Analysis and design of energy storage capacity of AC-DC hybrid power distribution unit with energy storage to improve the reliability of power grid

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Abstract. Based on the development of AC-DC distribution network, a new AC-DC distribution device with energy storage structure is designed in this paper. This paper first analyzes the existing AC-DC power distribution equipment and network reliability assessment methods. On this basis, the design is put forward, the energy storage link is placed at the DC high voltage side. The constraints of energy storage as a critical load backup power supply are defined and the mathematical model is established. In this paper the timing Monte Carlo method is used to calculate the reliability of the device and the power grid. The model in this paper can be applied to a variety of distribution network structure and energy storage scenarios, with high accuracy. It is concluded that the AC-DC distribution unit has remarkable effect in improving reliability.

1. Introduction

Compared with traditional power distribution network, AC-DC power distribution network has the obvious advantages of friendly access to new energy, adapting to the demand of multiple loads, convenient control, high power quality and strong transmission capacity. AC-DC power distribution equipment is a key node in the comprehensive energy application system characterized by the extensive application of power electronics. The AC-DC distribution network should not only solve the problem of overall reliability but also meet the demand of new energy access and electricity distribution. Therefore, it is of great significance to improve the reliability of AC-DC power distribution unit and to analyze the reliability of the whole network.

Document [1] uses the method of reliability assessment to calculate the influence of energy storage power stations with different access capacities and different nodes of the distribution network on the power supply reliability index of the distribution network respectively. Document [2] evaluated the reliability index of power generation system composed of wind farm and energy storage system by analytical method. It considers the effects of charging and discharging rate, capacity limitation and failure rate of energy storage equipment. Document [3] builds energy storage equipment and wind power generation system on the basis of [1,3], and analyzes the reliability index model and method of power supply at the same time. On the macro level, it considers the influence of different energy storage and release control strategies on the reliability of power generation system. Document [4] comprehensively considers the economy, power supply reliability and environmental protection of the
system; The influence of different optimization models on the optimal power supply configuration was analyzed. Based on the adaptive weighted particle swarm optimization algorithm, the optimal power supply configuration under different optimization models was simulated and analyzed, and the feasibility and correctness of the proposed model were verified. However, the influence of energy storage on planning is not considered in this paper.

This paper aims to improve the reliability of network power supply. A new AC/DC power distribution device containing energy storage on the high voltage side is set up, and the power supply reliability constraint is added, so the calculation result is relatively accurate. In this paper, the monte Carlo method is used to calculate the reliability of power supply, which can simulate the power supply scene more accurately, and the accuracy is higher in the calculation of complex network structure.

2. Design method of energy storage capacity

2.1. Energy storage model

The characteristic of the new AC-DC power distribution unit is that the high voltage port on the DC side is equipped with an energy storage structure, so that it has the ability to improve the reliability of power supply. In this paper, the internal charging and discharging process of the battery energy Storage system (BESS) is not considered when studying the optimal configuration of the battery energy Storage system (BESS), so the mathematical modeling of BESS can be carried out from the aspects of remaining electric quantity, charging and discharging power, etc [3]. The recurrence relation of the quantity is as follows.

- Charging process:
  \[
  \text{SOC}(t) = \text{SOC}(t-1) + \frac{P_c \cdot \Delta t \cdot \eta_c}{E_c}
  \]  
  \[ (1) \]

- Discharge process:
  \[
  \text{SOC}(t) = \text{SOC}(t-1) - \frac{P_d \cdot \Delta t}{E_c \cdot \eta_d}
  \]  
  \[ (2) \]

Where \( \text{SOC}(t) \) is the battery charged state of the energy storage system at the end of time period \( t \); \( \text{SOC}(t-1) \) is the charged state of the battery at the end of the \( t-1 \) period; \( P_c \) and \( P_d \) are respectively the charging and discharging power of the energy storage system, kW; \( \eta_c \) and \( \eta_d \) represent the charging and discharging efficiency of the energy storage system respectively, \%. Rated capacity of \( E_c \) energy storage system, kW·h.

Battery parameters are shown in the table below (Table 1).

| The parameter                      | The value |
|-----------------------------------|-----------|
| Maximum charged state             | 0.9       |
| Minimum charged state             | 0.1       |
| Charge and discharge efficiency   | 0.8       |
| Charging and discharging power    | 100       |
| Rated energy storage capacity     | 200       |

2.2. Energy storage capacity configuration strategy

The function of energy storage in the system is determined first when calculating the power capacity. In this paper, energy storage is used as a backup power source for critical loads. At this time, it is generally not put into operation. It will only be put into operation to maintain the normal operation of critical loads when there is a fault in the power grid. It can maintain the power supply of important loads for two hours [5].

The steps for calculating the maximum capacity required for the energy storage system are as follows:

- The function of the energy storage device is to provide power supply for critical loads. Therefore, the capacity of the energy storage device should be set at least as the maximum power demand of the critical load within two hours.
1) Where, $W$ is the capacity of the energy storage system under ideal conditions. Considering the fluctuation of load, $W$ should be selected with a certain margin. $P_K$ is the actual critical load power. $T_c$ is the power supply time for the energy storage device to meet the key requirements. In this paper, take 2 hours.

$$W = P_K \times T_c$$  \hspace{1cm} (3)

2) Considering the limitations of the Depth of discharge (DOD) temperature and actual operating efficiency of the energy storage system, the capacity that should be possessed by the energy storage system can be modified by the following formula.

$$W' = \frac{W \times A \times K}{\eta \times DOD}$$  \hspace{1cm} (4)

Where, $A$ is the safety factor (generally 1.1~1.4); $K$ is the temperature correction coefficient (1 for above 0°C, 1.1 for above -10°C, and 1.2 for below -10°C); $\eta$ is the power conversion efficiency of the energy storage system; DOD is the discharge depth[6].

2.3. Reliability calculation method
In the above paper, we introduce the model of energy storage to equivalent the energy storage of AC-DC power distribution unit, and then combine with the time-series Monte Carlo method to construct the reliability-based configuration of energy storage capacity of AC-DC power distribution unit containing energy storage [7].

![Figure 1. Schematic diagram of Monte Carlo simulation element operation.](image)

Monte Carlo method is a method of sampling from known probability distribution by constructing or describing probability process. By simulating the historical process of system operation, the extracted system state is analyzed. It simulates the state alternation process of “run - repair - run - repair” of each component according to the time sequence to obtain the duration of each component's run - repair state. By combining the operation and repair process of each component, a time-ordered sequence of system states can be obtained, as shown in Figure 1. Therefore, the timing Monte Carlo method can take into account the advantages of the operation strategy of complex power system, but its disadvantages are difficult programming and long calculation time [5].

The basic steps of sequential Monte Carlo simulation are as follows:
Step1: Set the initial state of the element. Generally, the initial state of all elements is considered to be working normally;
Step2: set the simulation time total. When the simulation time exceeds this time, set the initial simulation time $i = 1$;
Step3: Sample the duration of staying in the current state for m components in the system. For different states, such as normal working state and failure state, it can be assumed that they follow different state duration probability distributions.
Step 4: Repeat Step 3 in the simulation time and conduct multiple sampling to obtain the sequential transfer process of m components;
Step 5: Combine the state transition process of m components to obtain the sequential state transition sequence of the system;
Step 6: Analyze each time sequence state of the system and calculate the required reliability index.

Table 2. Failure rate and repair time of each component.

| Device                      | Failure rate/(Times per year) | Time to repair/h |
|-----------------------------|-------------------------------|------------------|
| AC circuit breaker          | 0.006                         | 4                |
| DC circuit breaker          | 0.2999                        | 10               |
| Converter                   | 0.0237                        | 2.55             |
| AC transformer              | 0.015                         | 10               |
| Photovoltaic generator set  | 0.518                         | 167              |
| Wind generator set          | 0.291                         | 72               |

It can be seen from the above content that the Monte Carlo method is used to calculate the reliability, which requires the failure rate and repair time of each component in the power grid. Table 2 shows the failure rate and repair time of each component. The repair time and repair rate of each component are reciprocal relations. The failure time and repair time of each component are as follows:

\[
\begin{align*}
T_{TTF}^i &= -(1 / \lambda_i) \cdot \ln u_1 \\
T_{TTR}^i &= -(1 / \mu_i) \cdot \ln u_2
\end{align*}
\]

Where \( T_{TTF}^i \) and \( T_{TTR}^i \) are the normal operating time and failure time of component \( i \) respectively, \( \lambda_i \) and \( \mu_i \) are the failure rate and repair rate of the component respectively, and \( u_1 \) and \( u_2 \) are random numbers with uniform distribution in the interval of \((0, 1)\). The calculation formula of power supply reliability is as follows[8]:

\[
ASAI = \frac{8760 - \sum U_i / N}{8760} \times 100\%
\]

Where, \( ASAI \) is the average power supply availability rate, which is used to represent the power supply reliability in this paper, \( N \) is the total number of loads, and \( U_i \) is the outage time of each user [9].

3. The port reliability of AC-DC hybrid power distribution unit with energy storage
The purpose of this paper is to explore the reliability improvement effect of AC-DC distribution network distribution equipment containing energy storage on the network. Therefore, firstly, the reliability changes of power distribution unit without energy storage and with energy storage are compared.

![Figure 2](image_url)

Figure 2. Schematic diagram of three-port AC/DC power distribution unit.

Figure 2 shows the schematic diagram of a three-port AC-DC power distribution device with energy storage on the high-voltage side proposed in this paper. The existence of the 4-port energy
storage structure will certainly change the reliability of the three internal ports of the device, and thus affect the reliability of power supply of the overall network. Therefore, it is very intuitive to make a quantitative analysis of the reliability change of the port.

As shown in Figure 2, Port No. 5 is connected to the AC high-voltage power grid. Ports No. 6 and 7 are the LOW-voltage sides of DC and AC respectively, and the energy storage device is in the high-voltage position No. 4.

According to the timing Monte Carlo method in 2.3 and the data in Table 2, the port reliability of the device as a whole was first calculated, and the port reliability of the equivalent three-port device was calculated by using the Monte Carlo method. This result can be used directly in computing network reliability. The specific calculation results are as follows:

| The port number | reliability (%) | Failure rate/(Times per year) | Average outage time per outage |
|----------------|----------------|-----------------------------|-------------------------------|
| 6              | 99.997         | 0.01                        | 0.26017                       |
| 7              | 99.9474        | 0.85                        | 4.61h                         |

Table 3. Without energy storage three-port AC/DC power distribution equipment port reliability comparison.

| The port number | reliability (%) | Failure rate/(Times per year) | Average outage time per outage |
|----------------|----------------|-----------------------------|-------------------------------|
| 6              | 99.9986%       | 0.008                       | 0.12583                       |
| 7              | 99.9508%       | 0.826                       | 4.3083                        |

Table 4. With energy storage three-port AC/DC power distribution equipment port reliability comparison.

The data in this paper are averaged after multiple sets of tests. It can be seen from Table 3 and Table 4 that the port reliability, average outage time and port reliability of the three-port power distribution device with energy storage are improved compared with those without energy storage.

4. The example analysis

Taking a load network in a certain region as an example, the calculation of energy storage capacity based on reliability is carried out according to the method described in this paper. The data of grid structure, load and distributed power output in this area are shown in Figure 3 and Figure 4. The load curve is shown in Figure 5. The capacity of wind farm and PV farm is shown in Table 5 [7].

Figure 3. Grid structure with energy storage device.

Figure 4. Grid structure without energy storage device.
4.1. Power supply reliability of the network without energy storage
In this paper, the reliability of the grid without energy storage is calculated as well as the reliability of the grid without energy storage. The results show that the AC-DC power distribution system with energy storage can improve the reliability of power supply. The overall grid structure is shown in Figure 4.

According to the above source network load data, the power supply reliability is calculated by monte Carlo method, and the result is: network reliability: 99.9294%.

4.2. When the energy storage as a critical load configuration energy storage component
The DC load with the power of critical load of 80kW can be guaranteed to support the operation of important load for two hours in the case of power failure of external power grid. The calculation results of energy storage link size and network reliability are as follows.

| The parameter | The value       |
|---------------|---------------|
| Energy storage capacity/kW • h | 324.6750      |
| Grid reliability   | 99.9587%     |

When the energy storage is used as the standby power supply, Table 6 shows the solution process and the final results. In Table 6 we get the final configuration results and the power supply reliability in this case. With energy storage, the reliability is 99.9587%, compared with 99.9294% without energy storage. Obviously, this scheme has higher power supply reliability than without energy storage components.

5. Conclusions and discussion
This paper starts from the energy storage link of AC-DC hybrid power distribution device, considers its own reliability and network reliability, and combines with the energy storage device. A new type of AC-DC hybrid power distribution device containing energy storage based on improved reliability is proposed by introducing Monte-Laro method in calculating reliability, and its effectiveness in improving network reliability is verified [10]. This is a new attempt in the problem of energy storage configuration in AC-DC hybrid distribution network. In the study of this paper, we can draw the following conclusions:
The energy storage system model based on DOD, function of energy storage device and charge/discharge power is introduced, and the variation of charge/discharge quantity of energy storage device in power system is basically characterized. According to the function of the energy storage device as load reserve, a method for calculating the maximum energy storage capacity is constructed, which can be used to configure the energy storage capacity required by the system.

The time-series Monte Carlo simulation method is used to calculate the reliability of the energy storage model. Compared with analytical method, it has higher efficiency, simpler calculation process and better adaptability to complex network structure.

It can be seen from the calculation results that the AC-DC hybrid power distribution unit with energy storage proposed in this paper has certain ability to improve the reliability of the device port and network power supply.

In this paper, the location problem of distributed generation is not considered in the process of capacity configuration of distributed generation, and the location problem of distributed generation can be introduced in future research. We can combine the distributed generation capacity selection problem with the location problem to make the research more practical.

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