Distribution System Risk Assessment with Intermittent Distribute Generation

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Abstract. In order to evaluate quantitatively the influence of intermittent distributed power supply on distribution system, the stochastic model of distributed power supply is improved. Vertical distribution system circuit random failure probability model, based on the full probability theory in the risk assessment in a random fault line road. Establish a negative charge voltage gain and the loss of the limit of the section point level and system level two levels of risk indicators, in the comprehensive evaluation system of the influence of many kinds of random factors, realized the quantitative evaluation of distribution system operation risk. The test example verifies the real use and effectiveness of the proposed algorithm.

1. Introduction
Distributed generator supply access to distribution system not only brings good economic benefits and environmental benefits, but also brings risks to distribution system due to its randomness of output. Therefore, how to quantitatively evaluate the randomness of distributed generator supply output and the risk of system safety and stability caused by component failures in the system becomes an urgent problem to be solved.

Literature [1], based on the fuzzy comprehensive evaluation theory, using the triangular fuzzy number complementary judgment matrix to assign the weight of risk index, constructs the risk assessment model of distribution network operation, comprehensively considers the uncertain factors, and evaluates the operation risk of distribution network. Document [2], based on the loss and risk of the probability assessment of the outage of power equipment caused by sudden events, establishes an emergency warning level determination method based on the power outage risk. Literature [3] adopts the value-at-risk method commonly used in finance and insurance to evaluate the risk of distribution network through system assets and shutdown losses. Literature [4] proposed system risk indexes based on reliability indexes and considering the influence of distributed generator supply. At the same time, for the distributed generator supply processing is rough, there is no corresponding risk model. Therefore, it is urgent to study the risk assessment model of intermittent distributed generator supply for distribution system risk assessment with distributed generator supply. Considering the impact of distributed generator supply on power flow of distribution system, risk assessment index system should be established to quantitatively evaluate the operational risk of the system, so as to assist planning and operational personnel in strategies. [5]

In this paper, based on the probability theory of stochastic flow calculation method, many kinds of random factors in the system, including distributed generator output of the intermittent, load lines of volatility and random failure, and to improve random flow calculation model of distributed generator
supply, to risk concept level node voltage, the more limited risk index and risk of loss of load index and the degree of overall risk indicators, to measure the risk to the safe operation of generator distribution system with distributed generator.

2. Risk Assessment Model of Distribution System Based on Stochastic Power Flow

2.1. Stochastic Power Flow Based on Semi-invariant Method

The power flow equation of the system is expressed as:

\[ S = f(V) \]  

In the formulation, \( S \) is the injected power vector of the node, \( V \) is the voltage vector of the node, and \( f(\cdot) \) is the power flow equation.

Formulation (1) is expanded by Taylor series, ignoring higher order terms:

\[ V = V_0 + \Delta V = V_0 + J_0^{-1} \Delta S \]  

Similarly, the branch power equation can be expressed as:

\[ H = g(V) \]  

In the formulation, \( H \) is the branch power vector and \( G \) is the branch power equation.

By expanding formulation (3) with Taylor series and ignoring higher order terms, we can obtain that:

\[ H = g(V_0) + G_0 \Delta V = R_0 + G_0 J_0^{-1} \Delta S \]

In the formulation: \( G_0 \) is the sensitivity matrix.

Formulation (2) and formulation (4) are both linear expressions. The probability distribution of state vectors \( V \) and \( H \) can be obtained by the probability distribution of \( S \). In this paper, the convolution calculation is simplified by the semi-invariant method, and the probability distribution of state variables of the system is obtained by the Gram-Charlier series expansion [6].

By using the characteristic of semi-invariants, we can get from formulation (2):

\[ \Delta V_k = (J_0^{-1}(i, j))^k \Delta S_k \]

In the formulation, \( \Delta V_k \) is the k-order semi-invariant of voltage, \( J_0^{-1}(i, j) \) is the element in the I th row and J th column of the sensitivity matrix. Similarly, the semi-invariants of each order of branch power can be obtained.

The probability distribution function of node voltage can be obtained by using Gram-Charlier series expansion:

\[ f(z) = \phi(z) + A_1 \phi^{(1)}(z) + A_2 \phi^{(2)}(z) + A_3 \phi^{(3)}(z) + \cdots \]

In the formulation, the probability density function of the standard normal distribution is \( \phi(z) \); \( \phi^{(k)}(z) \) is the k-th derivative of \( \phi(z) \); \( A_k \) is the coefficient, which can be obtained from the center distance of each order semi invariant.

2.2. Stochastic Power Flow Model for Distributed Generation

The output of distributed generator generation using wind energy depends on wind speed, so it is necessary to study wind speed to accurately calculate the output of wind turbine. It is generally believed that the wind speed obeys the Weibull distribution [7].

\[ f(v) = \left( \frac{k}{c} \right)^{k-1} \left( \frac{v}{c} \right)^{k-1} \exp \left( -\left( \frac{v}{c} \right)^k \right) \]  

In the formulation, \( k \) is the shape parameter, \( c \) is the scale parameter and \( v \) are the wind speed.
The probability distribution of fan output can be derived from the probability distribution of wind speed and the power curve of fan. Where \( P_r \) is the rated output power of the fan; \( P_w \) is the output power of the fan; \( v_{ci}, v_r, \text{ and } v_{co} \) are the cut-in wind speed, rated wind speed and cut-out wind speed of the fan respectively. Therefore, according to formulation (7), the probability distribution of the active power output of the fan is shown as follows.

1) When \( v \leq v_{ci} \cup v \geq v_{co} \), \( P_w = 0 \)

\[
P(P_w = 0) = \int_0^{v_{ci}} f(v)dv + \int_{v_{co}}^{\infty} f(v)dv
\]

(8)

2) When \( v_{ci} < v < v_{co}, 0 < P_w \leq P_r \)

\[
F(P_w) = P(P_w < p_w) = \int_0^{v_{ci}} f(v)dv + \int_{v_{ci}}^{v_{co}} + \frac{v - v_{ci}}{P_r} f(v)dv
\]

(9)

3) When \( v_r < v < v_{co}, P_w = P_r \)

\[
P(P_w = P_r) = \int_{v_r}^{v_{co}} f(v)dv
\]

(10)

Assuming that the fan is controlled by constant power factor, the reactive power can be expressed as follows:

\[
Q_w = P_w \tan \varphi
\]

(11)

In the formulation, \( \varphi \) is the power factor angle. The probability distribution of the reactive power output of the fan can be obtained from formulation (8) to formulation (11).

From formulation (8) to formulation (10), it can be seen that the probability distribution of fan's active output is neither continuous nor discrete. According to Lebesgue theory, fan's active output is a mixed variable, so its origin distance is defined as:

\[
a_n = \int_0^{v_{ci}} P^n_w dF(P_w) + P^n_r P(P_w = P_r)
\]

(12)

The first half of formulation (12) considers the continuity of the active output of the fan, i.e. the wind speed is between the cut-in wind speed and the rated wind speed, while the second half considers the discreteness of the output, i.e. the wind speed is between the rated wind speed and the cut-out wind speed. The relationship between wind speed and fan output is described.

According to the transformation relationship between formulation (12) and point moments and semi-invariants, the semi-invariants of each order of fan active power output can be calculated. Similarly, the semi-invariants of each order of fan reactive power output can be obtained by combining formulation (11).

2.3. Stochastic Power Flow Model Considering Line Random Faults

Random faults of transmission lines are important uncertainties in distribution systems, so their effects must be considered in risk assessment. Based on the theory of total probability, the stochastic power flow considering the stochastic faults of transmission lines can be expressed as follows [8]:

\[
P(B) = \sum_i P(B|S_i)P(S_i)
\]

(13)

In the formulation, \( P(B) \) is the probability distribution of the variable to be solved; \( P(S_i) \) is the formation probability of the i-th network structure; \( P(B|S_i) \) is the conditional distribution of variables to be solved under the i-th network structure. \( P(S_i) \) can also be expressed as a function of the line failure rate, i.e.

\[
P(S_i) = \prod_{j=1}^{n} (1 - P_j)\prod_{j=1}^{n} P_j
\]

(14)
In the formulation, \( P_i \) and \( P_j \) are respectively the probabilities of line faults of \( i \) and \( j \); \( n_u \) and \( n_u \) are respectively the number of fault free lines and the number of fault lines. Where, the probability of line failure can be expressed as:

\[
P = \frac{L \lambda r}{8760} = \frac{LU}{8760}
\]  

(15)

In the formulation, \( L \) is the line length; \( \lambda \) is the wiring failure rate; \( r \) is the line fault repair time; \( U \) is the average annual blackout duration of the line.[9]. In order to simplify the calculation, this paper considers only a single fault of line and does not consider the related faults of line, thus greatly reducing the space of network structure and improving the calculation efficiency. When \( S' \) denotes the reduced network structure space, \( P(S_i) \) can be denoted as \( P'(S_i) \), which is defined as:

\[
P'(S_i) = \frac{P(S_i)}{P(S')} = \frac{P(S_i)}{\sum_{k=1}^{n'} P(S_i)}
\]  

(16)

In the formulation: \( n' \) is the number of reduced network structures [10].

3. Index System and Assessment Procedure of Distribution System Risk Assessment

3.1. Indicators

This article uses this concept to the probability distribution of voltage and line fault probability model of quantitative possibility, using the theory of utility type to take risk preference utility function to establish the severity function quantitative result.

1) Node Voltage Overrun Risk Index

The node voltage over-limit risk index reflects the risk that the voltage exceeds the given threshold under different operating states of the system, i.e

\[
R_{V_i} = \sum_k P_k \int_{0}^{0.95} f(V_{ki}) U_{dl}(V_{ki}) dV_{ki} + \sum_k P_k \int_{1.05}^{\infty} f(V_{ki}) U_{ul}(V_{ki}) dV_{ki}
\]  

(17)

In the formulation, \( P_k \) is the probability of the formation of the \( k \)-th network structure, \( f(V_{ki}) \) is the probability density function of the node \( i \) voltage under the \( k \)-th network structure, and \( U(\cdot) \) is the severity function of voltage over-limit, specifically

\[
U_{dl}(V_{ki}) = e^{0.95-V_{ki}} - 1 \\
U_{ul}(V_{ki}) = e^{V_{ki}-1.05} - 1
\]  

(18)

2) Loss of Load Risk Indicators

Load loss risk index reflects the risk of load loss at the point when the line fails, i.e

\[
R_{B_i} = \sum_k P_k F_{ki} U(B_i)
\]  

(19)

In the formulation, \( F_{ki} \) is the sign of node \( i \)'s load loss under the \( k \)-th network structure, if the load loss is 1, otherwise 0; \( U(\cdot) \) is the severity function of load loss, which can be expressed as

\[
U(B_i) = e^{E(F_i)} - 1
\]  

(20)
In formulation $E(P_i)$ is the active expectation of node $i$.

3) Node Comprehensive Risk Indicators

Nodal comprehensive risk index comprehensively reflects nodal voltage over-limit and load loss risk in a weighted form, and represents nodal level risk, i.e.

$$R_i = b_1 R_{v_i} + b_2 R_{b_i}$$  \hspace{1cm} (21)

In the formulation: $b_1$ and $b_2$ are weight coefficients, which can be adjusted according to risk preference. This paper takes 0.5.

4) Overall risk

The overall risk degree index takes the node importance as the coefficient to weight the comprehensive risk of all nodes in the system, and represents the overall risk of the system, i.e.

$$R = \sum_{i=1}^{n} \omega_i R_i$$  \hspace{1cm} (22)

In the formulation, $n$ is the total number of nodes in the system, $\omega_i$ is the importance of nodes, which can be expressed by considering the power characteristics and network characteristics of nodes.

$$\omega_i = \frac{0.5 E(P_i)}{E(P_i) + 0.6 M_i}$$  \hspace{1cm} (23)

Formulation: $M_i$ is the degree of node $i$, i.e. the number of lines connected by this node.

3.2. Overall process of risk assessment

According to the foregoing discussion, the overall process of risk assessment for distribution system with intermittent distributed generations is as follows.

1) Input grid parameters, including grid structure parameters, distributed generation, load probability distribution parameters, line failure rate parameters.

2) Determine the set of line faults, i.e. the complete set of system lines.

3) After identifying the system network structure in the case of concentrated line faults, the effective islands are determined according to the islands partitioning strategy mentioned in Section 1.3. Then the load loss risk is calculated for "dead island", the random power flow is calculated for "live island", and the voltage overrun risk is calculated by using the voltage probability density function.

4) Traversing the fault line and calculating the risk index by formulation (13).

4. Analysis of three examples

In this paper, IEEE33 bus distribution system is taken as an example. The standard deviation of node load is 10% of its expected value. Wind speed probability distribution parameters: shape parameter $k$ is 2.80038, scale parameter $c$ is 8.141687. The rated power of the fan is 2MW. The cut-in wind speed, rated wind speed and cut-out wind speed are 3m/s, 14m/s and 25m/s respectively. In order to more comprehensively analyze the influence of distributed generator supply on its safe operation after it is connected to the distribution system, this paper is divided into six cases for research and analysis.

Case 1: The influence of rated output of distributed generator supply on the system is studied. Taking the distributed generation accessing system from node 17 as an example, the rated output is 1 MW, 1.5 MW and 2 MW respectively.

Case 2: Study the impact of changes in access points of distributed generator on the system. The rated output of distributed generator supply remains unchanged at 2MW. The connection of distributed generator supply from node 5, node 10, node 32 and node 17 to the system is studied respectively.

Case 3: Study the impact of distributed generator supply access mode on system risk. The decentralized access and centralized access were compared and studied.

Case 1 studies the impact of accessing distributed generator supplies of different capacities on system risk. When the distributed generator supply rated output is 1MW, the overall risk of the system
is the lowest, and it can be seen that the system risk is not positively related to the access capacity. Therefore, if the overall risk is used as a measure, then a distributed generator supply with a rated capacity of 1 MW should be selected. Therefore, given the acceptable degree of risk of the system, the access capacity of the distributed generator source will be limited, and the penetration rate of the distributed generator of the system can be studied.

Case 2 studies the impact of distributed generator access points on the overall risk of the system. It can be seen that the distributed generator source has the lowest risk of accessing the system from the node 10. When the access from node 5, node 10 access and node 32 access, the overall risk of the system changes little, but when the node 17 is connected to the system, the overall risk is increased by more than 6 times, because the distributed generator is from When the node 17 is connected to the system, the risk of the system voltage exceeding the limit increases sharply. Therefore, the risk index can provide a reference for the optimized selection of the distributed generator access point.

In case 3, the distributed generator access capacity does not change to 2 MW, and the access mode is changed from centralized access to distributed access: two distributed generator sources with a single unit capacity of 1 MW are respectively connected to the system from node 17 and node 32. Therefore, in order to reduce system risk, a distributed generator multipoint access system can be considered.

5. Conclusion
In this paper, the method of stochastic power flow based on total probability theory is used to evaluate the risk of distribution system with distributed generation. By defining a new origin moment, the stochastic power flow model of distributed generation is improved, and the influence of stochastic faults of transmission lines in the system is fully considered in the risk assessment. The risk evaluation indexes such as voltage overshoot, load loss risk index and system overall risk degree are established, which comprehensively reflects the influence of uncertain factors such as output power of intermittent distributed generator generation, load fluctuation and random fault of transmission line on the safe operation of the system, and quantifies the safety risk of the system. The example analysis based on IEEE33 bus system shows that the proposed algorithm can comprehensively evaluate the impact of random factors in the system, quickly and accurately calculate system risks, and provide decision-making basis and support for power system operation planners.

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