Study on reliability assessment of distribution networks containing distributed power supplies

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Abstract. With a large number of distributed power sources connected to the distribution network, power supply reliability has always been one of the most concerned indicators for power supply companies. Fault mode and effect analysis (FMEA) can predict the impact of fault isolation and load switching diversity in active intelligent distribution networks. In this paper, a standardized model of reliability system evaluation is constructed by FEMA table, and the reliability index is solved by combining Monte Carlo analysis method. The simulation with IEEE-RBTS BUS6 as an example shows that the method can quantify the effect of distributed power supply on the reliability of active distribution network, which proves that the proposed method is effective and feasible to solve the index.

1. Introduction

With the development of new energy technologies and power electronics, distributed power supplies (DG), power electronics devices and loads will be connected to the distribution network in large numbers. The power generated by distributed power sources relying on renewable resources may fluctuate greatly, and short-time outages account for an increasing proportion of customer outage events, becoming an important factor affecting power supply reliability[1]. The inability to calculate short-time outage indicators is an important shortcoming of the existing distribution network reliability assessment methods[2].

The traditional reliability assessment considers that the feeders of the distribution network are all powered by a single power point, and a failure on any of the feeders will result in a total loss of power to the load behind the feeders and a large area outage in the system. With the development of traditional distribution system to intelligent power grid, it is beneficial to promote DG access. With a large number of DG access to distribution grid, the analysis and calculation model of its reliability has changed fundamentally. Distributed access to distribution grid transforms the radiation mode of single power source into the network mode of multiple power sources with complex operation, the traditional reliability assessment method is no longer applicable, and the new method needs further research[3].

In order to measure the current state of the smart distribution network and its benefits and impacts on the country and society, a proven smart distribution network assessment system is needed[4]. International and domestic reliability index standards have been published for distribution network assessment, and a reliability assessment procedure was proposed in the literature [5] to accurately assess...
the impact of conventional power equipment failures on reliability by modeling the time-varying failure rate of conventional power equipment. The literature [6-7] gave a reliability assessment of the distribution network of a hybrid wind/light/wood generation system by discrete convolution. Literature [8] proposed a unitary planning system and method based on distribution network topology, which provided theoretical support for the refined research and evaluation of distribution networks. Literature [9] established a grid-based medium-and low-voltage smart distribution network evaluation index system, and proposed a combined least squares and gray correlation analysis method for the shortcomings of existing evaluation methods. The literature [10] proposes reliability indicators reflecting customers' electricity experience at 2 levels: customer-side indicators and comparison indicators.

For this reason, this paper combines the characteristics and the current situation of the distribution network, by generating the FEMA table of the system generated by traversing all the expected accidents, getting the load outages when different faults occur and listing the faults and their impacts in the fault mode impact table [11], combined with the Monte Carlo method for solving the reliability indexes. The experimental part takes IEEE-RBTS BUS6 as an arithmetic example, and proposes a more realistic reliability index calculation method by considering the real-time failure rate of components in the process of sequential Monte Carlo simulation.

2. Forms of distributed power access to the grid
The influence of different access methods of DG on the power supply reliability of distribution network, from the current research on DG at home and abroad, there are mainly 3 forms of DG access to distribution network, and the influence of each form on the power supply reliability is different.

2.1. DG operates in parallel with the conventional grid
When DG operates in parallel with the conventional grid, the distribution network changes from a radial network to a network with interconnected power sources and customers all over. It has both positive and negative effects on reliability. If the control is not good it may make the system power supply reliability level decrease and not meet the customer's requirement for power supply reliability, on the contrary, it can improve the reliability of the distribution network. After DG is connected to the conventional grid, the traditional distribution network reliability model needs to consider new factors, such as the emergence of islands. Therefore, a new reliability model is needed to evaluate the impact of joining DG on the distribution network power supply reliability and to quantify the index impact of reliability.

In the traditional distribution network, the load can only get power from the superior grid, and in the absence of backup, any failure of the components in the superior grid will affect the load, whereas in the distribution network with DG, when the components in the superior grid fail, the load within the capacity of DG can maintain power supply, and DG can operate in isolation, which is also a feature of the reliability calculation model of the distribution network with DG. Islanded operation is a special operation mode of DG-containing distribution network, and its impact on the reliability assessment model is large. As shown in Fig.1 typical operation modes exist for DG-containing distribution networks.

![Fig 1. Distribution network with DG](image-url)
Most DGs cannot provide stable power output like a large power supply, the response of power output with load changes is limited, and the stability of islanding operation can be affected by factors such as changes in DG status.

2.2. DG as backup power for traditional distribution network
When the power supply is interrupted by a system fault in the traditional distribution network, the DG is activated and the load is transferred to the DG to continue supplying power through the operation of the switch. When the distribution network fault is eliminated, it is then transferred to the distribution network for normal power supply. In this case, DG can improve the reliability of power supply to the distribution network as long as DG coordination is reasonable. However, the economy of such power supply is poor, unless to meet the needs of special important loads. Otherwise, a large amount of DG investment can only meet a small amount of load cutting in case of fault, and it is difficult to stimulate investment in the power market environment. It is difficult to achieve a win-win situation in terms of economy and reliability.

2.3. Conventional distribution network as back-up power for DG
DG operates independently and the fluctuation of power load makes it difficult to ensure that the generator meets continuous fluctuating load operation. By using the distribution grid as a backup power source for DG, when DG generates more power than the supplied load, the excess power of the unit will be injected into the distribution grid. When the power generated by DG is not enough to meet the load demand, the shortage will be supplemented by the distribution grid, and the power quality of users will be improved due to the support of a large distribution grid. This allows the generator to always operate at a more economical operating condition. Moreover, by measuring the power injected into and absorbed from the distribution grid, the customer pays only the difference in power. This maximizes the economy of the DG, takes into account the interests of the investors and better reflects the concept of smart grid, but the reliability aspect of the distribution network is unknown. This paper studies this form of access.

3. Smart distribution network fema tables and reliability standardization model
The impact of DG access on the power supply reliability of small distribution networks is analyzed, and the supply reliability of distribution networks containing DGs is calculated and analyzed using the Failure Mode and Effect Analysis (FMEA)\(^\text{[12]}\) method, and it is concluded that the supply reliability is improved after accessing DGs compared with that before accessing DGs, so the correct way of accessing DGs to distribution networks is adopted to help improve the supply reliability of customers. The basic method of distribution network reliability assessment is FMEA. This method analyzes all possible faults, determines the impact of each fault, and forms a fault impact statement. It is the basic method used to assess the reliability of the distribution system, and this method is usually used for distribution network power supply reliability calculations.

3.1 FEMA table standardization establishment
The FEMA table in a distribution network can describe the fault outage time at each load point under a predefined set of component fault incidents. Mathematically, for a distribution network with M elements and N load nodes, the FEMA table can be expressed as a two-dimensional matrix, denoted as:

\[
A_p = \{A_{mn}\}_{M \times N}
\]

Where: \(A_p\) is the FEMA composition; \(A_{mn}\) is the fault outage time of the nth load when the mth component fails.

After a fault occurs in any element of the active intelligent distribution network, the type of fault can be divided into four categories according to the resulting load outage time:
- category a, when the fault is not affected by the fault node, the equipment works normally.
- category b, where the fault occurs by isolating the faulty area making the equipment work normally and the outage time is the isolation time.
Category c, when a fault occurs, through the isolation of the fault area and switching recovery operation to start the backup power supply, so that the equipment works normally, the downtime is the isolation time plus the switching time.

Category d, when a fault occurs, the equipment is restored to power supply by repairing the components, and the outage time is the component repair time.

Since the load type of the load under different component failures is also different, therefore, considering M components of the active intelligent distribution network, for the active intelligent distribution network with N load nodes, its post-fault load classification is identified as a three-dimensional matrix of MxNx4, denoted as S which can be specifically expressed as:

\[
S = [S_a, S_b, S_c, S_d]
\]  

Where \( S_a, S_b, S_c, S_d \) is the 4 M\times N dimensional binning matrix of matrix S, denoted as:

\[
\begin{align*}
S_a &= \{A_{a,mn}\}_{M \times N} \\
S_b &= \{A_{b,mn}\}_{M \times N} \\
S_c &= \{A_{c,mn}\}_{M \times N} \\
S_d &= \{A_{d,mn}\}_{M \times N}
\end{align*}
\]  

Where the element \( A_{a,mn}, A_{b,mn}, A_{c,mn}, A_{d,mn} \) takes the value of 0 or 1, indicating the category of the nth load after the mth component failure, if the category is a class a load, then \( A_{a,m} \) take 1, \( A_{b,m}, A_{c,m}, A_{d,m} \) take 0; if it is a class b, c or d load, take the same case.

In the load classification after the fault, there is no outage time for class a load, and the outage time for class b and c loads are \( t_b, t_c \), respectively, and the outage time for class d load is \( t_d,m \). Denote \( t_d \) as the diagonal matrix composed of elements \( t_d,m \), and \( t_d,m \) denote the average repair time of component m faults, the formula is:

\[
t_d = \begin{pmatrix}
    t_{d,1} & 0 & 0 & 0 & 0 \\
    0 & \ldots & 0 & 0 & 0 \\
    0 & 0 & t_{d,m} & 0 & 0 \\
    0 & 0 & 0 & \ldots & 0 \\
    0 & 0 & 0 & 0 & t_{d,M}
\end{pmatrix}_{M \times N}
\]  

Considering the identification of each load classification after the failure, the two-dimensional matrix \( A_{FEMA} \) standardized calculation model of FMEA table is:

\[
A_{FEMA} = t_b S_b + t_c S_c + t_d S_d
\]  

### 3.2 Reliability index calculation method

The large number of DGs connected to the distribution system will have the following effects on reliability indicators.

- Introduce the reliability index of generator sets into the distribution system. With the access of DG in the system, the failure rate, average fault-free availability hours, and start-up reliability of the generator set should also be considered.
- Evaluation of access capacity. Access to the system will raise operational and coordination issues, and security metrics are used to assess DG capacity reliability.
- Coordinated system control scheme. DG access to the system will lead to increased short-circuit current, voltage fluctuation due to uncoordinated power output and load, thus interfering with voltage control, reducing or increasing network losses, etc. If the system and DG protection equipment and its control scheme are not properly set or not coordinated, it will weaken the reliability and safety of the system power supply, for this reason, it is necessary to introduce indicators to measure the impact of DG protection control on the distribution system. For this
reason, indicators to measure the impact of DG protection control on the distribution system need to be introduced.

- Indicators for assessing the impact of DG need to be introduced into the system metrics. Traditional system metrics for reliability assessment include system outage frequency, outage duration and average power supply availability, which are derived based on the weighted average value of load point metrics.

Based on the above analysis, the distribution network reliability indexes can be calculated and analyzed, and the common indexes at home and abroad are as follows shown below.

- System Average Outage Frequency Indicator $SAIFI$, refers to the average number of outages per customer powered by the system per unit of time, in units of times/(household-year).

$$SAIFI = \frac{\sum \lambda_i N_i}{\sum N_i}$$

Where: $\lambda_i$ is the average failure rate at the load point; $N_i$ is the number of users at the load point.

- System Average Outage Duration Indicator $SAIDI$, which refers to the average duration of outages per unit of time per customer powered by the system in units of h/(household-year).

$$SAIDI = \frac{\sum U_i N_i}{\sum \lambda_i N_i}$$

- Average user outage duration indicator $CAIDI$, refers to the unit time user average time per outage unit h/(household year)

$$CAIDI = \frac{\sum U_i N_i}{\sum \lambda_i N_i}$$

- The total system power shortage indicator $ENS$, refers to the total outage of the outage load in the system in kWh/year.

$$ENS = \sum L_{ui} U_i$$

Where: $L_{ui}$ The average load size of load point i.

- The average power supply availability index $ASAI$, refers to the ratio of the time per unit of time that a customer actually receives power supply to the time that it is requested to receive power supply.

$$ASAI = \frac{8760 \sum N_i - \sum U_i N_i}{8760 \sum N_i} = 1 - \frac{SAIDI}{8760}$$

### 3.3 Simulation and solution method for distribution network reliability

The distribution network reliability simulation solution method uses Monte Carlo simulations. The typical approach to assessing reliability includes the following steps: simulating network faults, operating protection devices, identifying affected load points, restoring the applied supply technology and calculating the reliability index. The performance of protective devices (circuit breakers, manual switches, fuses, reclosers, automatic sectionalizers) and reconfiguration scenarios are also included in the reliability assessment methodology.

The method is based on component failure rates and fault fitting with random probabilities, where the states of the components are sampled by computer-generated random numbers and then combined to obtain the state of the system. When the simulation time is long enough, the error generated by this randomness can be ignored, and it can be solved by the combination of FEMA and Monte Carlo methods, and the solution block diagram is shown Fig 2.
4. Example analysis

4.1 Example parameters
Based on the IEEE-RBTS BUS 6 system, a regional intelligent distribution network is used as a simulation case, and a photovoltaic power generation system is added to the original system. The simulation model is shown in Fig.3. The distribution network is a radial network structure with multiple load points, which is a widely used grid configuration in China at present. The fault handling process with and without distribution network automation technology and the time required for each step are given.
Table 1. Equipment reliability index

| Parameters | Line | Power distribution transformer | Circuit Breaker | DG |
|------------|------|--------------------------------|-----------------|----|
| Failure rate | 0.065 times/(km·a) | 0.015 times/unit | 0.004 times/(km·a) | 5 times /a |
| Average repair time | 5 | 70 | 4 | 50 |

Based on the methodology of the FEMA table first established, the indicators were derived and compared using a combination of Monte Carlo. The contribution of distribution network automation technology to reliability was quantified by subdividing the fault handling process, so that more reasonable reliability index calculations were obtained and both the $SAIFI$ index and $SAIDI$ index of the distribution network were substantially improved.

Table 1. Reliability index of the system

| Reliability index of the system | Evaluation Index |
|--------------------------------|------------------|
| $SAIFI$ (times/) | $SAIDI$ (h/) | $EENS$ (MWh/year) | ASAI (%) | CAIDI (h/) |
| Results of this paper | 1.4719 | 4.5329 | 89.27 | 0.9995 | 9.6063 |
| Literature Results | 1.967 | 6.527 | 88.496 | 0.9992 | 10.23 |

5. Conclusions
As a new type of new energy generation technology, the access of distributed energy can make the whole grid operation more flexible. In this paper, by studying the unitary active distribution grid power supply reliability affected by fault index system and outage index system, the FMEA table establishment process takes into account the topology of distribution grid and the influence of distributed power sources, and by automatically and quickly establishing FMEA tables for different types of complex distribution, it improves the the calculation efficiency of the reliability assessment procedure.

The impact of DG access to the distribution network is correctly considered, and the future analysis of the impact of DG access to the distribution network power supply reliability provides a method. The calculation results are reasonable and the effectiveness of the algorithm is verified. Reasonable configuration of DG type and capacity can effectively meet the uninterrupted power demand of important loads. How to balance operation cost-efficiency, power supply capacity and other requirements, the reasonable selection of DG type and capacity further study is still needed.

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