Study on Power Supply Structure of AC / DC Distribution Network Considering Different Proportion of New Energy Access

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Abstract. Considering the diversification of energy and load, according to the different situation of new energy access to distribution network, three typical AC-DC hybrid distribution network power supply modes are summarized. On the basis of these three power supply modes, the indexes of AC-DC hybrid distribution network are extracted, and the comprehensive evaluation index system is established. A comprehensive evaluation model of AC / DC hybrid distribution network suitable for new energy access is proposed, which aims to maximize economic benefits. The example shows that the optimal power supply mode can be selected through the evaluation model when the proportion of new energy is different, which can lay a foundation for the future distribution network to better serve users on the premise of distribution network profitability.

1. Introduction
The distribution network is an important platform for various types of users, such as distributed power sources, AC and DC loads, and energy storage. It is a key link to promote the construction of smart grids and resolve the energy crisis. Compared with AC distribution networks, AC and DC distribution networks have the characteristics of high transmission efficiency, large transmission capacity, long transmission distance, high reliability of power supply, and flexible power supply, which can meet the access needs of various types of AC and DC users. The transition from the traditional AC power distribution system to the future mature AC-DC hybrid power distribution mode is the current development trend[1-2].

Due to the emergence of DC distributed power sources such as photovoltaic power generation and DC loads such as data centers, DC distribution network technology has received extensive attention and great development. Some scholars' research on DC distribution network mainly includes topology, grid structure, and the access model was introduced [3-4]. The literature [3-4] analyzes the necessity and feasibility of the DC distribution network, and analyzes in detail the radial, two-end, ring network structure and the AC/DC hybrid microgrid suitable for connecting to the low-voltage DC distribution network. Structure. Reference [5] aimed at the new distribution mode of distributed photovoltaic power supply connected to the traditional distribution network. The paper proposed a photovoltaic power model and reliability model. Using sequential Monte Carlo method, a reliability analysis was performed. Reference [6] applied the improved ant colony method to find the optimal solution for evaluation, established economic, load rate, network loss, network reliability and other evaluation indicators, and established a comprehensive evaluation system based on fuzzy pattern recognition. Reference [7] makes quantitative economic and technical quantitative comparison calculations of...
regional grid planning schemes, and establishes an efficiency evaluation coefficient for grid planning schemes. A power grid project evaluation model based on collaborative optimization efficiency evaluation is established to guide the selection of power grid planning schemes. With the continuous research on the typical mode of power distribution, the assessment of DC distribution network has been increasing, but there has been no substantial progress in the selection of the power supply structure after considering the connection of new energy. This paper selects three typical power supply structures through comparative analysis, and proposes an objective function that maximizes economic benefits. It also evaluates and analyzes different power supply structures with the constraints of new energy consumption. Finally, a simulation example is used to select a power supply mode suitable for different consumption ratios.

2. Typical scenarios of AC/DC distribution networks after new energy grid connection

2.1. New energy access to radial distribution network
New energy is connected to the radial power distribution network and changed from a single power source to a dual power source to improve the reliability of power supply. New energy sources such as photovoltaics are connected to the DC link from the user side, thereby saving the AC/DC converter and directly passing Access, reliability and power quality will all improve. As show in Figure 1.

![Figure 1. New energy access to radial distribution network](image)

2.2. New energy access to double-ended distribution network
The connection of new energy to the dual-end power distribution network is equivalent to a power end of new energy too. Similar to Figure 1, connect new energy to the user side.

2.3. New energy access to ring distribution network
New energy is connected to the ring-shaped power distribution network to form an AC/DC hybrid power distribution network. The DC part can be closed-loop designed for closed-loop operation to improve the reliability of the power distribution network. Similar to Figure 1.

3. Comprehensive evaluation index system
According to DL/T 1563—2016 Guidelines for Reliability Evaluation of Medium Voltage Distribution Networks.

3.1. Power supply reliability
a) System average interruption frequency index (SAIFI)

\[
SAIFI = \frac{\sum \lambda_i N_i}{\sum N_i}
\]  

(1)

b) System average interruption duration index (SAIDI)
Where $U_i$ is the annual average power outage time of load point $i$.

c) Average service availability index ($ASAI$)

$$ASAI = \frac{\sum N_i \cdot D - \sum U_i N_i}{\sum N_i \cdot D} \quad (3)$$

### 3.2. Power quality

DC does not consider frequency-related indicators. The main indicator is voltage-related indicators. Access to a large number of power electronics. Frequent actions of power electronic inverters will cause harmonic pollution to the system. So the indicators are power quality and voltage harmonic distortion.

a) Comprehensive voltage deviation

Voltage fluctuation refers to the change of the voltage amplitude of the same node in two adjacent sampling periods.

$$U_d = \frac{U_i' - U_i^{t+T}}{T} \quad (4)$$

b) Voltage harmonic distortion rate

$$THD = \sqrt{\frac{\sum_{k=2}^{\text{max}} U_k^2}{U_1^2}} \times 100\% \quad (5)$$

### 3.3. Economy

Economics is divided into two categories: investment economy and operation economy.

#### 3.3.1 Economics of investment

Considering the life cycle cost, a VSC access cost model is established. The total cost $C_{total}$ includes: investment ($C_0$), operation ($C_{VSC}$) and maintenance ($C_{DC}$).

$$C_{total} = C_0 + C_{VSC} + C_{DC}$$

$$C_{VSC} = d(1+d)^m \sum_{i=0}^{m} \frac{e^{i \frac{\Delta t}{t}}}{(1+d)^m} E_{vsc}$$

Where $d$ is the discount rate, $m$ is the life cycle of the VSC device, $e$ is the unit capacity cost of the VSC, and $E_{vsc}$ is the capacity of the VSC.

#### 3.3.2 Operational economy

a) Comprehensive loss rate of converter

$$r_{con} = \frac{P_{con}}{P_{in}} \quad (7)$$

Where $P_{con}$ represents the total loss of converter, $P_{in}$ represents the total input of converter.

b) Network average line loss rate

The number of main lines in a power grid is $n_i$. For a certain period of time, the average line loss rate of the network is $r_{avg}$ if the power loss of line $i$ is $\Delta P_i$ and the active power of the power flow at the outlet of the line is $P_{r,i}$.
4. Comprehensive Evaluation Method

4.1. Indicator weighting and normalization

4.1.1 Indicator weighting In order to reduce the subjectivity given to the weight of each objective function, this paper uses the judgment matrix to perform quantitative and qualitative analysis on the indicators based on Delphi method.

a) Judgment value selection
According to the actual situation, the data to be analyzed is divided into n intervals, which are represented by $X = \{x_1, x_2, \ldots, x_n\}$. Take two intervals $x_a$ and $x_b$ for comparison, and note that the importance of $x_a$ to $x_b$ is $J_{ab}$, and the importance of $x_b$ to $x_a$ is $J_{ba}$, which is the inverse of $J_{ab}$.

b) Judgment Matrix Composition
According to the judgment value given, the judgment matrix is:

$$
J = \begin{bmatrix}
J_{11} & \cdots & J_{1b} & \cdots & J_{1n} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
J_{n1} & \cdots & J_{nb} & \cdots & J_{nn}
\end{bmatrix}
$$

(9)

Among them, the comprehensive opinion is $Y$, and the weighted average calculation of m reference opinions is calculated according to the following formula:

$$
Y = \frac{1}{m} \sum_{x=1}^{m} J_x
$$

(10)

c) Disagreement and weight consistency check
Use the degree of divergence $x_g$ to determine whether the dispersion of the index weight meets the requirements. If the degree of divergence of an index is greater than $x_g$, the weight of the index needs to be discussed again. $x_g$ is calculated as follows:

$$
x_g = \sqrt{\frac{1}{m-1} \sum_{x=1}^{m} (J_{xy} - Y_{xy})^2}
$$

(11)

Use weight consistency $A_{c1}$ to determine whether weights are objectively representative. If $A_{c1}$ is greater than 0.1, the initial weight matrix needs to be modified and calculated as follows:

$$
A_{c1} = \frac{\lambda_{max} - n}{n - 1}
$$

(12)

Where $\lambda_{max}$ is the maximum eigenvalue of the comprehensive opinion matrix $Y$.

d) Finding indicator weights
According to the matrix theory, the maximum characteristic root $\lambda_{max}$ in $J$ is calculated from the characteristic equation $J - \lambda E = 0$; $\lambda_{max}$ is substituted into $J - \lambda_{max} E = 0$ to find the characteristic vector corresponding to the maximum characteristic root, which is $\omega = [\omega_1, \omega_2, \ldots, \omega_n]$; $\omega$ is standardized, and the normalized result obtained is used as Index Weight.
4.1.2 Index normalization In this multi-index evaluation system, due to the different nature of each evaluation index, in order to ensure the reliability of the results, the original index data needs to be normalized. This article uses the range transformation method.

Calculation method of forward indicator:

\[ y_{ij} = \frac{x_{ij} - x_{\min}}{x_{\max} - x_{\min}} \]  \tag{13}

Reverse indicator calculation method:

\[ y_{ij} = \frac{x_{\max} - x_{ij}}{x_{\max} - x_{\min}} \]  \tag{14}

4.2. Objective function with optimal economic benefits

The evaluation indicators are divided into two categories, forward indicators and reverse indicators. The objective function is:

\[ K = \frac{V}{I \times B} \]  \tag{15}

\[ V = \sum_{i=1}^{N} R_{i} \times \omega_{i} \]

\[ I = \sum_{i=1}^{N} R_{i}^{*} \times \omega_{i} \]

\[ B = \sum_{i=1}^{N} R_{i} \times \omega_{i} \]  \tag{16}

Where N is the number of indicators in each type of comprehensive evaluation index, \( R_{i} \) is the comprehensive evaluation score obtained by the normalization process of formula (13,14), \( R_{i}^{*} \) is the score of the i-th evaluation index of the k type, \( \{k = 1, 2, 3 \mid 1\text{-reliability}, 2\text{-economical}, 3\text{-power quality}\} \).

5. Examples

The calculation example uses three kinds of power supply structures selected in this paper. The actual data in a certain area is used as a reference, as shown in Table 1.

| Proportion of new energy | Photovoltaic power | Wind power | Energy storage | DC Load | AC load |
|-------------------------|-------------------|------------|----------------|---------|---------|
| 20%                     | 1.5 MW            | 0          | 8*60kw         | 3.5MW   | 2.5MW   |
| 40%                     | 1.5 MW            | 1.5 MW     | 8*60kw         | 3.5MW   | 2.5MW   |
| 60%                     | 2.5 MW            | 1.5 MW     | 8*60kw         | 3.5MW   | 2.5MW   |
It can be concluded that the radial distribution network's economic benefits have not increased significantly with the continuous increase in the rate of new energy consumption, and even began to decline. With the increase of new energy access, the economic benefits of double terminal distribution network are increasing, and the effect is obvious. The economic benefit of ring distribution network is obviously lower than the other two distribution structures, which is mainly due to the high price of DC equipment, resulting in the imbalance between input and output.

6. Conclusion
In order to further improve the stability and profitability of the distribution network, this article first summarizes three classic distribution network structures, constrains new energy access capacity, and aims to maximize economic benefits. Comprehensive evaluation index system and objective function. The selected typical distribution structure is evaluated, and a distribution network suitable for different new energy consumption situations is selected.

a) Because this article considers the AC/DC hybrid distribution network connected to new energy, AC indicators such as frequency will not be considered in the power quality, but common indicators of the AC/DC distribution system will be considered. Can evaluate the distribution network more objectively.

b) Propose the objective function with the greatest economic benefits, which can more reliably choose the power supply structure of the current and future distribution networks.

c) In the example, the index calculation is performed for three typical power supply structures, and the corresponding power supply structures under different consumption rates are optimized.

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