Operation optimization of AC/DC hybrid distribution network considering uncertainty

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Abstract. In order to solve a series of problems such as the increase of AC/DC hybrid distribution network loss caused by the uncertainty of wind and solar output. Based on the uncertainty theory, wind power plants and photovoltaic generation are modeled, and a power flow calculation method for AC/DC distribution networks is proposed. Considering that when consuming fixed distributed generation, the minimum network loss is the objective function, and a particle swarm optimization-based AC/DC operation optimization method is proposed. Finally, the validity and feasibility of the proposed method are verified by simulation examples.

1. Introduction
The AC/DC hybrid distribution network combines the advantages of the traditional distribution network and the DC distribution network, which can realize the consumption of distributed generation on the user side, improve the economics of the distribution network, and is the development trend of the future distribution network.

As the intermittent energy represented by wind power is connected to the distribution network, the obvious fluctuation and intermittency of its output pose challenges to the optimal operation of the distribution network. Research on uncertainty modeling of intermittent energy output at home and abroad mainly focuses on fuzziness and randomness. Reference[1-2] According to the forecast error of intermittent energy output obeys the normal distribution, based on the sequence operation theory, the probability sequence is used to characterize the uncertainty of wind power output; Reference[3] establishes the uncertainty of wind power based on the Weibull distribution. In the economic dispatch model, the reserve cost and wind abandonment cost caused by uncertainty are taken into account.

With the continuous in-depth study of AC/DC hybrid distribution network, the operation optimization of AC/DC hybrid distribution network has attracted increasing attention. Reference [4] considers the on-state voltage drop of the DC solid-state circuit breaker, and establishes the optimal power flow model of the DC distribution network to solve the optimal power flow problem of the distribution network. Reference [5] established a multi-condition constraint optimal power flow convex programming model, and improved the calculation efficiency by introducing a model solving method based on the alternating direction multiplier method. In summary, in considering the
uncertainty of distributed power generation, there are few studies on the operation optimization of AC/DC distribution networks.

In response to the above problems, this article first establishes the probability model of wind turbines and photovoltaics. Secondly, the power flow model of AC/DC distribution network is established, and the alternating iterative method is used for power flow calculation. On this basis, the minimum network loss is taken as the objective function, and the particle swarm algorithm is used for optimization calculation. Through the optimal control of the operating power of the AC/DC distribution network, the loss of the AC/DC hybrid distribution network is reduced and the efficiency of system operation is improved.

2. Output models of wind power plants and photovoltaics

Reference [6] Simplified method, the wind farm uses a piecewise function to express the relationship between wind power output and wind speed, as in equation (1).

\[ p_w = \begin{cases} 0 & \text{if } v < v_{in} \text{ or } v > v_{out} \\ \frac{v - v_{in}}{v_r - v_{in}} & \text{if } v_{in} \leq v \leq v_r \\ \frac{v_r}{p_w} & \text{if } v_r \leq v \leq v_{out} \end{cases} \]  

\( v_r, v_{in}, v_{out} \) are the rated wind speed, cut-in wind speed, and cut-out wind speed of the wind turbine respectively; \( p_w \) is the rated power of the wind turbine. The size of the wind speed approximately obeys the distribution of the two-parameter Weibull function, and the corresponding probability density function can be expressed as (2).

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

\( k \) is the shape parameter of the wind speed probability distribution function, and \( c \) is the scale parameter. Comprehensive formula-conclusion, the probability density of wind power is expressed as (3-6).

\[ P\{P_{\text{wind}} = 0\} = 1 - \exp\left[-\left(\frac{v_{in}}{c}\right)^k\right] + \exp\left[-\left(\frac{v_{out}}{c}\right)^k\right] \]  

(3)

\[ P\{P_{\text{wind}} = P_w\} = 1 - \exp\left[-\left(\frac{v_{in}}{c}\right)^k\right] + \exp\left[-\left(\frac{v_{out}}{c}\right)^k\right] \]  

(4)

\[ f_v(P_{\text{wind}}) = \frac{k}{c} \left( \frac{v}{c} \right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] \cdot \frac{v - v_{in}}{N_w \cdot P_w} + v_{in} \]  

(5)

\[ \eta = \frac{P_{\text{wind}}(v - v_{in})}{N_w \cdot P_w} + v_{in} \]  

(6)

Among them, \( P\{P_{\text{wind}} = 0\} \) is the probability of no output, \( P\{P_{\text{wind}} = P_w\} \) is the probability of full power output, and \( f_v(P_{\text{wind}}) \) is the continuous probability density of output. \( N_w \) is the number of wind turbines in each wind farm.

The distribution of photovoltaic output has a strong time sequence, which can be considered to obey the Beta distribution, and its basic probability density distribution can be expressed as (7).

\[ \phi_G(G) = \frac{\Gamma(k_1 + k_2)}{\Gamma(k_1) \Gamma(k_2)} \left( \frac{G}{G_{\text{max}}} \right)^{k_1-1} \left( 1 - \frac{G}{G_{\text{max}}} \right)^{k_2-1} \]  

(7)

Among them, \( G \) and \( G_{\text{max}} \) are the light intensity and the maximum light intensity, respectively, and \( k_1 \) and \( k_2 \) are the shape parameters of the Beta distribution, respectively. This article assumes that wind speed and illumination are independent of each other, and considering geographical proximity, it
is considered that the wind speed (illumination) conditions at each distributed resource in the distribution network follow the same probability distribution, and a large number of initial scene random sample sets are obtained through independent sampling.

3. Power flow calculation of AC/DC hybrid distribution network

First, model the AC/DC system [7-8] and perform sequential power flow calculation [9]. The AC/DC power flow problem is solved in order, that is, the program solves the AC/DC power flow through iteration between the AC system and the DC system. In this way, the power of the DC system remains unchanged in the power flow of the AC system, and vice versa.

3.1. Power flow on the AC side

Calculate the flow using the Newton-Raphson method on the AC side, as shown in (8-9).

\[
P_i(U, \delta) = \sum_j G_{ij} \cos(\delta_j - \delta_i) + B_{ij} \sin(\delta_j - \delta_i)
\]

\[
Q_i(U, \delta) = \sum_j G_{ij} \sin(\delta_j - \delta_i) - B_{ij} \cos(\delta_j - \delta_i)
\]

(8)

(9)

The active and reactive power flowing into the converter can be regarded as AC loads, so the power mismatch vector equation can be expressed as (10-11).

\[
\Delta P_i^{(j)} = P^{(m)}_i - (P^{(d)}_i - P_i^{(j)})
\]

\[
\Delta Q_i^{(j)} = Q^{(m)}_i - (Q^{(d)}_i - Q_i^{(j)})
\]

(10)

(11)

The most common control strategies for inverters are: constant voltage control, droop control, and constant power control. In the case of multiple converters, usually one and only one converter adopts constant voltage control, and the others adopt constant power or droop control. Assuming there are k converters, the first converters adopts constant voltage control.

\[
P_i^{(0)} = \sum_{j=1}^{k} P_{ij}
\]

(12)

Using the power on the AC side, according to the converter loss model, calculate the converter loss and then calculate the converter side power flow.

\[
P_{\text{loss}} = a + b I_c + c I_c^2
\]

\[
I_c = \frac{P_{\text{loss}}}{\sqrt{3}U_c}
\]

(13)

(14)

3.2. Power flow on the DC side

The DC side power flow can also be solved by the Newton-Raphson method. Compared with the AC side, the DC side does not need to consider the reactive power and the calculation is easier. First of all, determine the control strategy of each node, and secondly perform the Newton-Raphson method power flow calculation for different nodes.

\[
P_{dc} = \left[ \begin{array}{c} P_{dc_1} \\ P_{dc_2} \\ \vdots \\ P_{dc_m} \\ P_{dc_{m+1}} \\ \vdots \\ P_{dc_k} \end{array} \right] \left[ \begin{array}{c} 0 \\ 0 \\ \vdots \\ 0 \\ \text{voltage control} \\ \text{outage} \right]
\]

\[
(U_{dc} \frac{\partial P_{dc}}{\partial U_{dc}}) = \Delta U_{dc} = \Delta P_{dc}
\]

(15)

(16)

In addition, neither the AC power flow calculation nor the DC power flow calculation can cause voltage and current overruns, that is,

\[
(U_{k,j_{\min}})^2 \leq U_{k,j} \leq (U_{k,j_{\max}})^2
\]

\[
0 \leq I_{k,j} \leq (I_{k,j_{\max}})^2
\]

(17)

(18)
Through the above formula, the power balance of each node and the voltage and current of each branch are not exceeded, where $U_{k,i,\text{max}}$ and $U_{k,i,\text{min}}$ are the maximum and minimum voltages of the $k$-th feeder node; $I_{k,i,\text{max}}$ represents the rated current of the $i$-th branch of the feeder $k$.

### 3.3. Alternate iterative process

First, input the original data of the distribution network, number the distribution network, and determine the initial value of the converter station and the corresponding control method. Secondly, calculate the power flow on the AC side until it converges, and calculate the injected power of the converter to determine whether the converter exceeds the limit. Then, calculate the power flow on the DC side until it converges and determine whether the AC and DC are both converged. If so, output the calculation result, otherwise return to continue the calculation.

### 4. Operation optimization of AC/DC distribution network

#### 4.1. Lowest objective function loss

$$\min f = \sum_{i=0}^{n} \Delta P_i + \sum_{i=1}^{N} \Delta P_{i,\text{VSC}} \quad (19)$$

In the formula, $\Delta P_i$ is the loss on the $i$-th feeder line, and $\Delta P_{i,\text{VSC}}$ is the loss of the $i$-th converter.

#### 4.2. Restrictions

1) Voltage constraints

$$U_{i,\text{min}} \leq U_i \leq U_{i,\text{max}} \quad (20)$$

In the formula, $U_{i,\text{min}}$ and $U_{i,\text{max}}$ are the upper and lower limits of the node voltage respectively; $U_i$ is the voltage of the node.

2) VSC power constraints

$$P_{\text{VSC},j,\text{min}} \leq P_{\text{VSC},j} \leq P_{\text{VSC},j,\text{max}} \quad (21)$$

In the formula, $P_{\text{VSC},j,\text{min}}$ and $P_{\text{VSC},j,\text{max}}$ respectively represent the upper and lower limits of the transmission power of the $j$-th VSC; $P_{\text{VSC},j}$ is the transmission power of the $j$-th VSC.

3) Line current-carrying capacity constraint

$$P_l^2 + Q_l^2 \leq S_{l,\text{max}}^2 \quad (22)$$

In the formula, $P_l$ and $Q_l$ respectively represent the active power and reactive power of line $l$; $S_{l,\text{max}}$ is the allowable maximum value of the transmission power of line $l$.

#### 4.3. Optimization

The operation optimization analysis of AC/DC hybrid distribution network in this paper is mainly composed of power flow calculation part and optimization program part. The optimization algorithm uses a particle swarm optimization algorithm. The essence of particle swarm optimization (PSO) is an optimized intelligent algorithm based on swarm behavior.

The basic process of the standard particle swarm algorithm is as follows:

1) Initialize the particle swarm algorithm, set the size of the particle swarm to $M$, the upper and lower limits of the inertia weight coefficient as $\omega_{\text{min}}$, $\omega_{\text{max}}$, determine the values of the learning factors $c_1$ and $c_2$, and set the termination condition of the algorithm to satisfy the maximum number of iterations $I_{\text{max}}$ etc.

2) Within the set feasible range, use the method of roulette to randomly initialize the position and velocity of the particles, as well as individual extreme values and global extreme values.

3) Update and adjust the position and velocity of particles.
4) Calculate the fitness value of each particle, and then update the individual extreme value and the global extreme value.

5) When the number of iterations reaches the predetermined $I_{\text{max}}$, the search is terminated and the optimal result is output.

5. Case study

In order to verify the effectiveness of the AC-DC hybrid distribution network model proposed in this paper, this article reforms the IEEE RBTS Bus6 system. The transformed AC-DC hybrid distribution network model is shown in the following figure [25,30,31], in the feeder F4 line A VSC converter is installed at the head end to transform it into a DC line, and AC and DC loads, photovoltaic, wind power and energy storage are connected to the feeder to form an AC-DC hybrid radiant power supply structure, in front of the F4 feeder bidirectional converter Lead out the AC feeder, and use the cable feeder for the AC and DC lines. Set the rated voltage of the DC system to ±10kV. There are 27 loads in the network, 8 DC loads and 19 AC loads.

The amount of distributed power access is different, and the degree of loss optimization is different. This paper solves the optimization results of network loss when the amount of distributed power access is 20%, 40%, and 60%.

![Figure 1. AC / DC hybrid distribution network](image1)

The active power loss of AC / DC system before and after optimization is shown in Figure 2. When the penetration rate of distributed generation is different, the loss is reduced by optimizing the system.

![Figure 2. Comparison before and after optimization](image2)
6. Conclusion
The AC/DC hybrid distribution network operation optimization method proposed in this paper takes the lowest system loss as the objective. Taking into account the uncertainty of distributed generation, the particle swarm optimization algorithm is adopted to reduce the network loss of the system and improve the economic efficiency of system operation.

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