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Topology study of AC-DC hybrid distribution system based on reliability combination calculation

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Abstract: With the increase in the proportion of new energy sources and the wide distribution of DC loads, DC distribution technology is receiving more and more attention. Based on the research of back-to-back flexible DC transmission HVDC DC transmission technology, a hybrid AC-DC distribution system is derived, through the combination of DC and traditional AC distribution networks, the hybrid AC-DC distribution system can reduce the steps of energy conversion and improve the operational efficiency and power quality. To enhance system power supply reliability and mitigate the randomness and volatility introduced by distributed energy sources, this paper first proposes common topologies for hybrid AC-DC distribution systems. It then applies three reliability analysis methods—the minimum path method, Monte Carlo simulation, and convolution integral method—to perform reliability calculations on several typical distribution system topologies. Finally, using the power supply reliability rates obtained from these methods as evaluation criteria, the Hierarchical Analysis Method is employed to determine the optimal architecture for current hybrid AC-DC distribution systems.

1. Introduction

With the rising demand for renewable energy, the scale of the distribution system is also expanding, and smart grids such as microgrids are joining them as relatively independent power systems. In order to realize the flexible networking of AC and DC power sources and loads in microgrids and to ensure the synergistic operation of power distribution, and to improve the power supply reliability, stability, and energy efficiency of the system, a device that can enhance energy conversion and maintain system stability is designed for this purpose. In order to design a device that can enhance energy conversion and maintain the stability of the system, it is an AC-DC hybrid distribution device based on flexible DC back-to-back mode, which is used to realize the connection of DC loads in the distribution network and the access of new energy sources, such as wind, light, storage, etc. [1].

The device can not only mix and distribute the DC power generated by distributed new energy generation equipment with the AC power of the grid to realize the efficient access and consumption of new energy, but also convert the DC power generated by photovoltaic modules into AC power through AC/DC converter after convergence of DC power distribution devices to provide power for the grid. At the same time, the device in the control and protection circuits will be real-time monitoring of current, voltage, frequency and other parameters, in the necessary device will maintain the stability of the system voltage, power to ensure the safe and stable operation of the system [2] [3].

In order to ensure system safety and stability on the basis of strengthening the distribution network control to improve reliability is essential, at this stage, power electronics technology is becoming more and more mature, so there are many excellent control system electrical quantity of equipment, and the price of these components is also getting lower and lower, more in line with our needs for economy [4]. Among them, the application of VSC brings more possibilities to the development of DC distribution network, which is easy for clean energy access, flexible control and other characteristics, and can reduce the traditional AC grid abandoned wind and light phenomenon. By combining the device with the distribution grid and microgrids, several structures are derived, and in order to derive the optimal structure, the minimum path method, Monte Carlo method, and convolutional integral method are used to calculate the power supply reliability rate of the several structures, and the calculation is used as a technical indicator, and the hierarchical analysis method is applied to derive the optimal topology [5].

2. AC/DC hybrid distribution system topology

The hybrid AC/DC distribution system structure connects photovoltaic, wind power, energy storage devices, AC/DC loads, large power grids and AC/DC microgrids to each other through one or several DC busbars at different DC voltage levels.

At present, the world DC microgrid bus voltage level mainly includes 48V, 120V, 170V, 220V, 380V, 400V, 750V, etc., of which the 400V voltage level is the most widely used due to the high transmission efficiency and easy to invert, etc.

Due to the diversity of voltage level and equipment device connection, there are many kinds of topologies, on which this paper mainly divides the AC/DC In this paper, the AC-DC hybrid distribution topology is categorized into the following three typical structures [6].

The first topology consists of a single bus with a voltage level of 400 V, where the PV, wind power, energy storage devices, loads and the grid are connected to the bus as shown in Figure 1.

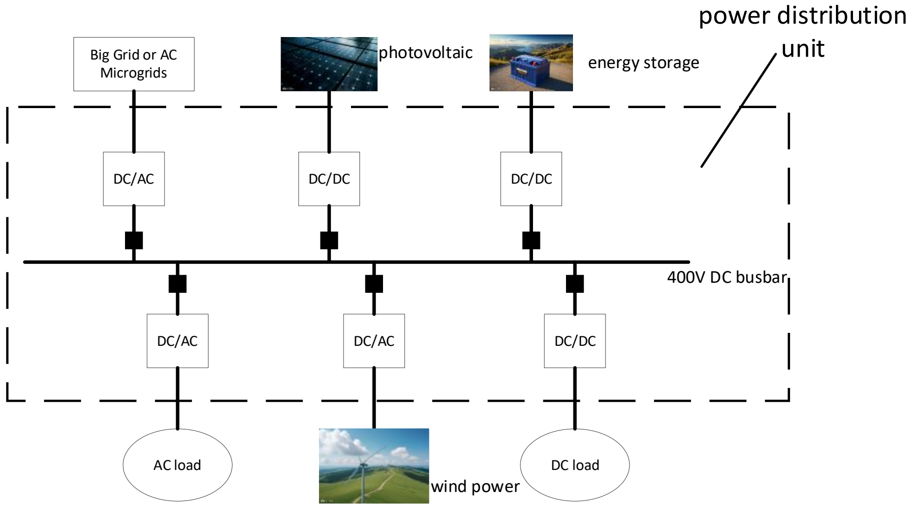

Figure 1 Radial topology

The second topology is a hybrid AC-DC power distribution unit composed of stratified busbars, in which there are two voltage levels, 750V and 400V, with energy storage devices, loads, grids, and other microgrids connected to the 750V voltage level, and distributed energy sources and energy storage devices connected to the 400V voltage level, and the hierarchical structure can have more than one voltage level to facilitate the access of loads of different voltage levels, and the topology is shown in Figure 2.

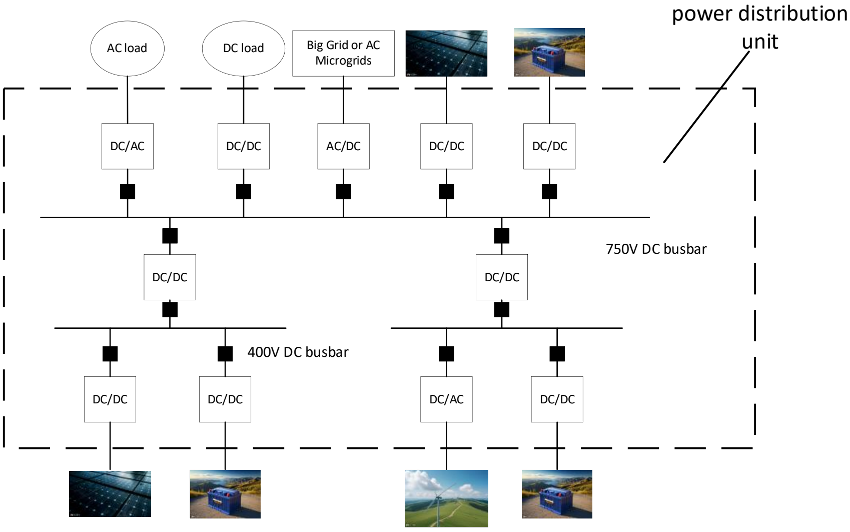

Figure 2 Hierarchical Radial Topology

The third topology is a hybrid AC/DC power distribution unit composed of ring-shaped bus, which contains three voltage levels including 750V, 400V, 220V, 750V voltage level connected to the grid and other microgrids, 400V voltage level connected to wind power, DC loads and energy storage devices, 220V voltage level connected to the photovoltaic AC loads and energy storage devices, the ring shape not only facilitates the access of multi-voltage loads and the structure of the backup wiring reliability is greatly improved, the topology is shown in Figure 3. The ring shape not only facilitates the access of multi-voltage loads, but also greatly improves the reliability of the structure with standby wiring, and the topology is shown in Figure 3.

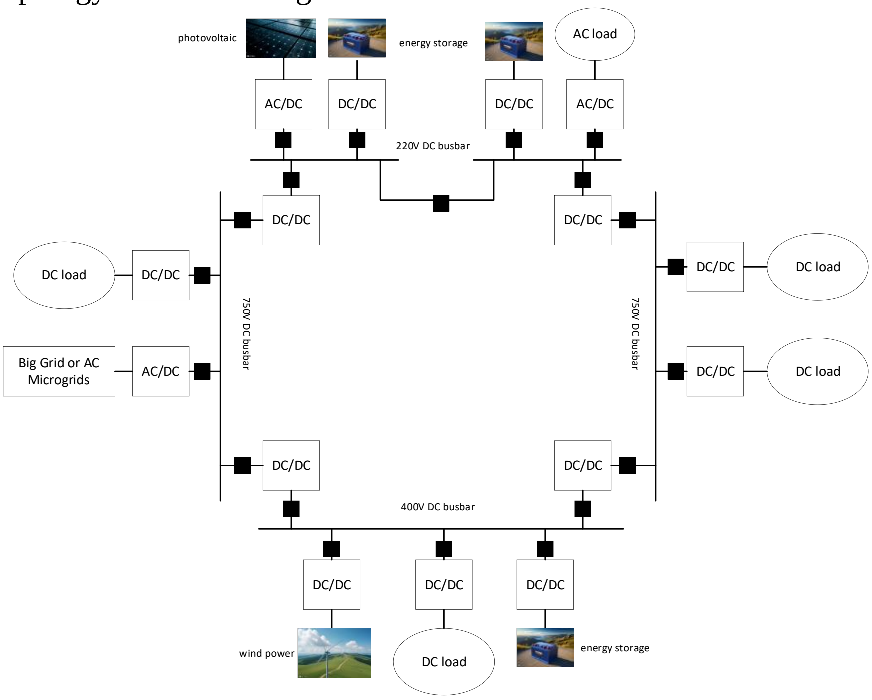

Figure 3 Ring topology

3. Reliability analysis and calculation of hybrid AC/DC power distribution units

3.1 Reliability Calculation Methods for AC/DC Hybrid Distribution Units

By analyzing the above three kinds of AC/DC hybrid distribution unit grid structure, the following reliability analysis and calculation of this system is carried out by three methods respectively [7].

3.1.1 Minimum Path Method Power Supply Reliability Calculation

Minimum path method is for each load point in the system to find its minimum path, the system components are divided into two categories, one in the minimum road, the other is not in the minimum road for the components not in the minimum road by analyzing its troubleshooting time approximation is equivalent to the minimum path components, which mainly consider the power supply, line, converter, intelligent soft switch and other components can be.

Minimum path method flowchart and schematic diagram shown in Figure 4.

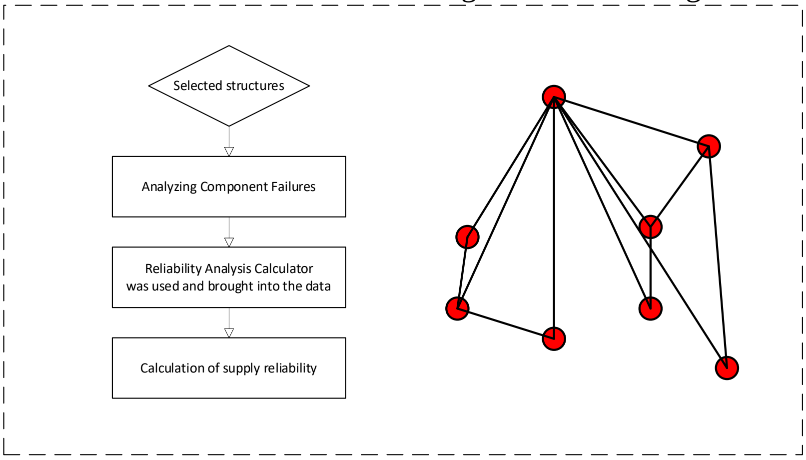

Figure 4 Minimum Path Method

The reliability parameters of each component in the system using previous experimental data are shown in Table 1 below.

Table 1 Component reliability parameter statistics

No.	Component	Failure rate (times)	Failure time
1	Photovoltaic power supply	0.00537836	0.6
2	400V DC Bus	0.01126	15.68
3	750V DC Bus	0.01089	15.68
4	220V DC Busbar	0.01175	15.68
5	Energy Storage Power Supplies	0.698	8
6	ventilator	0.01536754	2
7	DC/DC	0.63658754	30
8	DC/AC	0.98643545	30

The load average outage formula is shown below.

$$T = (1-q)(T_{d1} - T_{d2}) + T_{d2} \tag{1}$$

Where T is the load outage duration, q is the PV and wind turbine output to meet the load power supply probability, Td1 is the total outage duration before joining distributed energy sources, and Td2 is the fault outage duration at the load node, and distributed power sources are unable to eliminate the load node fault triggering duration.

The power supply reliability rate ASAI is usually not less than 99.99%, and the ASAI calculation formula is as follows.

$$ASAI = \frac{8760 - \sum_{i=1}^{N} u_{id}}{8760} 100\% \geq 99.99\% \tag{2}$$

The power supply reliability rate is calculated for the three topologies by the above equation and the magnitude of the power supply reliability rate is obtained as shown in Figure 5, in which the ring topology has the highest reliability rate of 99.9937%.

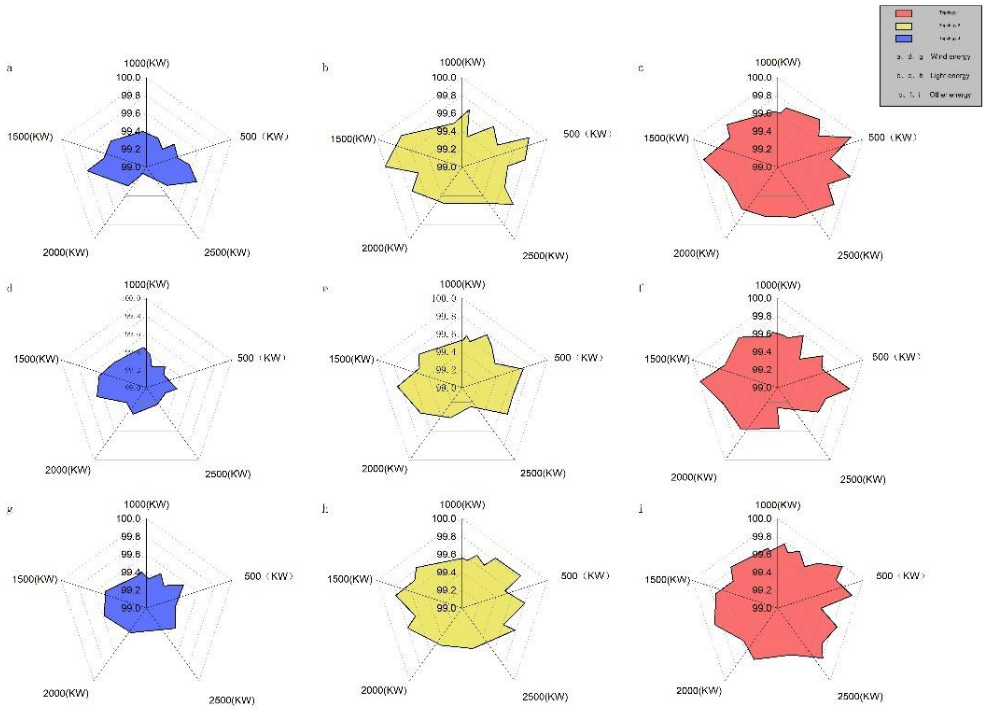

Figure 5 Distributed Energy Supply Reliability Radar Map

3.1.2 Monte Carlo method of power supply reliability calculation

The basic principle of Monte Carlo method is to estimate the probability of occurrence of the event probability in a large number of experiments, establish a probability model to obtain the parameters and mathematical solutions, through the experimental parameters characteristics, the arithmetic mean as an approximation of the solution, as long as the number of experiments is sufficiently large to obtain a more accurate results. Since the topology of AC/DC hybrid power distribution unit contains uncertainty of output power of PV and wind power generation, the reliability calculation can not guarantee the accuracy only through the prediction of past historical data, and the calculation by Monte Carlo method is relatively simple and more accurate.

The reliability assessment process is based on Monte Carlo simulation, and the flow chart of the AC/DC hybrid system reliability assessment process of this algorithm with high integration of AC/DC hybrid distribution units and renewable energy sources is shown in Figure 6.

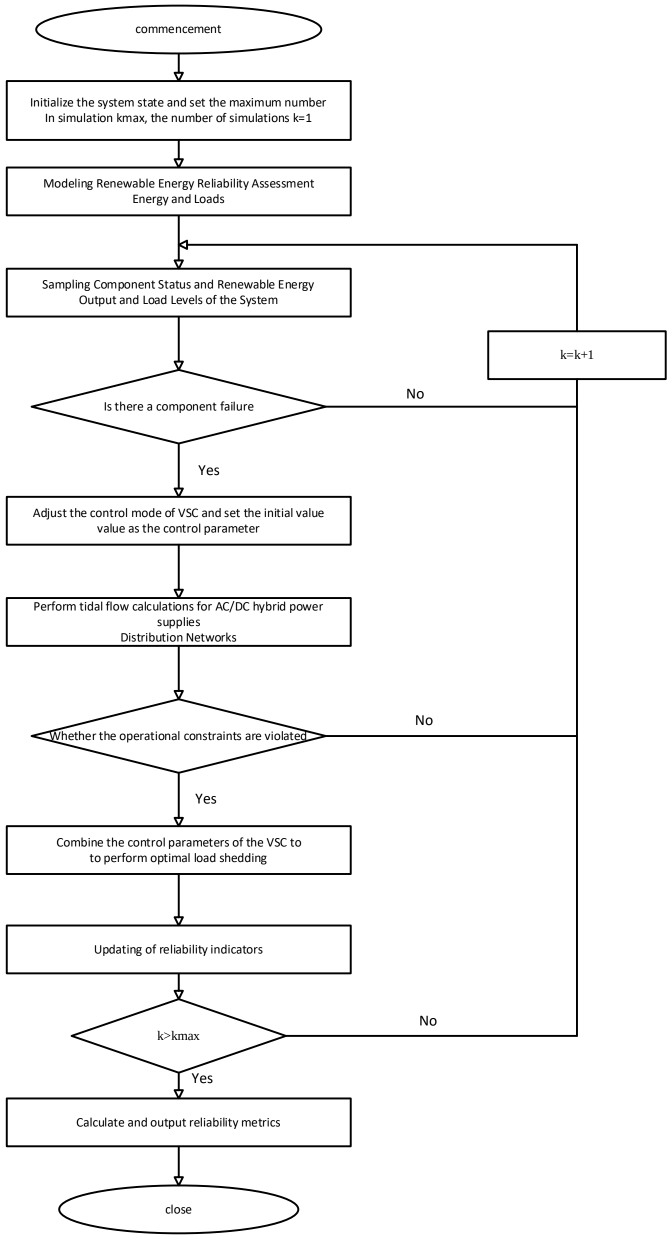

Figure 6 Reliability evaluation of AC/DC hybrid distribution unit

Reliability assessment process based Monte Carlo simulation, which gives the reliability assessment process of the algorithm AC/DC hybrid distribution unit, the highly integrated energy of the distribution unit with renewable energy sources can be expressed as, as shown in the figure above.

(1) Set the maximum number of simulations and establish an annual output power curve based on the historical load curve.

(2) The state of each component is sampled and the renewable energy output and load level are sampled.

(3) Determine whether the requirements are met. If not, go to step 4; otherwise, return to step 2.

(4) Adjust the control mode of VSC and set the initial value as the control parameter.

(5) Obtain the operation scene distribution and perform calculations

(6) Determine whether there is an operational constraint violating the system. If yes, perform step 7; otherwise, return to step 2.

(7) Solve the load shedding model parameter optimization with the controller to obtain the

minimum value load.

(8) Determine whether the results meet the requirements. If yes, the result is output; the reliability indicator is obtained; otherwise, return to step 2 above.

Renewable energy improves economic efficiency allocation and introduces high uncertainty in the network. When remembering this feature, common methods are not considered comprehensively; this may affect the accuracy of the calculation results. To solve this problem, this paper adopts a multi-state probabilistic model renewable energy and load established by time series sampling method.

Based on the historical data, the annual output renewable energy power curve and annual load curve equations are formed as follows.

$$P_{wt} = \left[P_{wt}^{1}, P_{wt}^{2}, P_{wt}^{3}, \cdots, P_{wt}^{T}, \cdots, P_{wt}^{8760}\right] \tag{3}$$

$$P_{v} = \left[P_{v}^{1}, P_{v}^{2}, P_{v}^{3}, \cdots, P_{v}^{T}, \cdots, P_{v}^{8760}\right] \tag{4}$$

$$P_{b} = \left[P_{b}^{1}, P_{b}^{2}, P_{b}^{3}, \cdots, P_{b}^{T}, \cdots, P_{b}^{8760}\right] \tag{5}$$

Pwt denotes the annual output power curve of WT, Pv denotes the annual output power curve of PV, and Pb denotes the annual load curve; T denotes the selected time for each simulation.

Assuming that the total length of the simulation is 8760 hours, one of the time scenarios is randomly selected to determine the moment level as shown in the following equation.

$$P_{wt}^{i} = P_{wt}^{T} \tag{6}$$

$$P_{v}^{i} = P_{v}^{T} \tag{7}$$

$$P_{b}^{i} = P_{b}^{T} \tag{8}$$

The uncertainty of renewable energy and load is determined by simulating the load in the scenario using time series sampling to reflect the relative relationship between PV, WT production and load level.

In terms of controlling the VSC, since it has two controllable parameters, the VSC can be operated in a variety of control modes according to different control parameters. The three most typical control modes are as follows:

(1) In PQ mode. Both controls are free, and both controls can react on the AC side.

(2) UdcQ mode. Control the AC side reaction capability by controlling the voltage on both sides of DC.

(3) Uacθ mode. These two control parameters are VSC AC measured voltage phase angle and amplitude.

Among them, the VSC active power and reactive power should satisfy the following constraints.

$$P_{VSC}^{2} + Q_{VSC}^{2} \le S_{VSC}^{2} \tag{9}$$

$$P_{VSC,DC} = -\ P_{VSC,AC} + \alpha \left|P_{VSC,AC}\right| \tag{10}$$

Where PVSC and QSVC are active and reactive power, SVSC is the SVC capacity; PVSC,AC and PVSC,DC are the active power on AC and DC side and is the loss factor.

The safe operation constraints are shown in the following equation.

$$U^{min\ 2} \le U_{i}^{2} \le U^{max\ 2} \tag{11}$$

$$I_i^2 \leq I^{max\ 2} \tag{12}$$

Where U^{min} and U^{max} are the lower and upper bound voltage of the node, and is the upper bound of the branch current.

By regulating the control mode and setting the initial parameters for the current calculation distribution network, the parameters are optimally combined for load shedding to obtain the reliability indexes to complete the reliability calculation and assessment.

In the following, the Monte Carlo method is applied to the above three topologies through the past data, and the new energy capacity is taken as a variable, and the reliability of power supply of the three topologies at the time of grid-connection is calculated through simulation as shown in Figure 7 below.

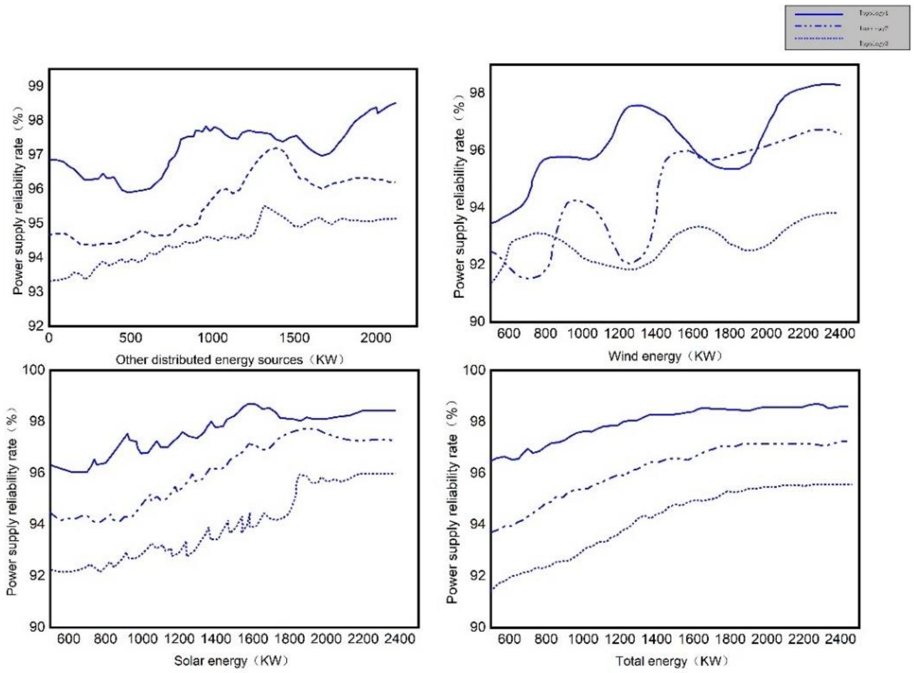

Figure 7 Simulation of power supply reliability rate of distributed energy sources

3.1.3 Convolutional Integral Method Power Supply Reliability Calculation

For mixed AC and DC power distribution units, the convolution method can be used to calculate the overall reliability by considering the independence of the AC and DC subsystems.

Among them, the AC subsystem reliability function Q AC(t) can be expressed as the reliability function of the AC/DC power distribution device, transformer, PV power supply, wind power supply, and energy storage battery pack in the system. For its parallel structure components, the AC side reliability function can be expressed as the following equation.

$$Q_{AC}(t) = 1 - \prod_{i=1}^{n_{AC}} \left(1 - Q_{i,\ AC}(t)\right) \tag{13}$$

Where Qi, AC(t) is the reliability function of the ith AC component.

Among them, the DC subsystem reliability function can be expressed as a function of the reliability of the AC and DC power distribution devices, photovoltaic power supply, wind power supply, and energy storage battery packs in the system. For its parallel structure components, the DC side reliability function can be expressed as the following equation.

$$Q_{DC}(t) = 1 - \prod_{i=1}^{n_{DC}} \left(1 - Q_{i,\ \mathrm{DC}}(t)\right) \tag{14}$$

Where, Q(t) the system reliability is obtained from the convolution of the subsystem reliability functions on both sides as follows.

$$Q(t) = \int_0^t Q_{AC}(t_1) \cdot Q_{DC}(t - t_1)\, dt_1 \tag{15}$$

Where, QAC(t) is the reliability of the AC subsystem at the moment t1 and QDC(t-t1) is the reliability of the DC subsystem at the moment t-t1.

When performing reliability convolution calculations by substituting historical data, the reliability analysis for the three aforementioned topologies is presented in Table 2 below.

Table 2 Reliability of power supply

framework	single busbar	Layered busbar	circular mesh
Reliability of electricity supply	99.6897%	99.7568%	99.9364%

4. Calculation of power supply reliability rate weights based on hierarchical analysis method

The hierarchical analysis method simplifies complex problems, classifies them according to important factors, compares the relative importance of structural factors in hierarchical analysis, and ranks them to obtain indicators of power supply reliability. The hierarchical model is divided into different levels, such as the objective layer, standard layer, and solution layer, as shown in Figure 8[8].

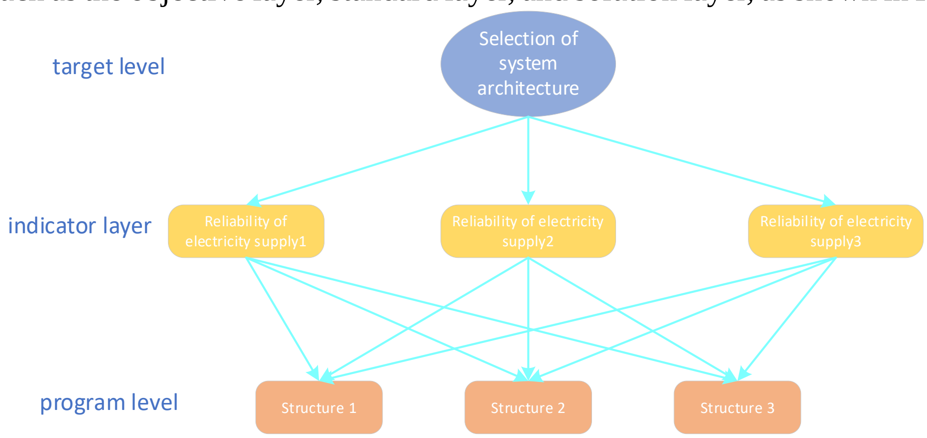

Figure 8 Hierarchical Analysis

Secondly, for each factor at the same level, a judgment matrix is constructed by comparing their importance to a factor at the previous level. The elements of the judgment matrix are usually determined using a scale of 1 - 9 and its reciprocal to reflect the relative importance of the two factors, and the quantitative provisions between the indicators are shown in table 3 below.

Table 3 Quantitative provisions between indicators

Factor i over factor j	quantitative value
equal importance	1
slightly important	3
more important **high priority**	5 7
vital	9
The median of two neighboring judgments from the bottom	2, 4, 6, 8 $a_{ij}=1/a_{ji}$

The reliability of the AC/DC hybrid distribution system is calculated by analyzing the reliability of power supply for three topologies (A, B, and C), which is analyzed and measured and results in the target and indicator level judgment matrices as shown in Table 4 below.

Table 4 Goal- and indicator-level judgment matrix1

Z	A	B	C
A	1	1/4	2
B	4	1	5
C	1/2	1/5	1

The above judgment matrices are obtained by the ensemble product method as shown in Table 5 below.

Table 5 Judgment Matrix for Goal and Indicator Levels2

Z	A	B	C	w	Aw
A	0.182	0.172	0.250	0.224	0.54
B	0.727	0.690	0.625	0.681	1.91
C	0.091	0.138	0.025	0.095	0.32

Where n represents the specific number of evaluation indicators, after deriving the judgment matrix P, the square root method is used to complete the work of solving the eigenvectors to derive the product M_i, and calculate M_i the nth root of the square $\overline{w_i}$, the formula is:

$$M_i = \prod_{j=1}^{n} A_{ij} \tag{16}$$

$$\overline{w_i} = \sqrt[n]{M_i} \tag{17}$$

The feature vector $\overline{w_i}$ can be obtained by normalizing $W^* = (w_1^*, w_2^*, w_3^*, \dots, w_n^*)$, which is calculated as shown in the following equation.

$$w_i^* = \frac{\overline{w}_i}{\sum_{i}^{n} \overline{w}_i} \tag{18}$$

To ensure the credibility of the judgment matrix, it needs to be tested for consistency by calculating its maximum eigenvalues λ_{max} and indicators C_I.

$$\lambda_{max} = \sum_{i=1}^{n} \frac{(AW^{*T})}{nw_i^*} \tag{19}$$

$$C_I = \frac{\lambda_{\max} - n}{n-1} \tag{20}$$

Given that matrix consistency can deviate uncontrollably, larger values represent poorer consistency. When $\lambda_{\max}$ =n, C_I =0, it represents the same consistency. When the judgment matrix order becomes more, it is more and more difficult to maintain consistency, in order to better grasp the consistency difference, we introduced R1 (average random consistency index), and the consistency ratio C_R can be obtained by comparing the two .

$$C_R = \frac{C_1}{R_1} \tag{21}$$

When CR < 0.1, it represents the weight coefficient is reasonable; if CR > 0.1, it represents the weight coefficient is unreasonable, the judgment matrix also need to re-optimize until its weight coefficient is reasonable.

Among them, check the table 3rd order matrix R1=0.52, find C1=0.0427, bring the above data to find CR=0.08204 < 0.1, so the weight coefficient under this method is reasonable.

A comparison of the weights under each indicator is shown in the table 6 below.

Table 6 Three topological methods A weights

A	1	2	3	w	Aw
1	1	1/2	1/5	0.122	0.366
2	2	1	1/3	0.23	0.69
3	5	3	1	0.648	1.944

Where, looking up the table 3rd order matrix R1 = 0.52, find C1 = 0.0054, bring the above data to find CR = 0.0104 < 0.1, so the weight coefficients are reasonable under this method.

A comparison of the weights under each indicator is shown in the table 7 below.

Table 7 Three topological methods B weights

B	1	2	3	w	Bw
1	1	1/2	1/7	0.103	0.31
2	2	1	1/3	0.216	0.648
3	7	3	1	0.681	2.042

Where, checking the table for the 3rd order matrix R1 = 0.52 yields C1 = 0.0034, and bringing the above data in yields CR = 0.00654 < 0.1, so the weighting coefficients are reasonable under this method.

A comparison of the weights under each indicator is shown in the table 8 below.

Table 8 Three topological methods C weights

C	1	2	3	w	Cw
1	1	1/2	1/9	0.086	0.255
2	2	1	1/4	0.177	0.533
3	9	4	1	0.737	2.212

Where, looking up the table 3rd order matrix R1 = 0.52, find C1 = 0.001628, bring the above data to find CR = 0.03131 < 0.1, so the weighting coefficients are reasonable under this method.

The overall weighting coefficient table is shown in Table 9 below.

Table 9 Table of weighting factors for indicators

Z		1	2	3
A	0.224	0.122	0.23	0.648
B	0.681	0.103	0.216	0.681
C	0.095	0.086	0.177	0.737

By calculating CR=0.02005<0.1, so the weight allocation is reasonable, and the scores under the three structures are 0.106, 0.215, and 0.679, respectively.Through the allocation of power supply reliability indexes of the three structures by the hierarchical analysis method, it can be obtained that the reliability of the topology 3 is much larger than that of the first two kinds of reliability.

5. Conclusion

AC/DC hybrid distribution system is an important part of the distribution grid, AC/DC microgrid can be flexibly connected, which can not only effectively undertake the new energy consumption problem, but also can make the DC system easily complete the grid connection.

This paper mainly focuses on the optimal structure of AC/DC hybrid distribution device to discuss the issue of AC/DC hybrid distribution system topology is divided into three kinds of topology, including single bus, layered bus radial and ring structure of the distribution device, through the three methods of reliability analysis of the system and the three methods of calculation of power supply reliability as a measure of the index, the application of hierarchical analysis method of weight allocation to derive the structure of the score, the final results of the AC/DC hybrid distribution system is a very important part of the new energy consumption problem, which can not only effectively undertake the new energy consumption problem, but also make the DC system easily complete the grid. Finally, the optimal topology for AC-DC hybrid power distribution is derived.

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