary, the risk evaluation of distribution network without considering photovoltaic cascaded tripping-off is carried out. Considering the four types of short-circuit faults, the total risk value of distribution network is calculated to be 0.028 by using equation (20). The risk values of distribution network under single-phase grounding fault, two-phase grounding fault, two-phase interphase fault and three-phase fault are 0.018, 0.002, 0.003 and 0.005 respectively.

TABLE II

THE VOLTAGE SAG NON-EQUIVALENT AMPLITUDE OF EACH PHOTOVOLTAIC NODE UNDER DIFFERENT FAULTS ON THE 6-28 LINE

The location of the photovoltaic node	single-phase grounding			two-phase grounding		two-phase interphase		three-phase		
	M1	M2	M3	M1	M2	M1	M2	M1	M2	M3
20	0.788	0.744	0.715	0.677	0.584	0.656	0.613	0.474	0.439	0.336
24	0.765	0.688	—	0.582	—	0.551	—	0.428	—	—
26	0.691	—	—	0.517	—	0.495	—	0.394	—	—
30	0.654	0.603	0.588	0.408	0.364	0.336	0.288	0.279	0.235	—

TABLE III

THE VOLTAGE SAG EQUIVALENT AMPLITUDE OF EACH PHOTOVOLTAIC NODE UNDER DIFFERENT FAULTS ON THE 6-28 LINE

The location of the photovoltaic node	single-phase grounding			two-phase grounding		two-phase interphase		three-phase		
	M1	M2	M3	M1	M2	M1	M2	M1	M2	M3
20	0.788	0.634	0.527	0.677	0.434	0.656	0.492	0.474	0.315	0.209
24	0.765	0.635	—	0.582	—	0.551	—	0.428	—	—
26	0.691	—	—	0.517	—	0.495	—	0.394	—	—
30	0.654	0.513	0.459	0.408	0.268	0.336	0.246	0.279	0.196	—

Note : M1 in the table is the first-stage voltage sag ; M2 is the second-stage voltage sag ; M3 is the third-stage voltage sag ; “—” denotes that the photovoltaic connected at this node occurs trip.

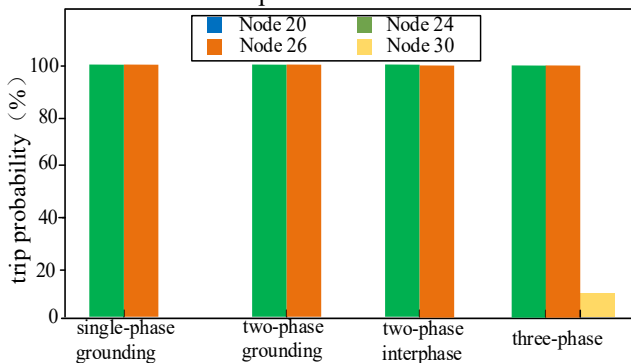


Fig.8. The trip probability of each photovoltaic under different faults

2) Scenario 2: Risk evaluation of distribution network considering the multi-stage voltage sag non-equivalent amplitude under photovoltaic cascaded tripping-off

The setting of fault type, location and photovoltaic is the same as above. The voltage sag non-equivalent amplitude of each photovoltaic node under different fault types is shown in Table II.

According to Table 2, it can be seen that each photovoltaic occurs the first-stage voltage sag under the single-phase grounding fault. The distributed photovoltaic at node 26 occurs trip. The photovoltaic at nodes 20, 24 and 30 occurs the second-stage voltage sag, and the voltage sag amplitude of the distributed photovoltaic at node 24 is 0.688p.u., which is less than the under-voltage protection threshold, and the distributed photovoltaic at node 24 occurs trip. Then photovoltaic power at nodes 20 and 30 occurs the third-stage voltage sag, and the voltage sag amplitudes are 0.71p.u.and 0.588p.u., respectively, both of which fall in the F area of the uncertain area, so both of them remain grid-connected operation. Similarly, each photovoltaic occurs the first-stage voltage sag under the two-phase grounding fault. The distributed photovoltaic at nodes 26 and 24 trip at the same time. Then photovoltaic power at nodes 20 and 30 occurs the second-stage voltage sag, and the voltage sag amplitudes are 0.584p.u.and 0.364p.u., respectively, both of which fall in the F area of the uncertain area, so both of them remain grid-connected operation. Each photovoltaic occurs the first-stage voltage sag under the two-phase interphase fault. The distributed photovoltaic at nodes 26 and 24 trip at the same time. Then

photovoltaic power at nodes 20 and 30 occurs the second-stage voltage sag. The voltage sag amplitude of the photovoltaic power at node 20 is 0.613p.u., which falls in the F area of the uncertain area, so the photovoltaic power at node 20 remain grid-connected operation. The voltage sag amplitude of photovoltaic power at node 30 is 0.288p.u., which falls in the C area of the uncertain area, and the trip probability of photovoltaic power at node 30 is calculated to be 5.21%. Each photovoltaic occurs the first-stage voltage sag under the three-phase short circuit fault. The distributed photovoltaic at nodes 26 and 24 trip at the same time. Then photovoltaic power at nodes 20 and 30 occurs the second-stage voltage sag. The voltage sag amplitude of the photovoltaic power at node 20 is 0.439p.u., which falls in the F area of the uncertain area, so the photovoltaic power at node 20 remain grid-connected operation. The voltage sag amplitude of photovoltaic power at node 30 is 0.235p.u., which falls in the C area of the uncertain area, and the trip probability of photovoltaic power at node 30 is calculated to be 43.75%. It is assumed that the photovoltaic power at node 30 occurs trip. At this time, the photovoltaic power at node 20 occurs the third-stage voltage sag. The voltage sag amplitude of photovoltaic power at node 20 is reduced from 0.439p.u.to 0.336p.u., but it still falls in the F area in the uncertain area, so the photovoltaic power at node 20 remain grid-connected operation. The trip probability of each photovoltaic considering the multi-stage voltage sag non-equivalent amplitude under photovoltaic cascaded tripping-off is shown in Fig.9.

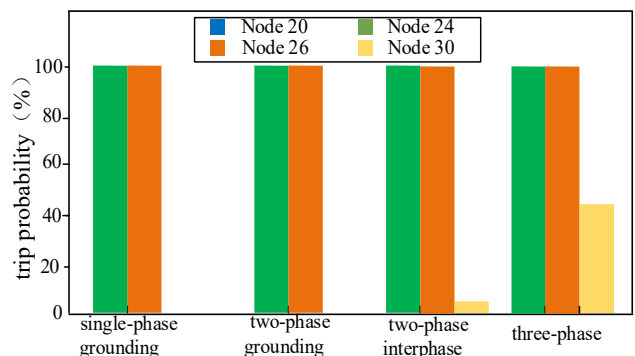


Fig.9. The trip probability of each photovoltaic the multi-stage voltage sag non-equivalent amplitude under different faults

In summary, the risk evaluation of distribution network considering the multi-stage voltage sag non-equivalent amplitude under photovoltaic cascaded tripping-off is carried out. Considering the four types of short-circuit faults, the total risk value of distribution network is 0.047. The risk values of distribution network under single-phase grounding fault, two-phase grounding fault, two-phase interphase fault and three-phase fault are 0.029, 0.003, 0.004 and 0.0011 respectively.

3) Scenario 3: Risk evaluation of distribution network considering the multi-stage voltage sag equivalent amplitude under photovoltaic cascaded tripping-off

The setting of fault type, location and photovoltaic is the same as above. The amplitude of the multi-stage voltage sag is calculated equivalently. Since the initial process parameters of photovoltaic under the first-stage voltage sag are normal value, the process parameters of photovoltaic under the second-stage and third-stage voltage sag are lower than the normal value. Therefore, it is not necessary to equivalently calculate the first-stage voltage sag amplitude, only the second and third-stage voltage sag amplitude needs to be equivalently calculated, and the equivalent amplitude is expressed in blue font. The voltage sag equivalent amplitude of each photovoltaic node under different fault types is shown in Table III.

According to Table 3, it can be seen that each photovoltaic occurs the first-stage voltage sag under the single-phase grounding fault. The distributed photovoltaic at node 26 occurs trip. The photovoltaic at nodes 20, 24 and 30 occurs the second-stage voltage sag, and the voltage sag equivalent amplitude of the distributed photovoltaic at node 24 is 0.635p.u., which is less than the under-voltage protection threshold, and the distributed photovoltaic at node 24 occurs trip. Then photovoltaic power at nodes 20 and 30 occurs the third-stage voltage sag, and the voltage sag equivalent amplitudes are 0.527p.u. and 0.459p.u., respectively, both of which fall in the F area of the uncertain area, so both of them remain grid-connected operation. Similarly, each photovoltaic occurs the first-stage voltage sag under the two-phase grounding fault. The distributed photovoltaic at nodes 26 and 24 trip at the same time. Then photovoltaic power at nodes 20 and 30 occurs the second-stage voltage sag. The voltage sag equivalent amplitude of the photovoltaic power at node 20 is 0.434p.u., which falls in the F area of the uncertain area, so the photovoltaic power at node 20 remain grid-connected operation. The voltage sag amplitude of photovoltaic power at node 30 changed from non-equivalent 0.364p.u. to equivalent 0.268p.u., from the F area to the C area in the uncertain area, and the trip probability of photovoltaic power at node 30 changed from 0% to 8.48%. Each photovoltaic occurs the first-stage voltage sag under the two-phase interphase fault. The distributed photovoltaic at nodes 26 and 24 trip at the same time. Then photovoltaic power at nodes 20 and 30 occurs the second-stage voltage sag. The voltage sag equivalent amplitude of the photovoltaic power at node 20 is 0.492p.u., which falls in the F area of the uncertain area, so the photovoltaic power at node 20 remain grid-connected operation. The voltage sag amplitude of photovoltaic power at node 30 changed from non-equivalent 0.288p.u. to

equivalent 0.246p.u., from the F area to the C area in the uncertain area, and the trip probability of photovoltaic power at node 30 changed from 5.21% to 22.16%. Each photovoltaic occurs the first-stage voltage sag under the three-phase short circuit fault. The distributed photovoltaic at nodes 26 and 24 trip at the same time. Then photovoltaic power at nodes 20 and 30 occurs the second-stage voltage sag. The voltage sag equivalent amplitude of the photovoltaic power at node 20 is 0.315p.u., which falls in the F area of the uncertain area, so the photovoltaic power at node 20 remain grid-connected operation. The voltage sag amplitude of photovoltaic power at node 30 changed from non-equivalent 0.235p.u. to equivalent 0.196p.u., from the C area to the B area in the uncertain area, and the trip probability of photovoltaic power at node 30 changed from 43.75% to 93.71%. It is assumed that the photovoltaic power at node 30 occurs trip. At this time, the photovoltaic power at node 20 occurs the third-stage voltage sag. The voltage sag amplitude of photovoltaic power at node 20 changed from non-equivalent 0.336p.u. to equivalent 0.209p.u., from the F area to the B area in the uncertain area, and the trip probability of photovoltaic power at node 20 changed from 0% to 79.57%. The trip probability of each photovoltaic considering the multi-stage voltage sag equivalent amplitude under photovoltaic cascaded tripping-off is shown in Fig.10.

Through the above analysis, it can be seen that using the voltage sag equivalent amplitude to evaluate the trip probability of photovoltaic is much larger than the non-equivalent trip probability. The reason for this phenomenon is that the voltage sag equivalent amplitude considers the influence of the multi-stage voltage sag to photovoltaic tolerance. Therefore, in the case of the multi-stage voltage sag, when evaluating the trip probability of photovoltaic, considering the change of photovoltaic tolerance will make the evaluation result of trip probability of photovoltaic more reasonable and accurate.

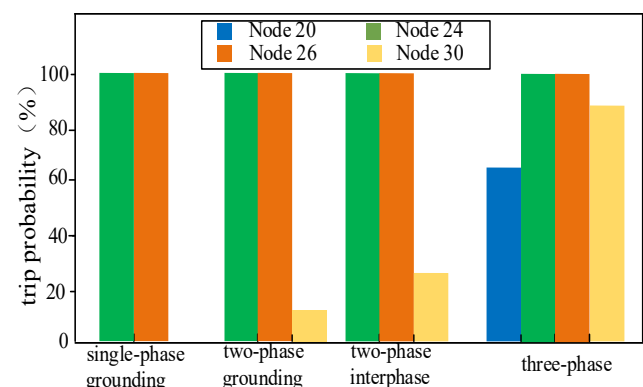


Fig.10. The trip probability of each photovoltaic the multi-stage voltage sag equivalent amplitude under different faults

In summary, the risk evaluation of distribution network considering the multi-stage voltage sag amplitude equivalent under photovoltaic cascaded tripping-off is carried out. Considering the four types of short-circuit faults, the total risk value of distribution network is 0.093. The risk values of distribution network under single-phase grounding fault, two-phase grounding fault, two-phase interphase fault and three-phase fault are 0.034, 0.006,

0.009 and 0.0044 respectively.

In order to more intuitively reflect the changes of distribution network risk in the above three scenarios, the total risk value under each scenario is statistically analyzed, and the result is shown in Fig.11. It can be seen that the total risk value of the system under scenario 2 is 0.019 larger than that of scenario 1, and the total risk value of the system under scenario 3 is 0.046 larger than that of scenario 2 and 0.065 larger than that of scenario 1. The above results show that after considering the influence of photovoltaic cascaded tripping-off and the multi-stage voltage sag to photovoltaic, the total risk value of distribution network increases sharply. It can be seen that considering photovoltaic cascaded tripping-off in the risk evaluation of distribution network makes the results of risk evaluation more reasonable and avoids under-evaluation.

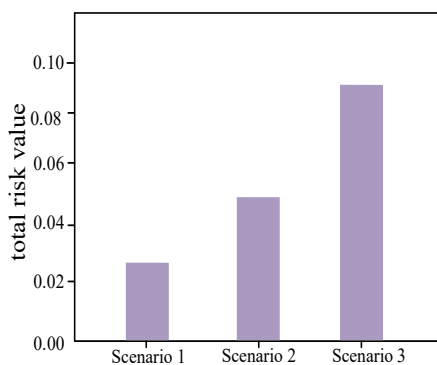


Fig11. The total risk of the system under each scenario

VI. CONCLUSION

1) The photovoltaic power cascaded tripping-off mechanism under short-circuit fault is analyzed, and the multi-stage voltage sag waveform caused by photovoltaic power cascaded tripping-off is described.

2) Combined with the LVRTC of photovoltaic power, considering the uncertainty of low voltage ride through, the virtual upper and lower limit curves of the uncertain area are described according to the characteristics of the normal distribution function. Based on the uncertainty area, a photovoltaic power trip probability evaluation method is proposed. Through the simulation analysis and comparison of different scenarios of the modified IEEE-30 node system, the results show that the trip probability evaluation method of photovoltaic power proposed in this paper is more reasonable and accurate.

3) From the two aspects of the possibility of the event and the severity of the consequences, and the risk evaluation method of distribution network considering photovoltaic power cascaded tripping-off is proposed. By setting different scenarios for simulation, the results show that the risk evaluation method of distribution network proposed in this paper is reasonable and effective, which avoids the under-evaluation without considering photovoltaic cascaded tripping-off, and provides a basis for reasonably quantifying the risk of distribution network.

REFERENCES

[1] Liu J, Xu Q H, Wang E Z, Li T C, Feng G L, "Voltage Regulation

Strategies for Photovoltaic Grid-Connected Systems Utilizing Electric Springs," *IAENG International Journal of Computer Science*, vol.52, no.6, pp.1704-1711, 2025.

- [2] F. Wen, P. Acuna, J. Yang, Z. Y, "Low-Voltage Ride-Through Scheme for Distributed Generation Inverters Using a Modified Current Reference Strategy," *IEEE International Conference on Industrial Technology*, pp.1-7, 2024.
- [3] Qiu C G, Zhang Z H, Li L Q, et al, "Static Voltage Stability Analysis of a Power Grid with New Energy Sources Considering DSCC," *Electric Power Construction*, vol.44, no.10, pp.33-40, 2023.
- [4] Ge L M, Qu L N, Chen N, Zhu L Z, Zhang L, "Characteristic Analysis of Low Voltage Ride-through and Parameter Test Method for Photovoltaic Inverter," *Automation of Electric Power Systems*, vol.42, no.18, pp.149-156, 2018.
- [5] Tan H Z, Li Y L, Chen X L, Zhao M Y, Liu N, Huang W F, "Reactive voltage control partitioning based on power network pilot node identification," *Electric Power Automation Equipment*, vol.35, no.8, pp.31-37, 2015.
- [6] Chen L, Zhang X, Dang X Y, Li H, Feng T C, "Low-voltage Ride-through Control of Photovoltaic Virtual Synchronous Generator Using Novel Model Prediction," *Journal of Power Supply*, vol.22, no.4, pp.163-172, 2024.
- [7] Xu D, Wang H T, "High Risk Cascading Outage Assessment in Power Systems With Large-scale Wind Power Based on Stochastic Power Flow and Value at Risk," *Power System Technology*, vol.43, no.2, pp.400-409, 2019.
- [8] Fu Y, Li W, Xiong N, "Influence of trip/grid-connected operation on stability of large-scale photovoltaic system," *Energy Reports*, vol.9, no.57, pp.904-910, 2023.
- [9] Ma L, Lou J H, Li Y, Chen Y Y, Liu X, Zhang Y H, "Severity Assessment of Nonrectangular Wave Voltage Sags from Load Side and Power Side Based on Curve Fitting," *IAENG International Journal of Computer Science*, vol.51, no.10, pp.1596-1603, 2024.
- [10] Wang Y, Luo H, Xiao X Y, "Joint Optimal Planning of Distributed Generations and Sensitive Users Considering Voltage Sag," *IEEE Transactions on Power Delivery*, vol.37, no.1, pp.93-104, 2021.
- [11] Zhang M, Liu J, Liu Y, "Lightning risk assessment of active distribution network with distributed photovoltaic system," *Energy Reports*, vol.12, pp.3711-3717, 2024.
- [12] Liu J, Li G F, Sun S Y, Li F J, Xu M M, "A Review of Early Warning and Risk Assessment Technologies for Distribution Networks under Rainstorm Disasters," *Journal of Northeast Electric Power University*, vol.42, no.6, pp.1-7+111-112, 2022.
- [13] Xiao X Y, Chen W, Yang H G, "Multi-uncertainty Assessment for Failure Level of Sensitive Equipment Caused by Voltage Sag, Proceedings of the CSEE," vol.30, no.10, pp.36-42, 2010.
- [14] Li D D, Xiao X Y, Liu Y, Li T N, Liu X N, "Voltage sag mitigation scheme using protection optimization with process immunity time," *Electric Power Automation Equipment*, vol.34, no.9, pp.95-100, 2014.
- [15] Ma L, Chen Y Y, Tian D R, Lou J H, Li Y, Zhang Y H, "Severity evaluation of multistage voltage sag based on an improved analytic hierarchy process," *Power System Protection and Control*, vol.51, no.17, pp.49-57, 2023.
- [16] Liu X N, Xiao X Y, Wang Y, "Voltage Sag Severity and Its Measure and Uncertainty Evaluation," *Proceedings of the CSEE*, vol.34, no.4, pp.644-658, 2014.
- [17] Bi P P, Xu X Y, Mei W M, Zhang L K, Li M C, Bai B H, "Study on Cascaded Tripping-off Risk Assessment Method and Delivery Capacity of Wind Power Base," *Power System Technology*, vol.43, no.3, pp.903-910, 2019.
- [18] Sun K C, Xue W L, Li T T, Zhang Q Q, "IT2FS-MARCOS method for risk assessment of water conservancy engineering construction," *Journal of Hydroelectric Engineering*, vol.43, no.7, pp.109-120, 2024.
- [19] Ma L, Zhang Y H, Chen Y Y, "Multi-stage voltage sag frequency evaluation based on process immunity in the distribution network," *International Journal of Emerging Electric Power Systems*, vol.26, no.2, pp.359-370, 2024.
- [20] Wang H J, Zhang Y, Yin S L, et al, "Voltage Instability and Harmonic Risk for the Distributed Photovoltaic Grid-Connected System," *Power System and Clean Energy*, vol.40, no.3, pp.128-138+146, 2024.